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Generation of A-type granitic melts during the late Svecofennian metamorphism in southern Finland

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Abstract: Across southern Finland the Late Svecofennian Granite Migmatite zone contains large amounts of migmatites and S-type granites formed during the high temperature and low pressure metamorphism between 1.84 and 1.80 Ga. Within this zone, the Karjaa granite intrudes the surrounding migmatites. The granite is more fine-grained and darker than the surrounding anatectic S-type granites, which are associated with the migmatites. The Karjaa granite cuts the migmatites suggesting that it is coeval or younger than the migmatites. It is a two-feldspar biotite granite containing apatite and zircon as accessory minerals. The granite displays elevated TiO_2, P_2O_5 and F contents and is characterized by high Ba, Zr, Nb, and Ga contents. The REE patterns indicate strong enrichment in LREEs and a pronounced europium minimum. The crystallization temperature of the granite is estimated to about 900°C using the P_2O_5 and Zr-saturation methods. Cathodoluminescence images on zircons indicate core domains and overgrowth structures. SIMS dating of the zircon cores and rims yielded concordia ages of 1880±16 Ma and 1826±11 Ma, respectively. On the basis of these data, it seems that c. 1880 Ma old igneous rocks at deeper crustal levels partially melted during at c. 1825 Ma metamorphism and generated hot melts having a composition close to A-type granites.

Keywords: A-type granite, geochronology, U–Pb, zircon, geochemistry, Karjaa, Finland.

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Introduction

Granitic rocks can be divided into I-, S-, M-types (orogenic granites), and A-type (anorogenic granites) according to Chappell & White (1974), White (1979), and Loiselle & Wones (1979). Post-orogenic or post-collisional are an important group that has been distinguished by several workers (e.g. Pearce 1996; Liégeois et al. 1998). Bimodal post-collisional intrusions where the felsic end members are high Ba-Sr or shoshonitic granites have been recognized in the Fennoscandian shield (Eklund et al. 1998).

Compared to I-, M- and S-type granites, A-type granites show generally high $K_2O + Na_2O$, Fe/Mg, and low Al_2O_3 and CaO contents (Collins et al. 1982; White & Chappell 1983). They are enriched in F, Zr, Nb, Ga, rare earth elements (except Eu), Y, and Zn, and they are depleted in Ba and Sr (Collins et al. 1982; Whalen et al. 1987; Eby 1990). Perhaps the most diagnostic feature of A-type granites seems to be their high Ga/Al ratios (Collins et al. 1982; Whalen et al. 1987). Fluorine and chlorine contents in A-type magmas can be particularly high (Collins et al. 1982; Eby 1990). Chlorine is more abundant in peralkaline types and fluorine in metaluminous and peraluminous types (Collins et al. 1982). According to Loiselle & Wones (1979) A-type granites are interpreted to have crystallized under low water fugacities (anhydrous). Most A-type granites do not exhibit evidence of strong fractionation (Whalen et al. 1987).

A-type granites are encountered all over the world in extensional tectonic settings. This kind of magmatism has taken place either at the end of an orogeny or in continental rift zones. A-type granites have formed throughout geological time. In the Fennoscandian shield, A-type granites are represented by e.g. the Mid-Proterozoic anorogenic rapakivi granites (see Rämö & Haapala (1995) and Andersson et al. (2002) for reviews).

Different models for the origin of A-type granites include (1) remelting of previously melted granulitic source rock (e.g. Collins et al. 1982; Whalen et al. 1987), (2) partial melting of dehydrated charnockitic lower crust at temperatures >900°C in a subduction-related tectonic setting (Landenberger & Collins 1996), (3) fluid-absent melting of tonalites in the lower crust (e.g. Anderson 1983; Skjerlie & Johnston 1993), (4) metasomatic origin (e.g. Taylor et al. 1981), and (5) differentiation from mantle-derived basaltic magma (e.g. Loiselle & Wones 1979; Beyth et al. 1994; Vander Auwera et al. 2003).

The purpose of this paper is to classify a granite intrusion in Karjaa, southern Finland, to date it, and to determine the conditions of its formation.

Geological background

The geology of southern Finland can be divided into two main terranes: the Central and the Southern Svecofennian Arc Complexes (Fig. 1). These arc complexes collided at c. 1.89–1.86 Ga (e.g. Rämö et al. 2001; Väisänen et al. 2002). Soon after the

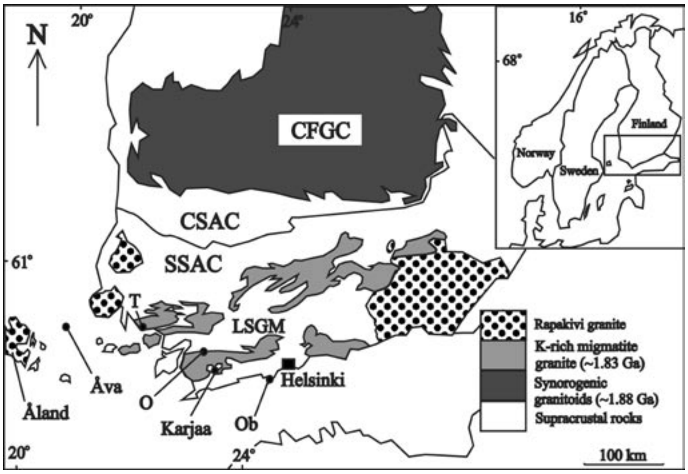

Fig. 1. Simplified geological map of southern Finland (after Ehlers et al. 1993). LSGM – Late Svecofennian Granite Migmatite zone, SSAC – Southern Svecofennian Arc Complex, CSAC – Central Svecofennian Arc Complex, CFGC – Central Finland Granitoid Complex, O – Orijärvi, Ob – Obbnäs and T – Turku. The boundary (solid line) between SSAC and CSAC from Korsman et al. (1997).

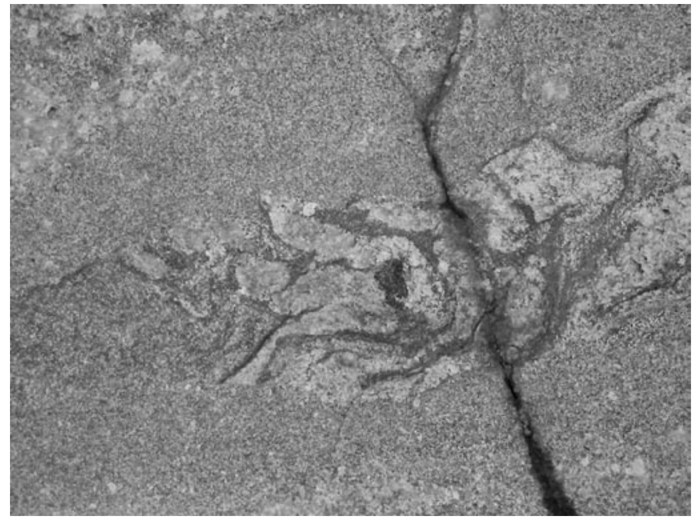

Fig. 2. Folded and veined gneiss xenolith in the finer grained Karjaa granite. The width of the photograph is 30 cm.

collision, the crust was cratonized in the northern terrane, but in the southern terrane the orogeny continued for about 100 m.y. as a result of a younger continent-continent collision at c. 1.85–1.80 Ga (Nironen et al. 2002).

The Southern Svecofennian Arc Complex was affected by new heating event during this younger collision that gave rise to upper amphibolite and granulite facies metamorphism, migmatization and production of S-type granites in a zone, which Ehlers et al. (1993) defined as the Late Svecofennian Granite Migmatite zone (LSGM). Ages of metamorphism and intrusion of the associated S-type late orogenic granites within the LSGM vary between c. 1.84 and 1.80 Ga (Korsman et al. 1984; Huhma 1986; Suominen 1991; Väisänen et al. 2002; Mouri et al. 2005).

The area studied here is located about 80 km west of Helsinki, in Karjaa (Fig. 1). The area comprises metapelites, volcanic rocks and granodiorites which were metamorphosed in upper amphibolite facies producing migmatites and anatectic granites. The hypersthene-in isograd is located c. 25 km to the northeast, where the West Uusimaa high-temperature/low-pressure granulites (750–800°C/5 kbars) occur (Schreurs & Westra 1986; Touret & Hartel 1990). Recent radiometric datings indicate that peak metamorphism in the West Uusimaa granulites took place between 1832±2 Ma and 1816±2 Ma (Mouri et al. 2005).

Field relations of the Karjaa granite

The Karjaa granite has so far been encountered in only one outcrop that comprises also migmatitic mica gneisses and associated granites and pegmatites. The exposed outcrop of the Karjaa granite in this case study is approximately 10×25 m. The regional distribution of this granite type is still unknown.

Near the contact to the pegmatite, the grain size of the Karjaa granite decreases. This fine-grained zone (c. 1 metre wide) contains elongated K-feldspar crystals, abundant K-feldspar megacrysts interpreted as xenocrysts engulfed from the country-rock pegmatites, and xenoliths composed of country rock mica gneisses and pegmatites. Several narrow granite-pegmatite veins also cut the fine-grained granite (Fig. 2).

The contact between this fine-grained granite and the pegmatite is mostly sharp. The cross-cutting relation to migmatites suggests that the investigated granite is younger than the leucosome veins but might be contemporaneous with the local pegmatitic granite, since in some places the granite forms embayments into this rock. The Karjaa granite is more homogenous and has finer grain size and darker colour than the anatectic granites associated with the migmatites.

Petrography and mineralogy

The Karjaa granite is a slightly foliated, brownish red medium-grained rock containing K-feldspar (c. 40 modal%), quartz (c. 30%), plagioclase (c. 20%) and biotite (c. 10%). The Karjaa granite plots on the line between syeno and monzogranite in the QAP-classification (Streckeisen 1974) (not shown). The granite is an even-grained or slightly porphyritic, having a few larger microcline, plagioclase and quartz grains. Some sericitic alteration is observed in plagioclase and myrmekite is abundant.

Accessory minerals are zircon, apatite, fluorite and sphene. Apatites occur as tiny elongated prisms with length-width ratios above 20. Zircons are found as small crystals evenly distributed in the rock.

The mineral compositions were analysed using the Cameca Camebax SX50 microprobe at the Department of Earth Sciences, Uppsala University (3–5 μm spot-mode, the ZAF correction followed the Cameca PAP procedure). The average compositions of K-feldspar and plagioclase are $Or_{95}Ab_5An_{0.1}$ and $An_{30}Ab_{69}Or_1$, respectively. Biotite has a Fe-index of 0.71–0.74 and the TiO_2 content is high, up to 3.55 wt.%. The concentrations of F and Cl in biotites are up to 1.77% and 0.52%, respectively (Table 1.).

Ion microprobe U–Pb zircon geochronology

Analytical methods

The zircons were separated by standard procedures and mounted in an epoxy resin disk that was polished to reveal zircon interiors. The ion microprobe analyses on zircons were made at the NORDSIM laboratory in August 2002 at the Swedish Museum of Natural History, Stockholm, using a Cameca IMS 1270 SIMS (Secondary Ion Mass Spectrometer). Before the ion-microprobe analyses were performed, the zircons were investigated in transmitted and reflected light and with a Philips scanning electron microscope (SEM) equipped with cathodoluminiscence (CL) and back-scattered electron (BSE) units. Details of the SIMS analytical procedure are found in Whitehouse & Bridgwater (2001). The plotting of the U–Pb data and the calculation of the concordia ages were done using the Isoplot/Ex program (Ludwig 1999).

Results

Two types of zircons were detected: euhedral elongated crystals (prismatic) and subhedral crystals with fractures (rounded). Some of the elongated prismatic crystals are broken. The length-width ratios vary between 1.5 and 4.6. For ion-microprobe analyses, six zircons were selected. CL images of the zircons reveal that two subhedral grains have dark and homogenous core domains. The rims of these crystals are radially fractured. One subhedral crystal is also fractured but the CL image does not reveal any core domain. The elongated crystal is transparent. BSE and CL-images of selected zircons are presented in Fig. 3.

The zircon overgrowth rims and one core domain of a homogeneous zircon overlap with 2σ error and yielded a concordia age of 1826±11 Ma (2σ, MSWD = 3.3). The discordant spot n1127-4ter was not used in calculations. The cores of the multiply grown zircons and one prismatic zircon yielded a concordia age of 1880±16 Ma (95% confidence, MSWD = 4.9), these data points do not all overlap within 2σ errors. The analytical results are presented in Table 2 and illustrated in Fig. 4.

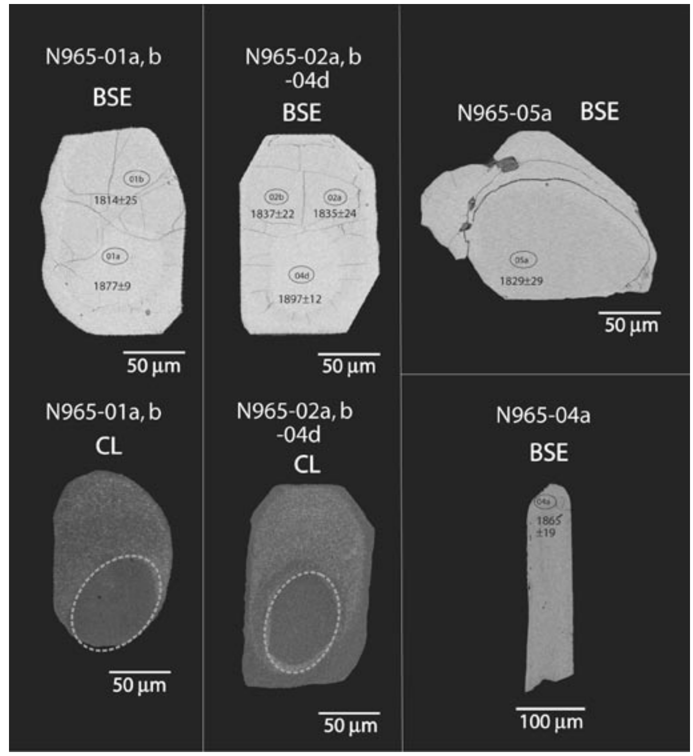

Fig. 3. Electron microscope images of zircons. Locations for SIMS analyses marked by ellipses in BSE images, with $^{207}Pb/^{206}Pb$ ages (±2σ errors). CL images reveal core domains and rims.

Geochemical characteristics

Major and trace element geochemical analyses of the Karjaa granite were performed at Activation Laboratories, Ontario, Canada. Major elements were analysed by ICP-AES, rare earth elements and other trace elements (Ba, Hf, Nb, Rb, Sr, Ta, Th, Y, and Zr) by the ICP-MS method. Fluorine was analysed by the ISE method. The whole-rock analyses are presented in Table 3.

Major elements

The peraluminous Karjaa granite has a SiO_2 content of 65–70 wt.%. It has slightly elevated TiO_2 and P_2O_5 contents (0.66–0.94 wt.% and 0.17–0.26 wt.%, respectively). Total alkalis of the Karjaa granite are relatively high (c. 8 wt.%) and K_2O/ Na_2O values vary from 1.48 to 2.38. In addition, the Karjaa granite has high fluorine contents, 0.13–0.21 wt.%.

Trace elements

The Karjaa granite has high Ba (1260–1790 ppm), Ga (23–28 ppm) and Zr (615–776 ppm) contents. Rb/Ba values vary from 0.09 to 0.13 and Rb/Sr values from 0.82 to 1.33. The REE patterns

Table 1. Analyses of micas from the Karjaa granite.

Sample Analysis	biotite P1	biotite P2	biotite P3	biotite P4	biotite P6	biotite P7
SiO_2	35.09	35.17	35.45	35.29	34.61	34.39
TiO_2	3.56	3.45	3.27	2.82	3.27	3.17
Al_2O_3	14.82	14.71	15.37	14.47	14.77	15.17
FeO_{tot}	26.5	26.45	25.54	27.29	26.12	26.16
MnO	0.16	0.11	0.15	0.1	1.3	0.15
MgO	5.31	5.36	5.41	5.75	6	5.71
BaO	0.18	0.21	0.21	0	0.11	0
CaO	0	0	0	0	0	0
Na_2O	0	0.04	0	0	0	0
K_2O	9.14	9.19	9.36	9.18	9.44	9.1
F	1.77	*	*	1.2	1.1	*
Cl	0.49	*	*	0.51	0.52	*
Total	97.02	94.69	94.76	96.61	97.24	93.85
O-F-Cl	0.86	*	*	0.62	0.57	*
a.f.u., based on 24 (O, OH, F, Cl)						
Si	5.854	5.873	5.883	5.893	5.759	5.787
$Al_{(IV)}$	2.146	2.127	2.117	2.107	2.241	2.213
$Al_{(VI)}$	0.766	0.765	0.887	0.739	0.655	0.793
Ti	0.446	0.433	0.408	0.354	0.409	0.401
Fe^{2+}	3.698	3.694	3.545	3.811	3.635	3.681
Cr	0	0	0	0	0	0
Mn	0.023	0.016	0.021	0.014	0.183	0.022
Mg	1.321	1.335	1.338	1.431	1.488	1.433
Ba	0.012	0.014	0.013	0	0.007	0
Ca	0	0	0	0	0	0
Na	0	0.014	0	0	0	0
K	1.945	1.959	1.982	1.955	2.005	1.947
total	16.211	16.23	16.194	16.304	16.382	16.277
Cl^-	0.278			0.291	0.293	
F^-	1.873			1.257	1.132	
Fe/(Fe+Mg)	0.74	0.73	0.73	0.73	0.71	0.72

* = not analysed.

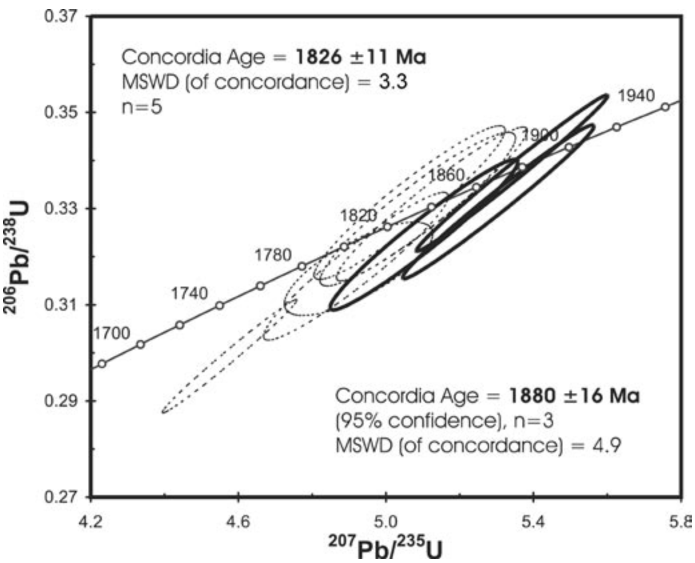

Fig. 4. Concordia plot for the Karjaa granite (sample TKJ-22/9/00-1). Dashed lines – the zircon overgrowth rims and one core domain of a homogeneous zircon. Solid lines – the cores of the multiply grown zircons and one prismatic zircon.

of the Karjaa granite show strong enrichments of LREEs and the trends are smoothly sloping. Europium shows a pronounced negative anomaly (Fig. 8). The trace element variation patterns reveal that the Karjaa granite has positive La, Ce, Nd, Zr and Hf spikes and negative Nb, Ta, Sr and Ti troughs (Fig. 9).

Discrimination diagrams

According to Whalen et al. (1987) fractionated felsic granites and unfractionated M-, I- and S-type granites could be distinguished from A-type granitoids using Zr + Nb + Ce + Y as a discriminator. The Karjaa granite plots among A-type granites on the (K_2O + Na_2O)/CaO vs. Zr + Nb + Ce + Y diagram (Fig. 5A). Also on the Zr vs. Ga/(Al_2O_3·0.5292) diagram the Karjaa granite plots within the A-type granite field together with the post-orogenic 1.76 Ga Åva high BaSr granite (Skyttä 2002; Eklund & Shebanov 2005), the 1.64 Ga Obbnäs rapakivi granite (Kosunen 1999), and the anorogenic 1.57 Ga Åland rapakivi granite (Eklund et al. unpublished data; Fig. 5B). Other reference data used in discrimination diagrams are the 1.89 Ga Orijärvi I-type granodiorite (Väisänen & Mänttäri 2002; Rötsä 2002) and the 1.83 Ga Kemiö S-type granite (T. Stålfors & C. Ehlers, unpublished data).

Temperature diagrams

According to Watson & Harrison (1984), accessory minerals such as zircon and apatite may resist complete dissolution during crustal anatexis. The amount of dissolved zirconium and phosphorus can thus be used as a measure of themperature in granitic melts. Since apatite has only been found as small elongated needles evenly distributed in the rock, this is evidence that all of it crystallized from the melt. On the other hand, part of the zircon population is fairly large and carry a significant inherited component, as shown by the U–Pb data. A rough estimate, based on the volume of the inherited components in zircons (Fig. 3 and other U–Pb data), suggests that c. 15% of the zircon material may be inherited. Assuming that all Zr reside in zircon, this leaves more than 600 ppm in zircon crystallized from the granitic melt. Crystallization temperature of the Karjaa granite was estimated by means of two diagrams, Zr (ppm) vs. M = (Na + K + 2Ca)/(Al•Si) and P_2O_5 (wt.%) vs. SiO_2 (wt.%) According to these diagrams, the crystallization temperature of Karjaa granite is between 900°C and 950°C (Fig. 6A, B). When the volume of the observed inherited zircons was taken into account, the Zr-content was reduced by c. 120 ppm. The estimated temperature for such a Zr-content is still high, close to 900°C. These temperatures are in accordance with liquidus temperatures estimated for A-type melts at 5 kbar (Shkodzinsky 1985). The Karjaa granite has no or just a few small phenocrysts, and contains small needles of apatite. This shows that the granite was rapidly crystallized from a melt. 5 kbar corresponds to the regional metamorphic pressure at c. 1.83 Ga, according to Mouri et al. (2005).

Comparison of data to other granitoids from southern Finland

According to Sylvester (1989) it is possible to distribute I-, S- and A-type granites by using (Al_2O_3 + CaO)/(FeO_{tot} + Na_2O + K_2O) vs. 100•((MgO + FeO_{tot} + TiO_2)/SiO_2) diagram, where A-type granites or highly fractionated felsic I-type granites plot within the alkaline field; S- and I-type granites within the field of strongly peraluminous and calc-alkaline granites. On this

Table 2. Ion-microprobe U–Pb SIMS data for zircons of the Karjaa granite.

Sample/ spot #	Derived ages[a] $^{207}Pb/^{206}Pb$ ±σ	$^{207}Pb/^{235}U$ ±σ	$^{206}Pb/^{238}U$ ±σ	Corrected ratios[a] $^{207}Pb/^{206}Pb$ ±σ %	$^{207}Pb/^{235}U$ ±σ %	$^{206}Pb/^{238}U$ ±σ %	r[b]	Disc. %[c] conv.	Elemental data U ppm	Th ppm	Pb ppm	Th/U calc	$^{206}Pb/^{204}Pb$ measured
TKJ-22/9-1													
n965-01a core	1877±5	1876±17	1874±32	0.1148±0.26	5.342±2.0	0.3374±2.0	0.99	–0.2	382	105	154	0.28	223914
n965-01b rim	1814±13	1830±18	1844±32	0.1109±0.70	5.064±2.1	0.3312±2.0	0.94	1.9	45	19	18	0.43	26069
n965-02a rim	1835±12	1805±18	1780±31	0.1122±0.67	4.919±2.1	0.3180±2.0	0.95	–3.4	66	31	26	0.46	31908
n965-02b rim	1837±11	1840±18	1843±32	0.1123±0.60	5.125±2.1	0.3310±2.0	0.96	0.4	64	29	26	0.44	>10^6
n965-04a rim	1865±10	1837±17	1812±31	0.1140±0.53	5.103±2.0	0.3246±2.0	0.97	–3.2	226	95	90	0.39	196696
n965-04d core	1897±6	1870±17	1845±32	0.1161±0.34	5.305±2.0	0.3314±2.0	0.99	–3.1	412	111	163	0.27	121951
n965-05a core	1829±14	1834±18	1839±32	0.1118±0.79	5.086±2.1	0.3299±2.0	0.93	0.5	43	17	17	0.38	48426
n1127-3ter rim	1841±20	1807±14	1777±19	0.1125±1.11	4.926±1.7	0.3175±1.2	0.75	–3.9	43	19	17	0.45	5956
n1127-4ter rim	1814±4	1745±14	1688±24	0.1109±0.24	4.576±1.6	0.2993±1.6	0.99	–7.9	2339	61	783	0.03	11545

[a] Errors are at the 1 sigma level.
[b] Error correlation for the $^{207}Pb/^{235}U$–$^{206}Pb/^{238}U$ ratios.
[c] Degree of discordance is calculated at the closest 2 sigma limit.

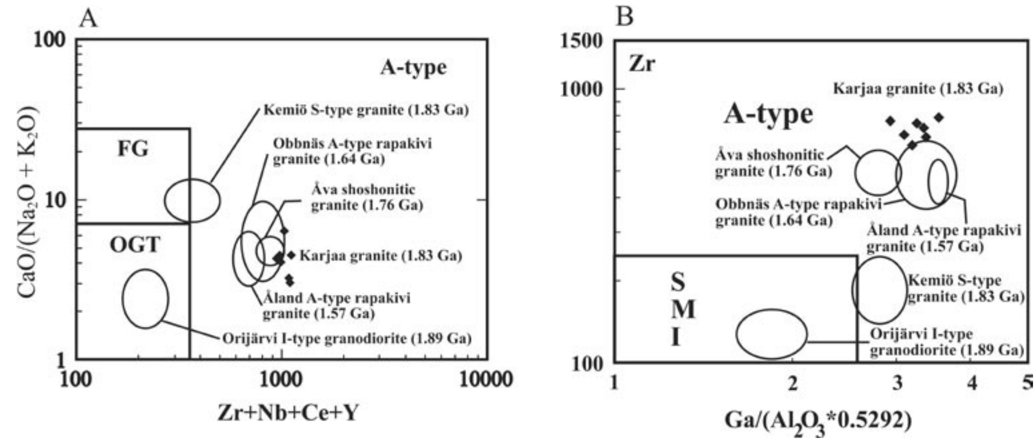

Fig. 5. The Karjaa granite (filled diamonds) and data for other granitoids for comparison plotted in discrimination diagrams after Whalen et al. (1987). FG – felsic granites, OGT – unfractionated M-, I- and S-type granites. Conversion factor for Al_2O_3 to Al according to Ragland (1989).

diagram the Karjaa granite plots mainly within the alkaline field together with the post-orogenic 1.76 Ga high BaSr Åva granite, the anorogenic 1.57 Ga Åland and the 1.64 Ga Obbnäs rapakivi granites (Fig. 7). This diagram includes also comparison data from the 1.88 Ga synorogenic I-type granitoids (Helenius 2003; Impola 2004) and 1.83 Ga Kemiö S-type granite (T. Stålfors & C. Ehlers, unpublished data) from southern Finland, and the c. 1.80 Ga post-orogenic granites (transitional from I-type to A-type) from Sweden, Bergslagen (Sundblad & Bergman 1997).

The Karjaa granite and the Åva granite have similar major element geochemistry, except that the Åva granite has clearly higher MgO content. Trace element geochemistry of the Karjaa granite shows higher Zr and Ga contents, but lower Ba and Sr contents. The REE patterns of the Karjaa granite and the Åva granite are very similar, and they both have a distinct Eu minimum (Fig. 8A). Their trace element variation patterns are also very similar (Fig. 9A).

The geochemistry of the Karjaa granite also resembles the geochemical features of Åland rapakivi granite. According to Rämö & Haapala (1995) Finnish rapakivi granites have high total alkali contents, usually 6.4–9.9 wt.% (7.6–8.4 wt.% in the Karjaa granite). The Karjaa granite has higher P_2O_5 and TiO_2

Table 3. Chemical analyses of the Karjaa granite.

Sample	TKJ22/9-1	TKJ8/10-1	TKJ28/9-9	TKJ25/4/02-1	TKJ25/4/02-2	TKJ25/4/02-3	TKJ25/4/02-4
SiO_2	66.17	65.83	67.52	67.91	69.25	67.26	67.88
Al_2O_3	14.62	14.95	14.55	14.64	14.24	14.75	14.84
Fe_2O_3	4.71	5.44	4.95	4.63	3.95	4.82	4.78
MnO	0.031	0.04	0.048	0.034	0.03	0.033	0.036
MgO	0.96	1.02	0.81	0.88	0.82	1.14	0.91
CaO	1.85	2.42	1.82	1.84	1.8	1.29	2.35
Na_2O	2.87	3.09	2.96	2.7	2.74	2.47	3.07
K_2O	5.58	4.59	4.8	5.71	5.42	5.89	4.61
TiO_2	0.676	0.938	0.943	0.697	0.668	0.875	0.843
P_2O_5	0.22	0.26	0.22	0.21	0.17	0.24	0.22
LOI	0.9	0.71	0.81	0.73	0.76	1.26	0.63
TOTAL	98.58	99.28	99.43	99.98	99.84	100.04	100.16
F	0.21	0.19	0.16	0.18	0.14	0.14	0.13
Ga	26	28	25	24	24	26	23
Rb	177	181	175	173	172	190	163
Sr	144	200	174	130	174	168	198
Y	28	40	28	27.2	23.3	37.8	35.8
Zr	656	776	740	667	615	709	755
Nb	20	29	31	17.1	18.4	23.8	23.9
Ba	1330	1790	1690	1260	1420	1700	1710
La	144	118	85.9	149	138	131	134
Ce	287	236	170	384	292	244	255
Pr	33.7	27.3	18.9	33.3	30.5	28.2	27.4
Nd	119	100	68	112	108	101	103
Sm	18.3	16.6	11.2	17.2	15.7	15.1	16.8
Eu	1.97	2.34	1.97	1.94	2.01	2.16	2.39
Gd	16.8	15.5	10.7	11.6	11.6	13.1	12.7
Tb	1.7	1.9	1.3	1.27	1.23	1.61	1.65
Dy	6.2	8.1	5.9	5.91	5.21	7.73	8.23
Ho	1.1	1.4	1.1	1.04	0.87	1.41	1.39
Er	3.3	4.3	3.1	2.67	2.35	3.85	3.46
Tm	0.4	0.54	0.39	0.289	0.267	0.461	0.429
Yb	2.1	2.9	2	1.71	1.53	2.48	2.49
Lu	0.28	0.39	0.28	0.249	0.208	0.335	0.331
Hf	17.7	20.3	19.4	17.4	17	18.8	19.8
Ta	0.7	1	1.2	0.4	0.51	0.83	0.67
Th	29.5	20.6	14.1	29.5	27.6	21.7	19.2

Main oxides are given in wt.%. Trace elements are given in ppm.

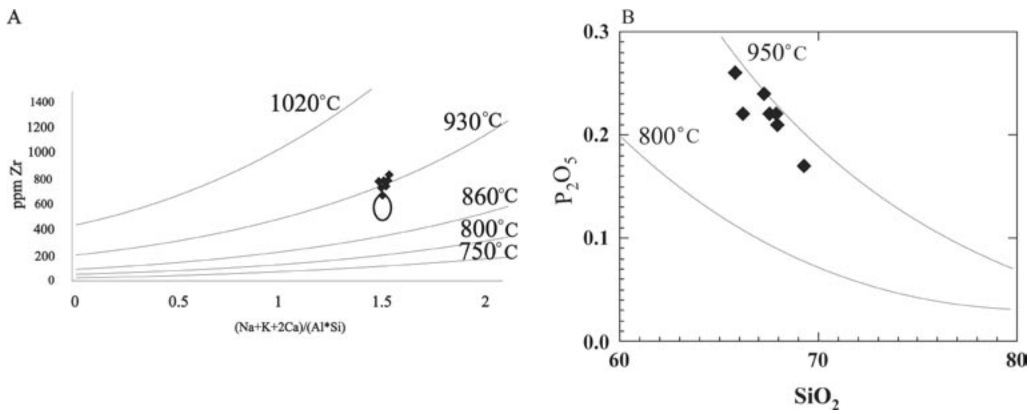

Fig. 6. **A.** Zr vs. M = (Na + K + 2Ca)/(Al·Si) (Watson & Harrison 1984). **B.** P_2O_5 vs. SiO_2 (Green & Watson 1982) plots with experimentally determined isotherms. Compositions of the Karjaa granites are plotted and indicate temperatures around and in excess of 900°C. The diamonds in A represent the Zr-content obtained from the chemical analyses. The ellipse represent the estimated Zr-content crystallised from the magma when the Zr-content of 15% inherited zircons is subtracted from the analyses.

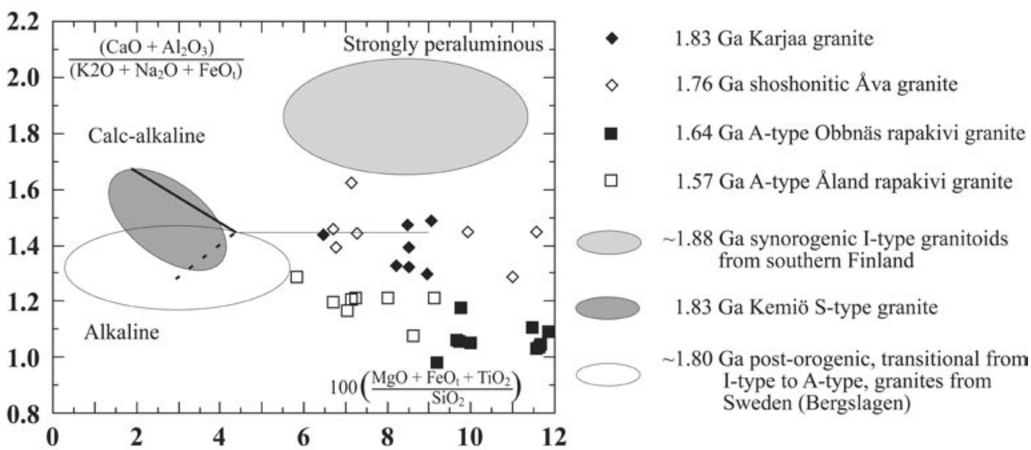

Fig. 7. Major element discrimination diagram (Sylvester 1989). Solid line divides most alkaline types from normal calc-alkaline and strongly peraluminous types. Dashed line separates those alkaline granites having compositions similar to highly fractionated calc-alkaline granites from those that do not.

contents than Åland rapakivi granite. According to Eby (1990) and Collins et al. (1982) A-type granites have high amounts of fluorine (0.05–1.7 wt.%, usually over 0.1 wt.%). In the Karjaa granite this amount is between 0.13–0.21 wt.%. High fluorine contents in A-type granites could be due to partial melting of the protolith, which contains F-enriched mica and/or amphibole (Whalen et al. 1987; Rämö & Haapala 1995). Both the Karjaa granite and the Åland rapakivi granite have similar LREE patterns, but the Åland rapakivi granite is more enriched in HREEs than the Karjaa granite (Fig. 8B). They both have pronounced negative Eu anomalies. Their trace element variation diagram patterns exhibit almost parallel trends (Fig. 9B). The Karjaa granite has, however, higher Zr and Nd contents, and lower Y and Yb contents than the Åland rapakivi granite. They have similar Ga, Ba, Sr and Nb contents.

The Obbnäs rapakivi granite is a porphyritic hornblende-biotite-granite (Kosunen 1999). It is metaluminous to weakly peraluminous, and its K_2O/Na_2O is 2.06 (1.48–2.38 for the Karjaa granite). The Karjaa granite has higher TiO_2 and P_2O_5 contents than the Obbnäs rapakivi granite. The Karjaa granite is strongly enriched in LREEs and depleted in HREEs, similar to the Obbnäs rapakivi granite (Fig. 8C). Both granites have a pronounced negative Eu anomalies, and their trace element variation diagram patterns are overlapping (Fig. 9C). The Karjaa granite has lower Y and Yb but higher Zr and Nd than the Obbnäs rapakivi granite. Ga, Ba, Sr and Nb contents are very similar.

According to Jung et al. (1998) A-type granites have high Nd concentrations (25–139 ppm) while migmatites and S-type granites have concentrations of 28–47 ppm and 31–42 ppm, respectively. Nd values for the Karjaa granite are between 60 and 120 ppm, mainly 100–120 ppm.

Discussion

Age of the Karjaa granite

The age data and the zircon morphology reveal that there are three different zircon types in the granite. The elongated prismatic zircon yielded a roughly similar age as rounded core domains of other zircons. The concordia age of 1880±16 Ma calculated for the cores and the prismatic zircon is interpreted to represent an average age of the protolith from which the granite melt was derived. Since these analyses do not overlap within errors, the individual grains may represent source lithologies ranging in age from 1900 to 1865 Ma. In the Southern Svecofennian Arc Complex (SSAC) early orogenic magmatism took place 1910–1880 Ma ago (Väisänen et al. 2002). Formation of synorogenic granitoids in the SSAC 1880–1860 Ma ago is connected to the collision of the SSAC with the Central Svecofennian Arc Complex (Väisänen et al. 2002). The ages of the zircon cores of the Karjaa granite thus matches well the 1910–1860 Ma igneous activity in the SSAC.

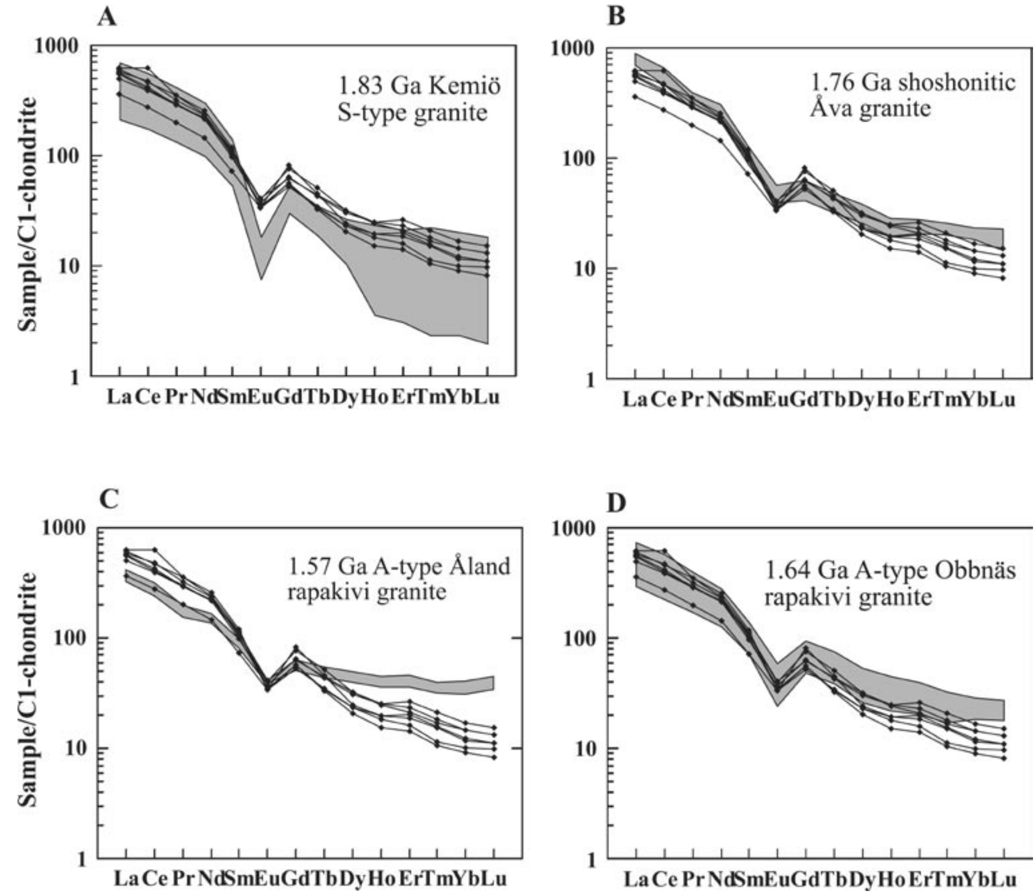

Fig. 8. **A–D.** Chondrite-normalized REE diagrams for the Karjaa granite (filled diamond) and other granites (gray shade) for comparison. Normalization factors according to Sun & McDonough (1989).

We interpret the concordia age of 1826±11 Ma for the rims of the zoned zircons and also one core of a homogeneous zircon the crystallization age of the granite. This is in accordance with high-temperature/low-pressure metamorphism and formation of anatectic granites within the Late Svecofennian Granite Migmatite zone (LSGM) at 1840–1810 Ma ago (Huhma 1986; Suominen 1991; Väisänen et al. 2000; Kurhila et al. 2004).

Age data suggest that some zircons were inherited from the source without any subsequent overgrowths while some of the inherited zircons have reacted with the melt producing a younger overgrowth. This stage also produced a new zircon generation.

Geochemistry of the Karjaa granite

The 1.83 Ga Karjaa granite lacks aluminous minerals such as garnet or cordierite which are typical for coeval S-type granites of southern Finland. Their geochemical features also differ in many ways.

In the discrimination diagrams by Whalen et al. (1987) the Karjaa granite shows similar affinity as the shoshonitic Åva granite and the A-type rapakivi granites of Åland and Obbnäs. The geochemical features of the Karjaa granite are closest to that of the shoshonitic Åva granite, except the higher amounts of Ba and Sr in the latter.

Many geochemical features of the A-type rapakivi granites of Åland and particularly Obbnäs are similar for the Karjaa granite, such as high concentrations of FeO/MgO, Zr, Ga, and F. However, there are some features that require further investigations, such as high TiO_2 and Ba contents.

Petrogenesis of the Karjaa granite

The high concentration of incompatible trace elements in the Karjaa granite may reflect a small degree of partial melting of the source material. Residual garnet in the source may be the reason why the concentrations of HREEs are low. The pronounced negative Eu anomaly may be correlated to plagioclase remaining in the source after partial melting generating the granite.

During the peak metamorphism at 1840–1800 Ma, S-type granites were formed at the mid-crustal level due to partial melting of meta-pelites within the LSGM. In addition, local melting of metaigneous rocks and amphibolites, producing tonalitic to granitic melts, can be observed in outcrops. This study implies that A-type melts were formed at the same time, indicating that roughly 900°C was reached locally in the crust. Such temperatures require an external heat source. The heat source, that caused the partial melting of the source rock and formation of these hot A-type melts, might be related to emplacement of mafic magmas at lower and middle crustal levels (e.g. Schreurs & Westra 1986; Väisänen et al. 2000). According to Tack et al. (1994) deep lateral shear zones might permit A-type melts to rise to the upper crust. We propose that also in Karjaa, A-type melts rose upwards as early as 1.83 Ga by using the lateral shear zone existing in the area.

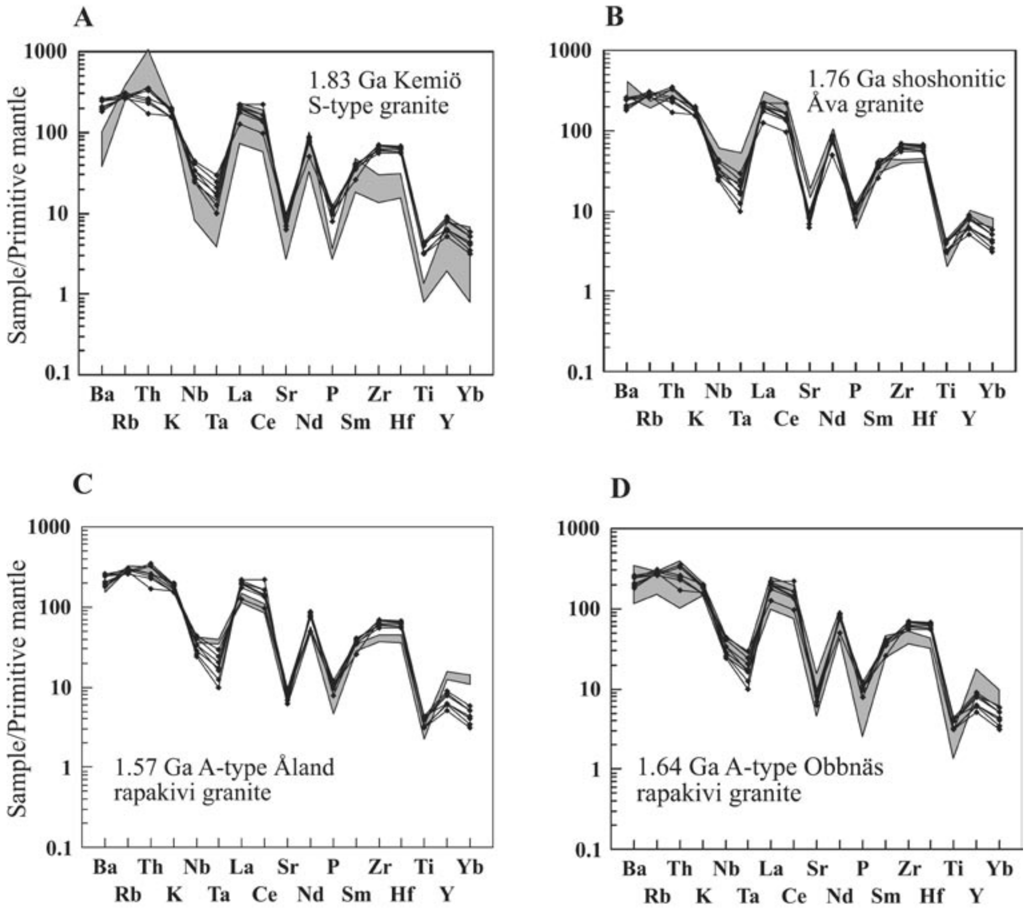

Fig. 9. **A–D.** Trace element variation diagrams for the Karjaa granite (filled diamond) and data for other granites (gray shade) for comparison. Normalization factors according to Sun & McDonough (1989).

The trace element compositions of the Karjaa granite and the Obbnäs rapakivi granite are relatively similar. It seems, from the to trace element variation diagram patterns, that they might be derived from similar source material. According to Kosunen (1999), the Obbnäs rapakivi granite is derived from tonalitic or quartz dioritic sources. Creaser et al. (1991) and Skjerlie & Johnston (1993) proposed that A-type granites can be generated by fluid-absent melting of rocks of tonalitic composition not affected by previous melt depletion. Based on experiments, Skjerlie & Johnston (1993) showed that extraction of A-type melt from a tonalitic source rock leaves behind a granulitic residue, and the temperatures required for extraction of melts is high, >900°C. These experiments support the hypothesis that the crustal precursor to the Karjaa granite was tonalitic in composition.

Conclusions

The Karjaa granite was formed during the metamorphic culmination c. 1825 Ma ago and has a geochemical composition close to A-type granites. It has elevated TiO_2, P_2O_5 and F contents and is characterized by high Ba, Zr, Hf and Ga contents as well as strong enrichments in LREEs. Europium shows a pronounced negative anomaly. The liquidus temperature of the granite is estimated to c. 900°C. Ion microprobe (SIMS) U–Pb dating of the zircon cores and rims yielded concordia ages of 1880±16 Ma and 1826±11 Ma, respectively. The former age represents the approximate age of protoliths and the latter the crystallization age of the Karjaa granite. K-rich S-type granites were formed at mid-crustal levels from pelitic material during the regional metamorphism in southern Finland. In addition, it seems that beneath the pelitic migmatites, at deeper crustal levels, igneous rocks were exposed to partial melting which yielded A-type melts.

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