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Timing and geochemistry of potassic magmatism in the eastern part of the Svecofennian domain, NW Ladoga Lake Region, Russian Karelia

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Abstract

The Puutsaari intrusion is a potassium-rich magmatic complex in the eastern part of the Svecofennian domain close to the Archaean border. The intrusion is generally undeformed in contrast to 1880–1875 Ma-old country rock tonalitic migmatites and diatectites. The main rock types are: (1) mafic rocks of a gabbro–norite–diorite–quartz monzodiorite series; (2) quartz diorite–tonalite–granodiorite; and (3) coarse-grained microcline granite. The three rock-types intruded coevally forming a peculiar three-component mingling system. The mafic rocks, enriched in K, P, Ba, Sr and LREE, have marked shoshonitic affinities ($K_2O = 1.97–5.40$, $K_2O/Na_2O = 0.6–2.37$). On a regional scale they demonstrate transitional geochemistry between less enriched syn-orogenic 1880 Ma-old gabbro–tonalite complexes and strongly enriched 1800 Ma post-collisional shoshonitic intrusions. The microcline granite as well as the tonalite–granodiorite rocks are geochemically similar to crustal anatectic granitoids of the NW Ladoga Lake area. The three rock groups do not form a single trend on Harker-type diagrams and are unlikely to be related by fractional crystallisation or mixing. Zircons from the Puutsaari microcline granite and from the mafic rock series have been dated by ion-microprobe (NORDSIM) at 1868.2 ± 5.9 and 1869 ± 7.7 Ma, respectively. Most zircons recovered from a granite sample had zoned or homogeneous cores and unzoned fractured rims. No statistically significant variation of zircon core and rim ages from the granite was established in the course of this study. Zircons from the mafic rock are unzoned. It is suggested that the mafic rocks at Puutsaari were derived from an enriched mantle shortly after the main Svecofennian collisional event and the roughly 1.88 Ga regional metamorphic culmination. The emplacement of the mafic melt caused anatectic melting of various crustal protoliths and produced coeval granitic and tonalitic compositions.

Keywords: Post-collisional magmatism; Shoshonitic rocks; Anatectic melting; Lithospheric mantle; U–Pb zircon

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1. Introduction

The Puutsaari intrusion is the northernmost composite potassium-rich magmatic complex in

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the Ladoga Lake region, situated in the Svecofennian domain (Fig. 1). The well-outcropped Isl. Puutsaari, composed of ‘orthoclase granite with peculiarly shaped dark-coloured enclaves’ was described in early works of Inostrantsev (1870) and Sederholm (1916), the latter compared the Puutsaari granite with the Siljan and Järna granites in Sweden.

As a result of these and later works Isl. Puutsaari became a regional type-locality of undeformed granite.

The enriched character of the lithospheric mantle under the NW Ladoga Lake region was emphasized by Konopelko (1997) and Eklund et al. (1998) who described strongly K, P, Ba, Sr and LREE enriched shoshonitic post-collisional intrusions formed ca. 1800 Ma ago. However, the timing of the early potassic magmatism postdating 1880 Ma-old peak metamorphism in the area is poorly constrained. Mafic intrusions in the region are mostly not dated, while available conventional U–Pb zircon ages of anatectic granites are few and not unequivocal due to commonly found metamict cores.

In this article we present the results of an ion microprobe U–Pb zircon study of the two major rock-types from Puutsaari intrusion. The geological and geochemical characteristics of the intrusion are presented with the emphasis on potassium-rich rock types. Svecofennian geology of the Ladoga Lake area is reviewed and petrological and regional implications of the obtained data are discussed.

2. Regional geology and available age data

A schematic geological map of the NW Ladoga Lake region and adjacent areas of SE Finland is compiled in Fig. 1. Most of the available U–Pb zircon ages are included in the map. In central Finland and Russian Karelia the transition between the Karelian craton (Archaean in age) and the Palaeoproterozoic Svecofennian domain occurs within the 50–150 km wide Raahe-Ladoga zone. Characteristic features of the zone are the Archaean gneiss domes penetrating the Palaeoproterozoic Kalevian metasediments and low e_{Nd} values of the Svecofennian granitoids indicating significant input of an Archaean component (Huhma, 1986). In the NW Ladoga Lake region the southwestern margin of the Raahe-Ladoga zone is defined by the Meijeri thrust (Baltibayev et al., 1996) separating the Svecofennian formations from the Raahe-Ladoga zone about 15 km north of Puutsaari.

Svecofennian supracrustal rocks in the NW Ladoga Lake area comprise a metasedimentary assemblage of schists, gneisses and calc-silicate rocks. The Svecofennian formations in the region are divided into two major blocks or terranes separated by the NW trending Priozersk shear zone. To the north of the Priozersk shear zone high temperature–low pressure granulite and amphibolite facies rocks with abundant tonalitic-trondhjemitic migmatites and diatectites are common, while towards the south there is an area of pronounced granitic migmatisation.

The relative tectonic position of the NW Ladoga Lake region is rather uncertain. Geographically the northern terrane corresponds to the Primitive Arc Complex of Central Finland and the southern terrane corresponds to the Accretionary Arc Complex of Southern Finland (Korsman et al., 1997; Rämö et al., 2001). The Late Svecofennian Granite-Migmatite zone, defined by Ehlers et al. (1993), was formed along the Accretionary Arc Complex of Southern Finland during the Late Svecofennian metamorphic event ca. 1830 Ma ago.

Fig. 1. Schematic geological map of the region to the northwest of Lake Ladoga and southeast Finland. Based on Koistinen and Saltykova (1999) and Konopelko (1997), modified by the authors. Available U–Pb zircon ages of intrusive rocks from a number of localities are shown. References: (1) Bogachev et al. (1999), (2) Glebovitsky et al. (2001), (3) Ivanikov, unpublished, (4) Konopelko (1997), (5) Korsman et al. (1984), (6) Nykänen (1983), (7) Vaasjoki et al., (1991), (8) Vaasjoki and Sakko (1988), (9) Vaasjoki and Kontoniemi (1991), (10) Vaasjoki (1996) and references therein, (11) Vaasjoki, pers. comm., (12) this study. * Position of the Isl. Puutsaari.

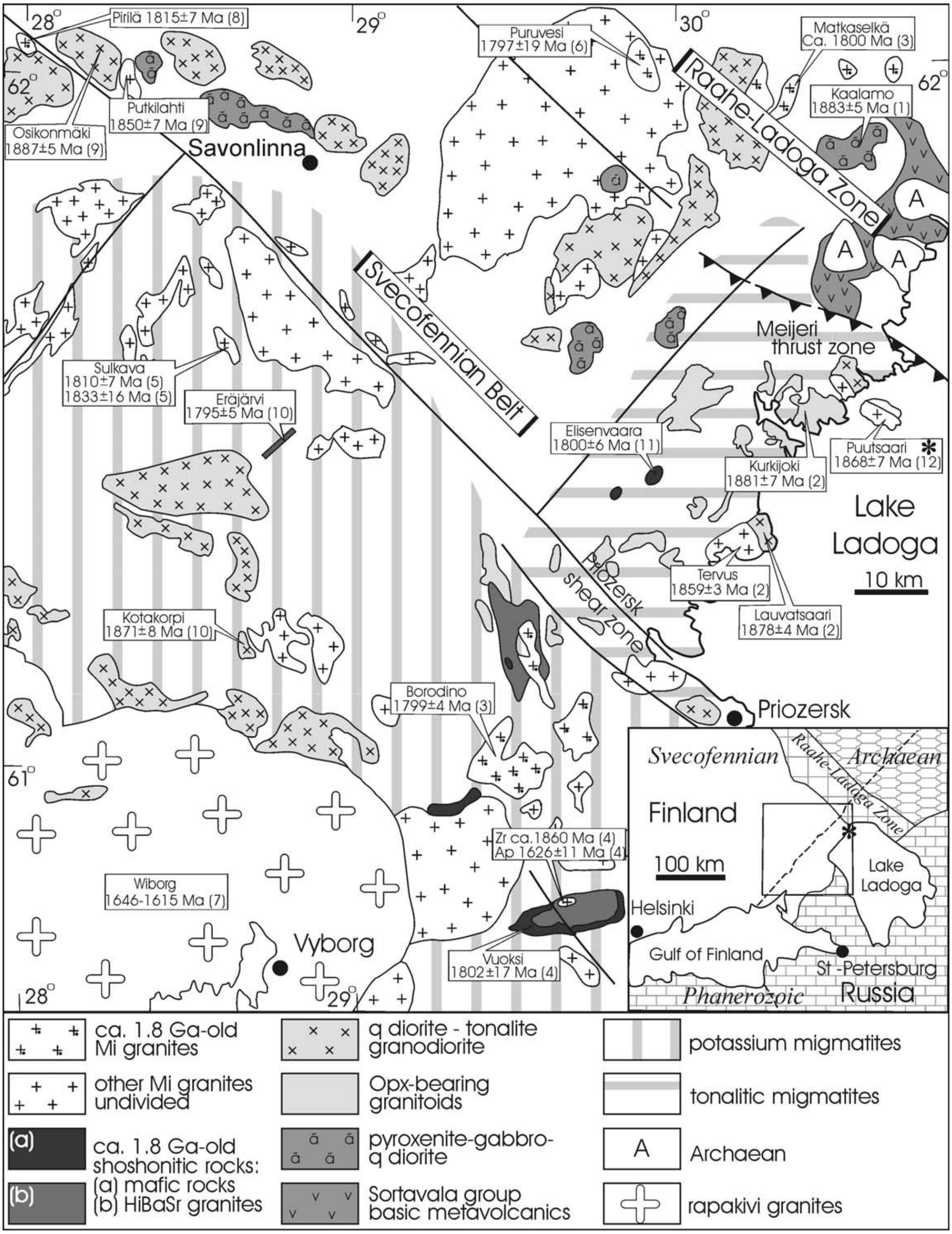
28°
29°
30°
62°
61°
Pirilä 1815±7 Ma (8)
Puruvesi 1797±19 Ma (6)
Matkaselkä Ca. 1800 Ma (3)
Kaalamo 1883±5 Ma (1)
Putkilahti 1850±7 Ma (9)
Osikonmäki 1887±5 Ma (9)
Savonlinna
Raahe-Ladoga Zone
Svecofennian Belt
A
Meijeri thrust zone
Sulkava 1810±7 Ma (5) 1833±16 Ma (5)
Eräjärvi 1795±5 Ma (10)
Elisenvaara 1800±6 Ma (11)
Kurkijoki 1881±7 Ma (2)
Puutsaari 1868±7 Ma (12)
Lake Ladoga
10 km
Priozersk shear zone
Tervus 1859±3 Ma (2)
Lauvatsaari 1878±4 Ma (2)
Kotakorpi 1871±8 Ma (10)
Borodino 1799±4 Ma (3)
Priozersk
Zr ca.1860 Ma (4) Ap 1626±11 Ma (4)
Wiborg 1646-1615 Ma (7)
Vyborg
Vuoksi 1802±17 Ma (4)
Svecofennian
Archaean
Raahe-Ladoga Zone
Finland
100 km
Lake Ladoga
Helsinki
Gulf of Finland
St-Petersburg
Phanerozoic
Russia
ca. 1.8 Ga-old Mi granites
other Mi granites undivided
(a)
(b)
ca. 1.8 Ga-old shoshonitic rocks: (a) mafic rocks (b) HiBaSr granites
q diorite - tonalite granodiorite
Opx-bearing granitoids
pyroxenite-gabbro-q diorite
Sortavala group basic metavolcanics
potassium migmatites
tonalitic migmatites
A
Archaean
rapakivi granites

Fig. 1

In the NW Ladoga Lake region, ages of granitic migmatisation in the southern terrane and tonalitic migmatisation in the northern terrane were recently studied by Baltibayev et al. (2002) who reported similar monazite ages of 1869–1872 Ma for leucosomes and their country gneisses in both the southern and the northern terranes. According to Baltibayev et al. (2002) both terranes were affected by the same 1880 Ma metamorphism and the compositional variation of the migmatites resulted from compositional variation of their supracrustal protoliths.

Intrusive magmatic series in the NW Ladoga Lake region comprise up to 40% of the present surface. The oldest complexes include syn-kinematic norite–enderbite series and tonalite–granodiorite intrusions with associated gabbroic rocks. Conventional U–Pb zircon dating has given an age of 1881±7 Ma for enderbite at Kurkijoki and 1878±4 Ma for a diorite from the Lauvatsaari gabbro–diorite–tonalite intrusion (Glebovitsky et al., 2001). These ages define the metamorphic culmination in the northern terrane and are in agreement with the ages of syn-kinematic tonalites and orthopyroxene-bearing granitoids that post-date the regional deformation in the southeastern and central Finland (Huhma, 1986; Hölttä, 1988; Rämö et al., 2001).

The transition to potassium-rich granites in the northern terrane is manifested by late- to post-kinematic intrusions where microcline granite represents the dominant rock type. The two major intrusions of this type in the northern terrane are the Tervus and the Puutsaari complexes. In the Isl. Puutsaari the microcline granite is associated with significant amounts of potassium-rich mafic rocks and with rocks of tonalite–granodiorite series. The intrusions crosscut migmatites and are less deformed compared to the country rocks. Conventional U–Pb zircon dating of the Tervus microcline granite has yielded an age of 1859±3 Ma (Glebovitsky et al., 2001). In southeastern Finland, similar ages have been reported from the intrusions with granodioritic to granitic compositions by Huhma (1986) and Vaasjoki (1996).

Ages of 1840–1815 Ma corresponding to the Late Svecofennian metamorphic event that formed the Late Svecofennian Granite-Migmatite zone in southern Finland (Ehlers et al., 1993) have not been reported from the NW Ladoga Lake area. However, some of the microcline granites in the Ladoga Lake area (Konopelko, 1997) and eastern Finland (Huhma, 1986; Vaasjoki and Kontoniemi, 1991) formed in a time span between 1815 and 1790 Ma overlapping with the youngest ages of S-type granites and migmatites within the Late Svecofennian Granite-Migmatite zone. According to Eklund et al. (1998) and Väisänen et al. (2000), these young microcline granites were formed by anatectic melting of the crust triggered by heat provided by the emplacement of post-collisional shoshonitic intrusions ca. 1800 Ma ago.

The mantle-derived post-collisional shoshonitic lamprophyre-granitoid intrusions represent the latest Svecofennian magmatic event in the region (Eklund et al., 1998; Konopelko et al., 1998). The shoshonitic rocks comprise a unique series extremely enriched in P, F, Ba, Sr and LREE. The source region for this shoshonitic association is considered to be a lithospheric mantle affected by carbonate metasomatism (Eklund et al., 1998). In the NW Ladoga Lake area the emplacement and mid-crustal fractionation of the shoshonitic lamprophyric melt was accompanied by crustal anatexis and produced significant volumes of the granitoid rocks varying in composition from anatectic S-type microcline granites to shoshonitic HiBaSr granites and syenites directly fractionated from the lamprophyric melt. A number of single grain ^{207}Pb/^{206}Pb zircon ages obtained by the evaporation method (Ivanikov, unpubl.; Konopelko, 1997) as well as conventional U–Pb zircon data (Shul'diner et al., 2000) and K–Ar amphibole ages (Konopelko, 1997) define an age interval of 1787–1809 Ma for the shoshonitic intrusions in this area. The intrusion at Elisenvaara, has been recently dated by conventional U–Pb zircon method at 1800±6 Ma (Vaasjoki, 2001, pers. com.).

After the emplacement of the shoshonitic intrusions there was a magmatically quiet period of ca. 150 Ma until the Wiborg massif of rapakivi granites and related anorthositic rocks formed within the age range of 1646–1615 Ma (Vaasjoki et al., 1991).

3. The Puutsaari intrusion

The intrusion crops out as an elongate composite body (ca. 2 × 6 km) on the Isl. Puutsaari and on the northwest shore of the Lake Ladoga. A simplified geological sketch of Isl. Puutsaari based on detailed maps of Volotovskaya (1948) and Saranchina (1972) is given in Fig. 2. The elongation of the intrusion is roughly parallel to the NW-striking regional foliation of the country rocks, which comprise granulite facies biotite ± garnet ± orthopyroxene gneisses as well as tonalitic migmatites and diatectites. The contact of the intrusion represents a 10–50 m wide transitional zone of predominantly tonalitic composition. In contrast to the country rock gneisses, the rocks of the intrusion are almost undeformed. However, a NW striking magmatic foliation in the mafic rocks and trachytoidal texture in the porphyritic granitoids is locally common.

The intrusion consists of the three major rock series: (1) gabbro–norite–gabbro–diorite–monzodiorite; (2) quartz diorite–tonalite–granodiorite; and (3) granodiorite–porphyritic microcline granite. The mafic rocks form few small bodies of ca. 100–200 m across and numerous smaller enclaves in the granitoid varieties. The rocks of the quartz diorite–tonalite–granodiorite series are abundant along the exposed northern contact of the intrusion and comprise several elongated bodies in its central and southern parts. The coarse-grained porphyritic microcline granite, containing enclaves of both mafic rocks and tonalites, makes up an irregular body occupying central and southern parts of the Isl. Puutsaari.

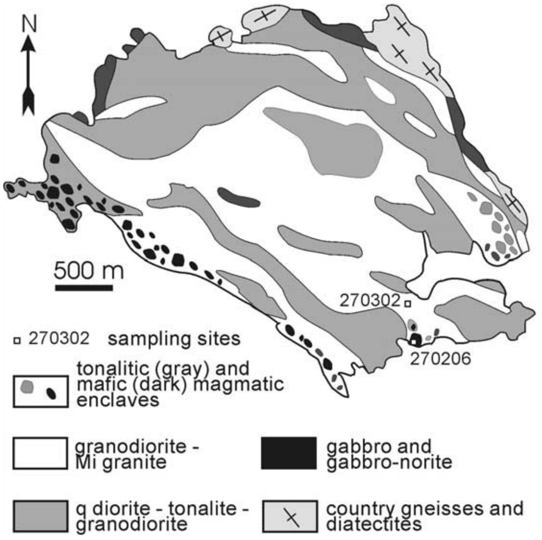

Fig. 2. Simplified geological map of the Isl. Puutsaari. Based on Volotovskaya (1948) and Saranchina (1972), modified by the authors.

In early works the enclaves in the microcline granite were described as xenoliths, and the whole system as an eruptive breccia (e.g. Saranchina, 1972). During this study we have recognised that large areas within the intrusion demonstrate signatures of coeval emplacement of melts with different compositions.

The mafic rock and the tonalitic granitoids form a net-veined system where mafic rocks occur as smooth rounded pillows in the granitoid. This suggests that the two melts were co-mingled together.

The microcline granite contains enclaves of both mafic and tonalitic composition as well as disrupted synplutonic mafic dikes. Where mafic enclaves are abundant, typical net-veined mingling-mixing systems are developed. The mafic enclaves appear as rounded, sometimes, mushroom-shaped bodies in the granodioritic to granitic host; back-veining of granitic material into the enclaves along late brittle fractures is common (Fig. 3). The mushroom-shape was formed when the more dense but less viscous mafic magma was transported in the cooler and more viscous granitic magma. The granitic magma was still viscous after the mafic enclave reached its solidus, whereas the granitic magma was able to break up and form veins (back-veining) in the brittle mafic enclave. The hybrid origin of the most silica-rich mafic enclaves is, occasionally, outlined by the amphibole-mantled corroded quartz grains and larger porphyritic K-feldspar crystals. These xenocrysts were encaptured from the surrounding crystal-saturated granitic magma when the viscosity of the mafic enclaves were lower than the viscosity of the granitic magma (Sato, 1975).

Rounded tonalitic enclaves, usually about a few tens of centimetres across, in the microcline granite are found in a large area in the north-eastern part of the intrusion.

Fig. 3. Photograph of mafic enclaves in hybrid granodioritic matrix. Note that the mushroom-shaped mafic enclave in the centre is back-veined by granitic material in its upper part. Southern shore of Isl. Puutsaari. Width of the photograph corresponds to 1.8 m.

Locally the three rock units are observed in the same outcrop. In these outcrops it seems that coeval emplacement of mafic and tonalitic melts slightly preceded the intrusion of the microcline granite. It is evident, however, that when the granitic melt was emplaced, all the three components were not yet entirely crystallised. To illustrate the relationships between the three rock-types the perfect sketch from an early work of Volotovskaya (1948) is reproduced in Fig. 4. On the other hand, later emplacement of microcline granite is locally emphasised by normal breccias that sometimes contain a mixed enclave assemblage of mafic rocks and country gneisses.

Thus, the three major rock types in the Puutsaari intrusion formed coevally as an unusual three-component mingling system producing a number of hybrid rock types.

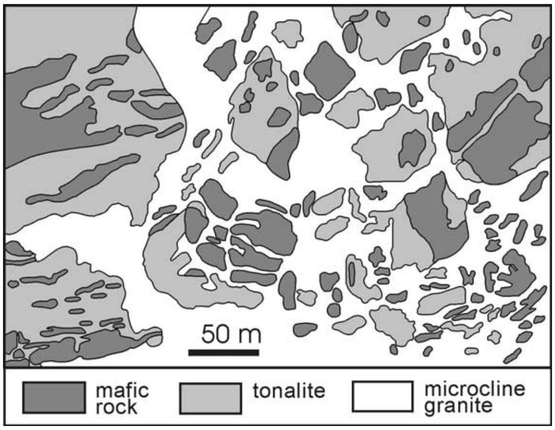

Fig. 4. Detailed geological map illustrating three-component mingling. Southern shore of Isl. Puutsaari. Modified by the authors after Volotovskaya (1948). See text for explanation.

3.1. Petrography and geochemistry

Representative analyses of the three rock groups from the Puutsaari intrusion and two hybrid compositions are given in Table 1. Major elements were analysed by XRF, trace elements by ICP-MS (Actlabs, Canada) and ICP-AES (Ecole des Mines de Saint Etienne, France) methods.

Selected Harker-type diagrams for the rocks of the Puutsaari intrusion are given in Fig. 5a–c. Chondrite-normalised REE concentrations and N-type MORB-normalised trace element concentrations for the Puutsaari rocks are given in Figs. 6 and 7, respectively. N-type MORB values have

Table 1
Chemical composition of the rocks from the Puutsaari intrusion

Rock type	Mafic rocks							Hybrid matrix		Ganodiorite		Mi-granite	
Sample N	270300	110B/97*	270206	PUTLAMP	PUTDI	270200	PUTMAF	114/97*	270201	89*	204/1*	PUTGRA	270302
SiO_2	46.18	46.50	50.02	50.98	51.40	52.98	55.42	58.90	64.80	63.12	73.29	67.39	72.50
TiO_2	1.75	2.30	2.16	1.88	2.05	1.22	1.87	1.40	0.92	1.26	0.38	0.63	0.44
Al_2O_3	13.29	16.70	15.62	16.90	15.59	15.33	14.66	17.60	15.42	16.13	14.33	14.84	13.44
FeO^{tot}	9.72	12.02	11.05	8.52	8.04	7.78	8.60	5.72	4.54	5.14	1.77	3.13	2.14
MnO	0.17	0.15	0.14	0.12	8.93	0.13	0.14	0.01	0.06	0.07	0.03	0.02	0.03
MgO	8.94	5.00	4.23	3.96	3.78	4.12	4.03	2.70	1.70	1.66	0.68	1.30	0.62
CaO	11.73	6.20	7.85	6.15	8.55	5.24	6.41	3.20	3.07	3.33	1.87	2.54	1.70
Na_2O	2.01	3.10	3.30	3.60	3.30	2.28	3.05	3.20	3.40	3.90	3.60	3.45	2.78
K_2O	1.97	3.50	1.98	3.21	1.97	5.40	2.30	4.40	3.93	3.60	3.61	4.27	5.04
P_2O_5	1.71	1.70	1.08	1.37	1.74	1.46	0.68	0.86	0.43	0.50	0.01	0.29	0.14
H_2O+	#	#	#	1.18	1.09	#	0.88	#	#	#	#	0.61	#
LOI	1.65	1.90	0.87	1.07	1.48	2.62	1.00	1.20	1.12	0.80	0.37	0.63	0.47
F	#	#	#	2477	2119	#	1249	#	#	#	#	1057	#
Cr	204	#	18	163	211	63	198	#	35	#	#	173	21
Ni	148	#	24	16	44	46	42	#	13	#	#	8	8
V	164	#	166	85	102	139	141	#	72	#	#	97	64
Rb	86	#	42	91	82	#	83	#	#	#	#	94	84
Ba	2625	#	1321	2070	720	2681	965	#	1747	#	#	1890	2016
Sr	2789	#	985	1430	921	1174	635	#	643	#	#	832	515
Zr	383	#	491	358	358	294	303	#	333	#	#	371	278
Hf	7.8	#	10.6	8.7	7.7	#	7.3	#	#	#	#	7.3	6.2
Y	36	#	39	37	51	34	33	#	12	#	#	9	4
Nb	19	#	31	41	46	33	31	#	22	#	#	21	8
Ta	1.11	#	1.88	1.62	2.00	#	1.70	#	#	#	#	0.53	0.40
Th	13.10	#	1.89	1.58	4.16	#	3.94	#	#	#	#	9.44	4.31
U	5.54	#	0.78	0.67	1.12	#	2.50	#	#	#	#	2.13	0.99
La	213	#	98	128	123	218	58	#	49	#	#	66	36
Ce	453	#	228	273	277	507	120	#	100	#	#	110	58
Pr	53.0	#	27.3	34.6	36.5	#	14.7	#	#	#	#	10.9	5.2
Nd	199.0	#	104.0	136.8	147.7	228.0	58.0	#	54.7	#	#	36.4	17.4
Sm	28.2	#	16.8	20.0	23.1	#	9.5	#	#	#	#	4.3	2.0
Eu	6.85	#	3.74	3.99	3.06	5.45	2.37	#	2.83	#	#	1.69	1.70
Gd	16.70	#	12.60	14.68	17.94	#	7.83	#	#	#	#	2.99	1.46
Tb	1.93	#	1.59	1.78	2.25	#	1.19	#	#	#	#	0.37	0.15
Dy	7.94	#	7.69	8.04	10.09	#	6.37	#	#	#	#	1.58	0.69
Ho	1.25	#	1.39	1.32	1.64	#	1.19	#	#	#	#	0.28	0.10
Er	3.18	#	3.78	3.49	4.16	#	3.28	#	#	#	#	0.75	0.30
Tm	0.35	#	0.48	0.43	0.51	#	0.46	#	#	#	#	0.10	0.04

Table 1 (*Continued*)

Rock type	Mafic rocks							Hybrid matrix		Ganodiorite		Mi-granite	
Sample N	270300	110B/97*	270206	PUTLAMP	PUTDI	270200	PUTMAF	114/97*	270201	89*	204/1*	PUTGRA	270302
Yb	2.25	#	3.08	2.47	2.59	2.51	2.85	#	1.18	#	#	0.63	0.31
Lu	0.31	#	0.36	0.30	0.28	#	0.38	#	#	#	#	0.09	0.05
Mg#	66	47	45	49	50	53	50	50	44	40	45	47	38
A/CNK	0.50	0.83	0.71	0.82	0.67	0.80	0.76	1.11	1.00	0.98	1.08	0.99	1.02

FeO^{tot} = total Fe as FeO; Mg# = 100 × MgO/(MgO+0.85 × FeO^{tot}) mol.; A/CNK = $Al_2O_3/(CaO+Na_2O+K_2O)$ mol.

* From Lyahnitskaya, 2000.

been chosen for normalisation to emphasise the incompatible element enriched character of Puutsaari mafic rocks. For a comparison in Fig. 5a,bFigs. 6 and 7 we included rocks of the slightly older 1878 Ma Lauvatsaari gabbro-quartz diorite–tonalite complex (unpubl. data of Kozireva compiled by Lyahnitskaya, 2000, used with the permission of both authors) and rocks of ca. 1800 Ma post-collisional shoshonitic intrusions (data from Rutanen et al., 1997), representing two major magmatic events predating and post-dating the Puutsaari intrusion in the NW Ladoga Lake area (Fig. 1).

The three rock groups from the Puutsaari intrusion define rather alkali-rich monzonitic trend on a TAS diagram (Fig. 5a). On K_2O versus silica diagram (Fig. 5b) the Puutsaari rocks plot into high-K and marginally into shoshonitic field indicating mostly potassic alkalinity.

3.1.1. *The mafic rocks*

The mafic rocks comprise a series from gabbro–norite to quartz monzodiorite with mafic index varying from 60 to 25%. Hypidiomorphic medium-grained textures dominate. Lamprophyric texture is locally observed in the monzodiorites. The mafic rocks comprise both amphibole- and pyroxene-bearing varieties. All rock types are rich in biotite. Small amounts of modal quartz and relatively Ab-rich plagioclase (An_{35-45}) are common. K-feldspar content reaches 15% in the monzodiorites. Minor minerals are apatite, zircon, allanite, titanite and opaque. Mafic rocks have SiO_2 content 46–57% (Fig. 5c), and plot within the calc-alkaline field in the AFM diagram. However, the relatively low Al_2O_3 content (12–16%) and the low Mg# (45–64) indicate an elevated FeO/MgO ratio which makes them similar to some tholeiitic basalt compositions. The mafic rocks are metaluminous. They are enriched in P_2O_5, Ba, Sr, LREE and F, have fractionated REE patterns sometimes with minor negative Eu anomaly (Fig. 6). The mafic rocks show negative spikes for Ta, Nb and Ti in the trace element abundance diagram (Fig. 7). Increased concentrations of K_2O, P_2O_5, Ba, Sr, LREE and F, and relatively low Rb, found in the

Puutsaari mafic rocks, are characteristic for the rocks of shoshonitic association (Morrison, 1980). However, as seen from Figs. 6 and 7 the shoshonitic affinities of the Puutsaari rocks are less pronounced compared to post-collisional shoshonitic intrusions formed in the same area ca. 1800 Ma ago (Konopelko, 1997; Eklund et al., 1998).

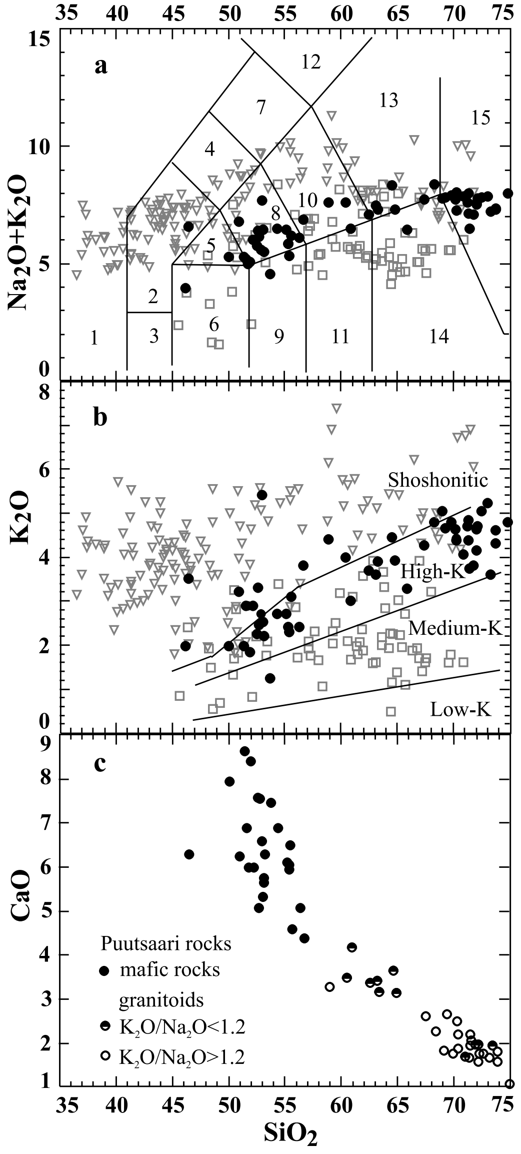

Fig. 5

3.1.2. The granitoids

The two Puutsaari granitoid types have SiO_2 contents of 60–75%. They are marginally peraluminous with A/CNK index up to 1.2.

The quartz diorite–tonalite–granodiorite series are even-grained or slightly porphyritic rocks consisting of varying amounts of plagioclase (An_{27-37}, 46–68 vol.%), biotite (10–12%, rarely up to 25%), quartz (15–40%) and amphibole (0–10%). Minor minerals are titanite, apatite, zircon, monazite and, locally, garnet. Elevated K_2O contents in the rocks of the tonalite–granodiorite series (Fig. 5b, Table 1) are explained by their high biotite contents, commonly found metasomatic microcline. As a consequence of magma mixing, hybrid compositions transitional to microcline granites are found. The tonalites are distinguished on CaO versus silica diagram (Fig. 5c) by their high CaO contents (3–4.5%) when compared to the microcline granites (1–3%). Fig. 5c also shows that most of the tonalite samples have $K_2O/Na_2O < 1.2$.

The microcline granite found in areas free of mafic enclaves is a coarse-grained porphyritic rock consisting of microcline (32–40 vol.%), plagioclase (An_{18-22}, 28–34%), quartz (28–34%) and biotite (up to 5–7%). Minor minerals are opaque, apatite, zircon and monazite. The granites are rich in alkalies (Na_2O+K_2O 6–9%, $K_2O/Na_2O > 1.2$–1.4) and have Mg# between 35 and 50. Similar to the mafic rocks, the microcline granites have relatively high concentrations of Ba, Sr, LREE and low Rb (Table 1, Figs. 6 and 7). The REE patterns of the microcline granites, in contrast to mafic rocks, show positive Eu anomalies. The

Fig. 5. Harker-type diagrams for the rocks of the 1868 Ma Puutsaari intrusion (circles). Rocks of 1878 Ma gabbro–diorite–tonalite Lauvatsaari complex (squares) and ca. 1800 Ma shoshonitic post-collisional intrusions (triangles) from the NW Ladoga Lake region are given for a comparison. (a) Total alkali vs. silica (TAS) diagram. Fields after Middlemost (1994): 1, foidolite; 2, foid gabbro; 3, peridotitic gabbro; 4, foid monzodiorite; 5, monzogabbro; 6, gabbro; 7, foid monzosyenite; 8, monzodiorite; 9, gabbroic diorite; 10, monzonite; 11, diorite; 12, foid syenite; 13, syenite and quartz monzonite; 14, granodiorite; 15, granite. (b) K_2O vs. silica diagram. Fields after Le Maitre et al. (1989). (c) CaO vs silica diagram.

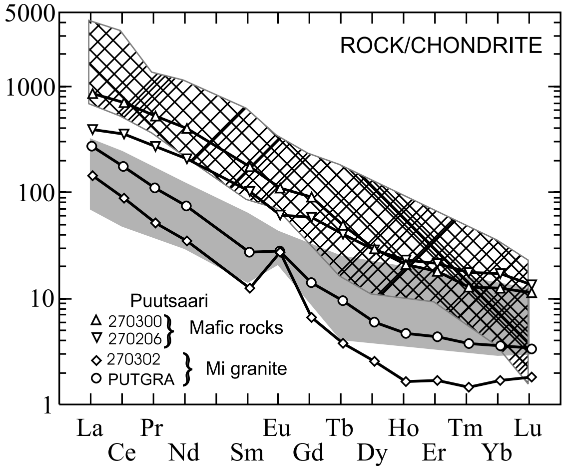

Fig. 6. Chondrite-normalised (Sun and McDonough, 1989) REE patterns for the rocks of the Puutsaari intrusion. The sample numbers in the legend correspond to those in Table 1. Shaded fields for 1878 Ma gabbro–diorite–tonalite Lauvatsaari complex (gray) and ca. 1800 Ma shoshonitic post-collisional intrusions (crosshatching) from the NW Ladoga Lake region are given for a comparison.

granites are relatively depleted in HREE and, thus, have more fractionated pattern when compared to the mafic rocks (Fig. 6). On a trace element abundance diagram (Fig. 7) the microcline granites have relatively depleted patterns (with the exception for LILE, Zr, Hf) and pronounced negative Nb and Ta spikes.

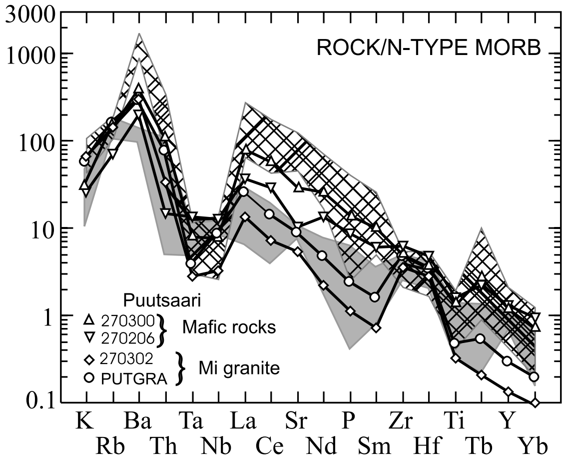

Fig. 7. N-type MORB-normalised (Sun and McDonough, 1989) trace element abundances for the rocks of the Puutsaari intrusion. See Fig. 6 caption for the legend.

4. Ion-microprobe U–Pb zircon geochronology

Two samples were selected for ion-microprobe U–Pb zircon geochronology: a typical coarse-grained microcline granite free of mafic enclaves (sample 270302) and a mafic rock (gabbro–diorite) from a homogeneous large enclave ca. 50 m across (sample 270206). Sampling localities are shown on Fig. 2 and the chemical compositions of the samples are given in Table 1.

4.1. Analytical procedures

Selected zircon grains were hand-picked from the heavy mineral separates, mounted in epoxy resin disk together with zircons used as a standard and polished to reveal zircon interiors. The zircons were studied at the department of geosciences, Stockholm University and at NORDSIM laboratory of the Swedish Museum of Natural History, Stockholm. Prior to analyses, the zircons were investigated in transmitted and reflected light and under a Philips scanning electron microscope (SEM) equipped with cathodoluminiscence (CL) and back-scattered electron (BSE) units. U–Th–Pb isotope analyses were performed on a high-mass resolution, high-sensitivity Cameca IMS 1270 ion microprobe (NORDSIM facility). The analysed spots were ca. 30 μm wide. Details of the analytical procedure and data reduction are given in Whitehouse et al. (1997) and Zeck and Whitehouse (1999). The calibration of the raw data was based on the analyses of the Geostandards zircon 91500 with an accepted age of 1065 Ma (Wiedenbeck et al., 1995).

4.2. Transmitted light, SEM, BSE and CL observations

The zircon population of the granite sample 270302 consists of subhedral and euhedral, prismatic and long prismatic crystals with fractures. In transmitted light they are pale brown or colourless, translucent, nebulous or partly metamictic.

Most of the zircon grains contain visible broad metamictic or partly metamictic brownish zoned cores and transparent zoned overgrowths with radial fractures. The grain size is 40–400 μm, and the length/width ratio is 2–4. Only a few individual zircon crystals are clean translucent and homogeneous grains. BSE images of the zircons from the granite demonstrate well-developed cores of two types: internally zoned and relatively homogeneous. Under CL the granite zircons show almost no contrasts or only diffuse zones with darker areas corresponding to the cores. BSE images of all analysed zircons from granite as well as one of the most contrast CL images and SEM image of the same grain are shown in Fig. 8.

Zircons recovered from the mafic rock sample 270206 differ significantly from zircons of the granite. They are strongly elongated, prismatic and unzoned crystals up to 700 µm with length/width ratio up to 6. BSE (Fig. 8), CL and SEM images of the zircons also reveal unzoned homogeneous interiors and much less fractures compared to the zircons from granite. None of the studied grains showed any contrast zoning under CL.

4.3. Results

For ion-microprobe analyses, the four most pure zircon grains from the Puutsaari mafic rock were selected. From the grains selected from the microcline granite homogeneous cores, rims and small unzoned zircons were analysed. The U–Th–Pb data are presented in Table 2 and plotted as 2σ error ellipses in Fig. 9. Age calculations were made using the Isoplot/Ex v. 2.05 program (Ludwig, 1999). All age errors quoted in the text are 2σ. Of all the analyses 13 are concordant and four are slightly reversely discordant in terms of 2σ errors.

Analyses of zircons from the Puutsaari mafic rock are rather consistent and yield a discordia age of 1867.0 ± 7.9 Ma (Fig. 9a). The discordia line was forced through zero since it was suggested that losses of lead were recent. If one discordant analysis is excluded, concordia age for zircons from mafic rock is 1869 ± 7.7 Ma (Fig. 9a).

The analyses of cores, rims and unzoned zircons from the Puutsaari granite do not register any statistically significant age difference and all together yield a concordia age of 1868.2 ± 5.9 Ma ($n = 11$, 95% conf., MSWD = 7.6). Being calculated separately, cores and rims (including unzoned grains) yield similar concordia ages of 1869.4 ± 13 and 1867.2 ± 5.6 Ma, respectively (Fig. 9b).

Thus, obtained ages for the Puutsaari mafic rock (1869 ± 7.7 Ma) and the microcline granite (1867.2 ± 5.6 Ma) coincide within error limits and are considered as crystallisation ages. If all the analyses from mafic rock and granite zircons are calculated together, the discordia age is 1866.6 ± 6.2 Ma (MSWD = 1.7). These data evidence the coeval emplacement and crystallisation for the different rock types on Puutsaari.

5. Discussion

5.1. Petrogenesis of the Puutsaari rock assemblage

On the Harker-type diagrams CaO, FeO^{tot}, TiO_2, P_2O_5 and MgO versus SiO_2 the Puutsaari rocks form inflected trends where the three rock groups, comprising the intrusion, are well distinguished. This is illustrated by the CaO versus SiO_2 diagram (Fig. 5c), where most of the tonalitic compositions are distinguished from the microcline granites by their high CaO contents. The inflected trends on the Harker-type diagrams as well as trace element geochemical features indicate that the three rock types at Puutsaari can't be correlated by simple fractional crystallisation of a common magma, but may rather be considered as magmas from three different sources.

The shoshonitic affinity of the Puutsaari mafic rocks indicates that they stem from an enriched lithospheric mantle. It is suggested that the enriched metasomatic layers are formed in the lithospheric mantle either during the subduction stage of an orogeny or by the enrichment by fluids from the asthenosphere, or both (Pearce et al., 1990). Negative Ta–Nb–Ti spikes at the trace element abundance diagram for the Puutsaari mafic rocks (Fig. 7) favour a subduction-related origin of enrichment. However, in the case of Puutsaari, the enriched character may also be due to the occurrence of an Archaean component in the lithospheric mantle.

Because tonalitic and trondhjemitic diatectites are common in the country rocks hosting the

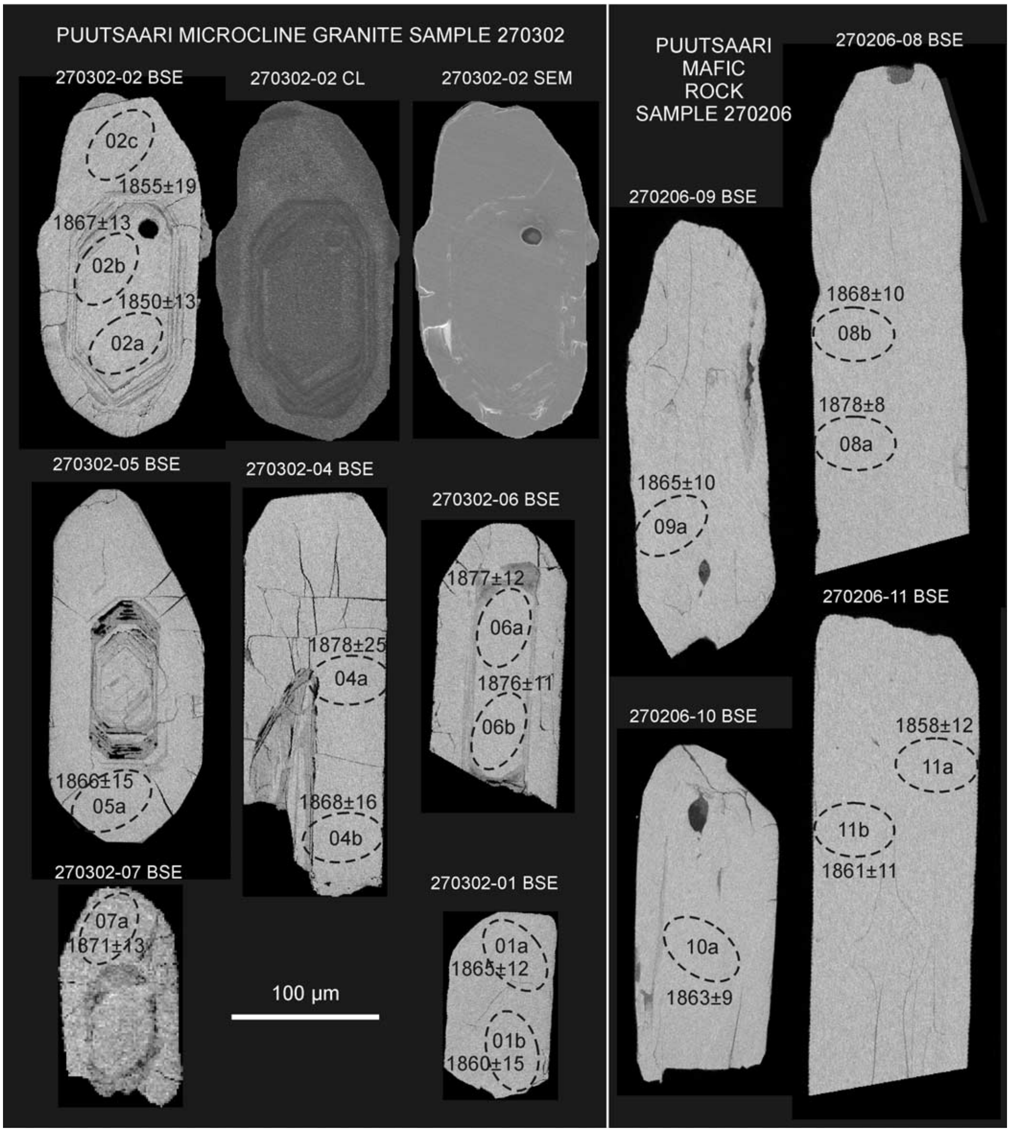

Fig. 8. Photographs of analysed zircons. BSE, back scattered electron image; CL, cathodoluminiscence image; and SEM, scanning electron microscope image in secondary electons. Analysed spots (dashed ovals) and obtained ^{207}Pb/^{206}Pb ages in Ma are shown on the BSE images. All errors are 2σ. Analysed spots are numbered as in Table 2.

intrusion, we suggest, following Grigoriev et al. (2000), that the Puutsaari tonalites are probably a result of crustal melting initiated by the emplacement of mafic rocks. However, because the age and the cooling history of the country rock diatectites are not constrained, more geochronological and geochemical work is needed to correlate the tonalitic rocks within and around the intrusion.

There is no direct geological or mineralogical evidence that the Puutsaari microcline granite is related to the mafic rocks by fractional crystal-

Table 2
U–Pb analytical data and calculated ages

	------Calculated ages in million years------							------Measured ratios------								-----Concentrations-----			
Sample-spot #[a]	^{207}Pb/^{206}Pb	±1σ	^{207}Pb/^{235}U	±1σ	^{206}Pb/^{238}U	±1σ	Disc.[b] %	^{207}Pb/^{206}Pb	±1σ	^{207}Pb/^{235}U	±1σ	^{206}Pb/^{238}U	±1σ	r[c]	^{206}Pb/^{204}Pb[d]	[U] ppm	[Th] ppm	[Pb] ppm	Th/U[e]
g-t 270302-01a	1864.7	5.8	1882.8	14.0	1899.3	26.3	2.1	0.11404	0.32	5.3872	1.63	0.34263	1.59	0.98	208160	323	112	135	0.348
g-t 270302-01b	1859.7	7.7	1904.6	14.5	1946.0	27.2	(5.4)	0.11372	0.43	5.5254	1.67	0.35239	1.61	0.97	75075	175	67	76	0.383
g-c 270302-02a	1847.9	6.5	1884.9	14.1	1918.6	26.5	(4.4)	0.11298	0.36	5.4001	1.63	0.34664	1.59	0.98	115527	348	130	147	0.373
g-c 270302-02b	1866.7	6.3	1870.8	14.0	1874.5	26.0	0.5	0.11416	0.35	5.3118	1.63	0.33747	1.59	0.98	6954	384	133	158	0.348
g-r 270302-02c	1855.4	9.4	1885.7	14.5	1913.4	26.5	3.6	0.11345	0.52	5.4055	1.68	0.34557	1.59	0.95	89526	154	66	66	0.431
g-r 270302-04a	1877.5	12.7	1856.7	15.0	1838.2	25.6	-2.4	0.11485	0.71	5.2250	1.75	0.32997	1.60	0.91	245519	133	53	54	0.402
g-r 270302-04b	1868.2	8.1	1865.4	14.3	1862.9	25.9	-0.3	0.11426	0.45	5.2786	1.66	0.33507	1.60	0.96	55371	133	55	55	0.411
g-r 270302-05a	1866.3	7.7	1870.6	14.4	1874.5	26.3	0.5	0.11414	0.43	5.3107	1.67	0.33747	1.61	0.97	51046	265	92	109	0.347
g-c 270302-06a	1877.1	6.1	1894.6	14.1	1910.7	26.4	2.1	0.11482	0.34	5.4619	1.63	0.34500	1.59	0.98	168606	399	230	176	0.576
g-c 270302-06b	1875.7	5.7	1891.7	14.0	1906.2	26.3	1.9	0.11473	0.32	5.4432	1.62	0.34408	1.59	0.98	81566	435	238	191	0.547
g-r 270302-07a	1871.2	6.7	1863.2	14.1	1856.0	25.8	-0.9	0.11445	0.37	5.2651	1.64	0.33365	1.60	0.97	90009	167	65	69	0.387
m 270206-08a	1878.2	4.2	1886.3	14.1	1893.6	26.6	1	0.11489	0.23	5.4090	1.63	0.34145	1.62	0.99	64475	436	220	188	0.505
m 270206-08b	1868.6	5.0	1885.9	14.0	1901.6	26.3	2	0.11428	0.28	5.4063	1.62	0.34310	1.59	0.98	62150	356	170	153	0.478
m 270206-09a	1865.2	5.1	1880.8	14.1	1895.1	26.4	1.8	0.11407	0.28	5.3747	1.63	0.34174	1.61	0.98	100422	451	285	200	0.632
m 270206-10a	1863.2	4.7	1917.0	14.1	1967.0	27.2	(6.5)	0.11394	0.26	5.6055	1.62	0.35680	1.60	0.99	238663	752	473	349	0.630
m 270206-11a	1858.2	5.8	1883.3	14.1	1906.1	26.4	3	0.11363	0.32	5.3901	1.63	0.34404	1.60	0.98	188644	358	184	156	0.514
m 270206-11b	1861.2	5.5	1895.2	14.0	1926.5	26.6	(4.1)	0.11381	0.30	5.4658	1.62	0.34830	1.59	0.98	154440	486	258	214	0.530

[a] g-t - granite, transparent, unzoned grain; g-r - granite, rim of the zoned grain; g-c - granite, core of the zoned grain; m - mafic rock, unzoned grains.

[b] Age discordance in conventional concordia space. Positive values are reverse discordant. Values in parentheses indicate that the analysis is discordant in terms of 2s error ellipse.

[c] Error correlation ^{207}Pb/^{235}U - ^{206}Pb/^{238}U.

[d] Measured values. Statistically significant fractions of common lead calculated from ^{204}Pb (f206 (%)) for two analyses: 270302-02b and 270206-08a are 0.27 and 0.03, respectively. For the rest of analyses f206 is insignificant

[e] Th/U ratio directly from measured Th and U concentrations.

lisation. It is also difficult to explain the more fractionated REE patterns of the granite and their strong HREE depletion, when compared to the mafic rocks, by any realistic fractional crystallisation scenario. On the other hand, the strongly HREE depleted patterns of the granite may result from anatectic melting of a crustal protholith leaving a garnet-rich restite. Positive Eu anomalies in the anatectic melts are explained by segregation of light and heavy REE-bearing accessory minerals in restite, while Eu sitting in feldspars is recruited into the melt (e.g. Mengel et al., 2001). We believe that the REE patterns of the Puutsaari granite, particularly the strong depletion in HREE and the positive Eu anomalies, point to its anatectic origin from a crustal protolith. The tonalitic character of the anatectic magmatism in the northern terrane of the NW Ladoga Lake area may indicate that the protoliths available at the present day erosion level were not suitable for production of potassium-rich melts. Thus, the melting episode that formed Puutsaari microcline granite might have taken place in lower horizons of the crust. The Svecofennian age of the protolith is suggested because no statistically significant older zircon core ages were established in the granite sample in the course of this study.

5.2. Timing and tectonic setting of potassic magmatism in the NW Ladoga Lake area

The age of the metamorphic culmination in the NW Ladoga Lake area is constrained by the ages of syn-kinematic intrusions at 1881–1878 Ma (Glebovitsky et al., 2001). There is a distinct group of 5–20 Ma younger late- to post-kinematic granodioritic and granitic intrusions dated at 1875–1860 Ma (Fig. 1). The age of 1867.2 ± 5.6 Ma, obtained by ion microprobe dating for the Puutsaari granite, may be considered as a refer-

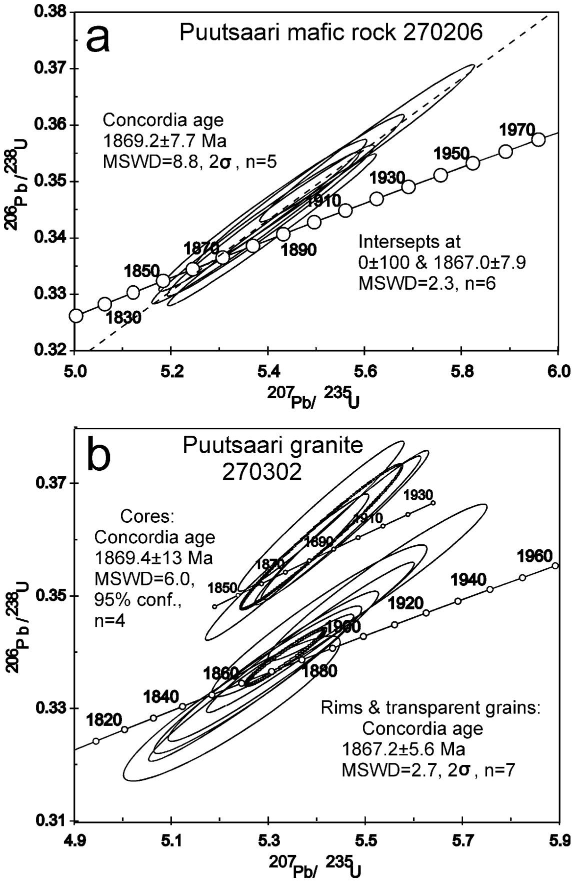

Fig. 9. U–Pb concordia diagrams for SIMS zircon data from (a) the mafic rock and (b) the microcline granite of the Puutsaari intrusion.

ence age for this group of intrusions because some of the conventional ages were earlier considered as slightly reset (e.g. Vaasjoki, 1996). On a larger scale, the obtained age corresponds to the 1885–1870 Ma ages of the post-kinematic granites crosscutting syn-kinematic tonalites of the Central Finland Granitoid Complex (Nironen et al. 2000).

The relatively early (1869 Ma), compared to peak metamorphism (1880 Ma), appearance of the enriched Puutsaari mafic rocks in the NW Ladoga Lake area is tectonically important. Culmination of the strongly enriched post-collisional shoshonitic magmatism took place in the region later, ca. 1800 Ma ago. The source region for this shoshonitic association is considered to be a lithospheric mantle affected by carbonate metasomatism (Eklund et al., 1998). The data presented here for the Puutsaari intrusion show that similarly enriched lithospheric mantle domains existed in the NW Ladoga Lake region as early as 1870 Ma ago. It is also notable that in the NW Ladoga Lake area many syn- and late-kinematic intrusions, similar to Puutsaari, contain enriched mafic rocks. This is illustrated in Figs. 6 and 7 where the most enriched compositions from the syn-kinematic Lauvatsaari complex almost overlap with the Puutsaari mafic rocks and plot rather close to the field of 1800 Ma strongly enriched shoshonitic intrusions. Thus, the enriched mafic rocks of Puutsaari, presented in this study, emphasise that occurrence of an enriched lithospheric mantle in the NW Ladoga Lake area is rather a regional feature than a characteristic of particular time interval.

The Puutsaari intrusion is situated on the joint of the Raahe-Ladoga zone and the tonalite-migmatite zone, which presumably corresponds to the Primitive Arc Complex of Central Finland (Korsman et al., 1997). The intrusion is only 20 km south of the closest Archaean domes and 40 km north of the area of granitic migmatisation (Fig. 1). Subduction-related origin of the enriched 1800 Ma shoshonitic rocks was shown geochemically by Eklund et al. (1998) and Väisänen et al. (2000). Similar geochemical features of the Puutsaari mafic rocks may indicate a subduction-related origin as well. In particular, they might be related to the subduction that formed the 1920–1890 Ma old Primitive Arc Complex of Central Finland (Kousa et al., 1994; Korsman et al., 1997). However, closeness to the thick Archaean lithosphere of the Karelian craton might have created a peculiar tectonic environment that influenced the enrichment as well. Rämö et al. (2001) reported negative ε_{Nd} values from the rocks of 1.46 Ga old dolerite sill at Valaam archipelago 25 km east of Puutsaari which clearly demonstrated a significant input of Archaean material. An additional isotopic study of the Puutsaari rocks aimed to distinguish between juvenile Svecofennian and ancient Archaean components of the enrichment is in progress.

6. Conclusions

The intrusion of Isl. Puutsaari represents late-kinematic composite potassium-rich magmatic complex in the eastern part of the Svecofennian orogen. The intrusion comprises three major rock types: mafic rocks, quartz–diorite–tonalite–granodiorite and microcline granite. All rock types were emplaced coevally as magmas with different compositions forming a peculiar three component mingling system.

The mafic rocks have marked shoshonitic affinities and demonstrate signature of an enriched lithospheric mantle. Tonalites and microcline granites are interpreted as a result of anatectic melting of various crustal protoliths initiated by the intrusion of the mafic magma.

Crystallisation ages of the mafic rock and the microcline granite have been obtained by ion microprobe zircon dating at 1869 ± 7.7 and 1867.2 ± 5.6 Ma, respectively. On a regional scale these ages characterise a group of late- to post-kinematic granitoids usually more potassium-rich compared to their 1890 Ma old syn-kinematic precursors.

The Puutsaari mafic rocks are geochemically similar to the rocks of the 1800 Ma old mantle-derived strongly enriched shoshonitic association (Eklund et al., 1998). The occurence of the enriched mafic rocks at Puutsaari indicate that similarly enriched domains of the lithospheric mantle existed under the NW Ladoga Lake area as early as 1870 Ma ago shortly after Svecofennian collision and peak metamorphism.

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