Available online at www.sciencedirect.com

SCIENCE DIRECT®

Precambrian Research 121 (2003) 251–262

Precambrian Research

www.elsevier.com/locate/precamres

Sources of Svecofennian granitoids in the light of ion probe U–Pb measurements on their zircons

Matti Vaasjoki [a,*], Hannu Huhma [a], Raimo Lahtinen [a], Jessica Vestin [b]

[a] Geological Survey, P.O. Box 96, FIN-02151 Espoo, Finland
[b] Laboratoriet för Isotopgeologi, Naturhistoriska Riksmuseet, Stockholm, Sweden

Received 29 May 2002; accepted 12 January 2003

Abstract

The presence of 1.91–1.93 Ga old granitoids at the Archean–Proterozoic boundary along the Raahe–Ladoga zone in Finland has been demonstrated on various occasions. These rocks have been considered to represent juvenile crustal material, as their $\varepsilon_{\rm Nd}$ values are markedly positive. However, as Svecofennian metasediments contain detrital zircons derived from a ca. 2 Ga old source, the possibility has existed that the 1.92 Ga age may have been a mixture between 2 and 1.89 Ga old zircon populations, as such mixing would not markedly affect their neodymium isotopic properties. Also, some syntectonic 1.89 Ga old Svecofennian granitoids contain heterogeneous zircon populations, but it has been impossible to determine the age and origin of the older zircons by conventional methods.

NORDSIM ion probe results on three samples from the 1.92 Ga age group confirm the earlier conclusions. Especially important is that no zircons older than 1.95 Ga were detected in the 1.92 Ga group samples. Thus, the 1.92 Ga event was the beginning of the formation of new continental crust in the primitive Svecofennian island arc and these granitoids formed by partial melting of basaltic magmas derived from a depleted mantle source. One sample also contains a younger zircon population formed during the orogenic culmination at 1.89 Ga. In contrast, one grain from a sample representing the 1.89 Ga age group contains an Archean core, which is considered to represent sedimentary detritus assimilated during either magma formation or intrusion.

While the results prove the true igneous nature of the 1.92 Ga event, they also rule out these rocks as a possible provenance for the ca. 2 Ga old zircons encountered in the Svecofennian metaturbidites. Thus, there is still no direct evidence from granitoid rocks for an extensive Svecofennian protocrust, the existence of which has been postulated on the basis of geochemical and Sm–Nd isotopic data.

Keywords: Absolute age; U/Pb; Zircon; Ion probe; Paleoproterozoic; Tonalite; Diorite; Finland

1. Introduction

The Svecofennian Domain is divided on the latest 1:1,000,000 bedrock map of Finland (Korsman et al., 1997) into three major complexes: (a) the primitive arc complex of Central Finland, (b) the accretionary arc complex of Central and Western Finland and (c) the accretionary arc complex of Southern Finland. These subareas differ from each other in geotectonic position (op. cit.), igneous histories manifested in geochronological data (Vaasjoki and Sakko, 1988; Vaasjoki, 1996) and in geochemical and isotope geological characteristics (Lahtinen, 1994; Lahtinen and Huhma, 1997), summarized briefly in the following sections.

---

* Corresponding author. Tel.: +358-205502251; fax: +358-2055012.
E-mail address: matti.vaasjoki@gsf.fi (M. Vaasjoki).

0301-9268/03/$ – see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0301-9268(03)00015-9

1.1. The primitive arc complex of Central Finland

The primitive arc complex of Central Finland strikes NW–SE along the so-called Raahe–Ladoga zone and is the Svecofennian terrane closest to the Archean craton. It is characterized by the occurrence of volumetrically small but wide-spread igneous rocks which register conventional zircon U–Pb ages in the range of 1.93–1.91 Ga (Helovuori, 1979; Korsman et al., 1984; Vaasjoki and Sakko, 1988). The rocks exhibit markedly positive $\varepsilon_{\mathrm{Nd}}$ values suggesting a derivation from source rocks with a depleted mantle source and a very short (if any) crustal residential time (Lahtinen and Huhma, 1997). Geochemical data for both intrusive and extrusive rocks of this age group (Lahtinen, 1994; Kousa et al., 1994) suggest arc-related affinities, the volcanic rocks being also bimodal, consisting principally of low-K tholeiitic basalts and rhyolitic rocks.

These oldest igneous rocks are intercalated with and overlain by a thick sequence of metaturbidites. The whole volcano-sedimentary sequence is penetrated by 1.90–1.88 Ga old intrusive rocks varying from gabbro to granodiorite in composition (Vaasjoki and Sakko, 1988; Kousa et al., 1994), with the felsic rocks forming the majority of these syntectonic intrusions. Apparently, the orogenic culmination involving the deformation of the whole rock package was of short duration as clearly late-posttectonic intrusive hypersthene (and amphibole) granites (Salli, 1983; Korsman et al., 1984; Vaasjoki and Sakko, 1988) are coeval with the syntectonic rocks within experimental error. Vertical movements were also rapid. Thus, clasts of syntectonic tonalites are found in conglomerates formed not later than 1.88 Ga ago (Korsman et al., 1988; Vaasjoki and Sakko, 1988).

1.2. The accretionary arc complex of Central and Western Finland

Most of the accretionary arc complex of Central and Western Finland is formed by the Central Finland granitoid complex containing some volcano-sedimentary inliers. The granitoid rocks are bordered in the south by the Tampere schist belt and by the Vaasa migmatite zone (Alviola et al., 2001) in west and northwest. Within these areas there is no solid evidence for igneous rocks older than 1.90 Ga. The metaturbiditic rocks exhibit minor Archean zircon populations, but their principal provenance seems to be 1.9–2.1 Ga old (Huhma et al., 1991; Claesson et al., 1993). Syntectonic intrusive rocks are 1.90–1.88 Ga old (Vaasjoki, 1996), but in contrast to the primitive arc complex, their protolith may be somewhat more evolved as $\varepsilon_{\mathrm{Nd}}$ values in the -1 to $+1$ range are common (Huhma, 1986). The volcanic rocks are predominantly intermediate-felsic high-K rocks with calc-alkaline affinities (Tiainen and Kähkönen, 1994; Kähkönen, 1994). Orogenic movements have proceeded rapidly also in this area, late-posttectonic intrusions being again coeval with the syntectonic ones within experimental error (Sjöblom, 1990; Rämö et al., 2001).

Geochemical data from the syntectonic granitoids in Central Finland support the Sm–Nd results as far as an origin from a more evolved source is concerned. Thus, Lahtinen and Huhma (1997) suggested that the syntectonic, mainly high-K calc-alkaline granodiorites of the Central Finland, granitoid complex were remobilized Svecokarelian protocrust separated originally from mantle material 2.1–2.0 Ga ago.

1.3. The accretionary arc complex of Southern Finland

The oldest igneous rocks in Southern Finland are tonalites and granodiorites which, as elsewhere in the Svecofennian domain in Finland, intruded 1.90–1.87 Ga ago. Recently, Väisänen et al. (2002) have argued that these rocks can, on a structural basis, be divided into an older synvolcanic and a younger synorogenic group. As one of the few minor “intraorogenic” intrusions (cf. Suominen, 1991) has been shown to contain a mixed zircon population consisting of 1.87 Ga magmatic and 1.82 Ga metamorphic phases (Väisänen et al., 2002), the concept of a lull in magmatic activity between 1.87 and 1.84 Ga (e.g. Vaasjoki, 1996) has been strengthened. Then commenced a new period of magmatism, which culminated in the emplacement of the migmatizing microcline granites at 1.83 Ga (Suominen, 1991) south of the Uusikaupunki–Mikkeli line (Vaasjoki, 1996). On the basis of Sm–Nd data (Huhma, 1986 and unpublished), the granitic material is remobilized Svecofennian crust. The magmatic activity waned between 1.82 and 1.77 Ga when the posttectonic granitoids were emplaced (Korsman et al., 1984; Suominen, 1991; Vaasjoki, 1995).

Lahtinen (1996) considered on geochemical grounds the volcanic rocks of the Häme schist belt as rather primitive, which is in concert with the concept of Nironen (1997), who postulated that these rocks originated as a separate island arc 1.89 Ga ago and were welded on the Central Finland complex at 1.88 Ga.

1.4. Analytical objectives

Although the various age groups of granitoid rocks within the Svecofennian domain are well established, some uncertainty has remained about the significance of their conventional bulk analytical zircon data. Thus, e.g. sample A217-Rastinpää (Korsman et al., 1984) exhibits some heterogeneity. Bearing in mind that Svecofennian metaturbidites contain bimodal zircon populations, the principal one being 1.9–2.1 Ga old with a maximum at 1.95–2.00 Ga (Huhma et al., 1991; Claesson et al., 1993), it is possible that the 1.91–1.93 Ga conventional ages would actually arise from 1.95–2.00 Ga zircons overprinted by the main Svecofennian phase at 1.90–1.88 Ga. As the analyzed zircons are relatively little discordant, such a history would not lead to a significant dispersion of the data. Also, because of the small time difference between the two episodes, Sm–Nd data would remain unaffected, i.e. if a possible 1.95–2.00 Ga protolith was of depleted mantle derivation, a crustal residence time of less than 0.1 Ga would leave a negligible trace in $\varepsilon_{\mathrm{Nd}}$ values. It was thus deemed necessary to carry out U–Pb spot analyses on zircons from several granitoids where conventional bulk analyses yielded ages of 1.91–1.93 Ga.

A property of some Svecofennian granitoids belonging to the 1.90–1.88 age group is the occurrence of slightly heterogeneous zircon populations (Vaasjoki et al., 1996). Deviating zircon fractions generally plot to the right of the discordia lines demonstrating the presence of an older zircon component. At times this is obviously due to inherited cores, as abraded fractions are more deviating than unabraded ones. This is, however, not always the case. The older component may have two sources: either Paleoproterozoic “protocrust”, the existence of which has been demonstrated by the metaturbidite zircon analyses, or zircon derived from both Paleoproterozoic and Archean sources, perhaps via partially absorbed metasedimentary rocks. Sm–Nd data are inconclusive in this matter. A significant influx of sedimentary material is excluded by standard geochemical data, but even a minor contamination could, under favorable circumstances, produce the heterogeneity observed in zircon bulk analyses. Thus, spot analyses on zircons were considered necessary to solve this problem, which has a profound bearing when considering the evolution of the Fennoscandian Shield.

2. The rocks studied and analytical procedure

2.1. Sample descriptions and previous conventional zircon analyses

Three samples from the 1.93–1.91 Ga age group granitoids and one syntectonic tonalite with a known heterogeneous zircon population were selected for analysis. The geographic locations of the samples are shown in Fig. 1.

A83-Laajamäki is a quartz diorite which intersects the supracrustal formation in the central part of the Pielavesi 1:100,000 map sheet. Oligoclase-andesine forms about 70% of the rock. The amount of quartz is minor, and hypersthene, diopside and biotite are the mafic constituents. The texture of the rock is hypidiomorphic and the weathered surfaces are often brownish in color. Accessory minerals are apatite, epidote and zircon (Salli, 1983). A conventional U–Pb analysis of four 5–7 mg zircon fractions has yielded a result of 1923 ± 4 Ma (Vaasjoki and Sakko, 1988).

A217-Rastinpää represents a gneissose tonalite forming an oval complex with a smaller satellite body to its northwesterly side in the Rautalampi map sheet area (Pääjärvi, 2000). The tonalite is normally grey on weathered surface with quartz ribbons. It is partly granitized and migmatitic in character with mobilized tonalitic veins. Migmatization is strongest in the satellite body and in the western part of the main body. Boudinaged amphibolite dykes and xenoliths and fine-grained felsic dykes occur locally. The tonalite is fine-medium grained and has normally a granoblastic texture. Quartz exhibits deformation bands and strong undulating extinction and occurs also as mobilized

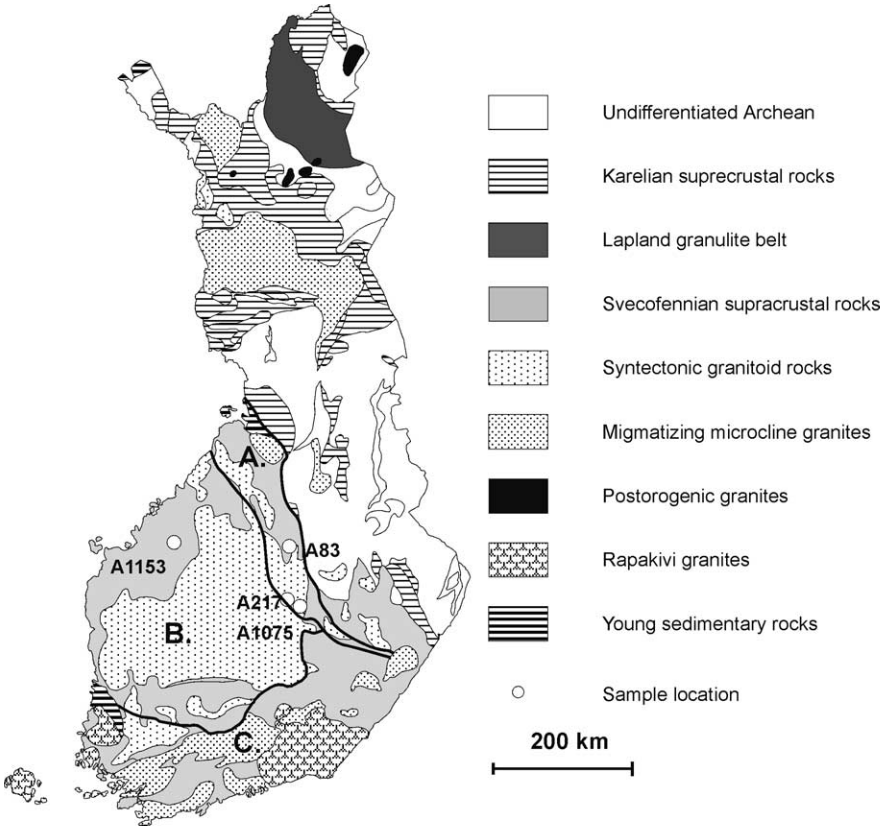

Fig. 1. Locations of the samples studied. Geological background simplified from Korsman et al. (1997). (A) The primitive arc complex; (B) the accretionary arc complex of Central Finland; (C) the accretionary arc complex of Southern Finland.

grain aggregates. The major minerals are plagioclase, quartz and biotite. Sporadic hornblende occurs as a minor constituent. Accessory minerals are potassium feldspar, epidote, magnetite, apatite, zircon, carbonate and sericite (Lahtinen, 1994). A conventional U–Pb analysis of ten 10–15 mg zircon fractions has yielded an age of 1922 ± 12 Ma (Korsman et al., 1984).

A1075-Pyöreänsuonvuori comes from the Toholampi gneissose tonalite within the same Rautalampi map sheet area as A217-Rastinpää. The rock is trondhjemitic–tonalitic in modal composition with plagioclase, quartz and biotite as the major minerals, with the exception that biotite is in the most felsic variants only a minor constituent. Otherwise, potassium feldspar, hornblende, garnet and orthopyroxene are the minor minerals. Apatite, magnetite and zircon are ubiquitous accessories. The gneisses contain locally more leucocratic fragments and oval enclaves rich in epidote and antiperthite. The texture is always granoblastic. Amphibolite layers within the gneiss consist of hornblende, plagioclase, pyroxene and biotite (Lahtinen, 1994). A conventional U–Pb analysis of five 5–7 mg zircon fractions indicates an age of 1914 ± 4 Ma (Vaasjoki and Sakko, 1988).

A1153-Kalliokangas represents one of the four smallish syntectonic tonalite bodies occurring in the Evijärvi map sheet area (Vaarma and Pipping, 1997). The rock is medium-coarse grained and orientated, and varies from dark to pale grey in color. Major minerals are plagioclase, quartz, biotite and occasional hornblende. Apatite, titanite and zircon occur as accessory minerals. Locally, there occur mica-schist enclaves of varying (3–15 cm) sizes (Vaarma, 1990), which were avoided during sampling. Conventional U–Pb analyses of seven 2–5 mg fractions shows that four analyses determine a discordia line with an upper intercept of 1883 ± 6 Ma, while three abraded fractions plot right of the discordia. This feature has been taken to indicate the presence of older inherited cores. A slightly reversely discordant titanite fraction with a ^{207}Pb/^{206}Pb age of 1838 ± 5 Ma has been interpreted as indicating the last regional cooling through the 500 °C isotherm (Vaasjoki et al., 1996).

From each of these samples, several tens of grains were selected from the heaviest zircon fractions available in the zircon archive of the Unit for Isotope Geology. The grains were mounted in epoxy resin, and the polished sections were examined both in transmitted and reflected light. This examination revealed that in the 1.93–1.91 Ga group samples (A83, A217, A1075; Fig. 2) there were no obvious differences between various grains. However, in the 1.89 Ga sample (A1153, Fig. 3) definite cores were detected in some grains. It should be noted in this context, that selection of the grains for analysis had to be done on optical grounds, as the SEM apparatus of the Geological Survey was not installed at the time of the analytical work.

2.2. *Results of the ion probe analyses*

The spot analyses were carried out on a CAMECA 1270 instrument of the NORDSIM laboratory at the Swedish Museum of Natural History, Stockholm. The analytical procedures and standardization techniques have been described in detail by Whitehouse et al. (1997).

From the four samples, a total of 68 spots from 59 grains (A83 11/10, A217 18/15, A1075 13/13, A1153 26/21) were analyzed. The final results are presented in Table 1 and shown on concordia plots in Fig. 4. Analytical errors are reported on the 1σ level.

2.2.1. *A83-Laajamäki*

Two analyses from one grain (2) deviate markedly from the others. Later examination by SEM revealed that this particular analytical point lies on a crack, which was not noticed during the optical examination, and thus, may be disturbed by later processes. One slightly reversely discordant point (3) plots just outside of the main cluster formed by the other eight

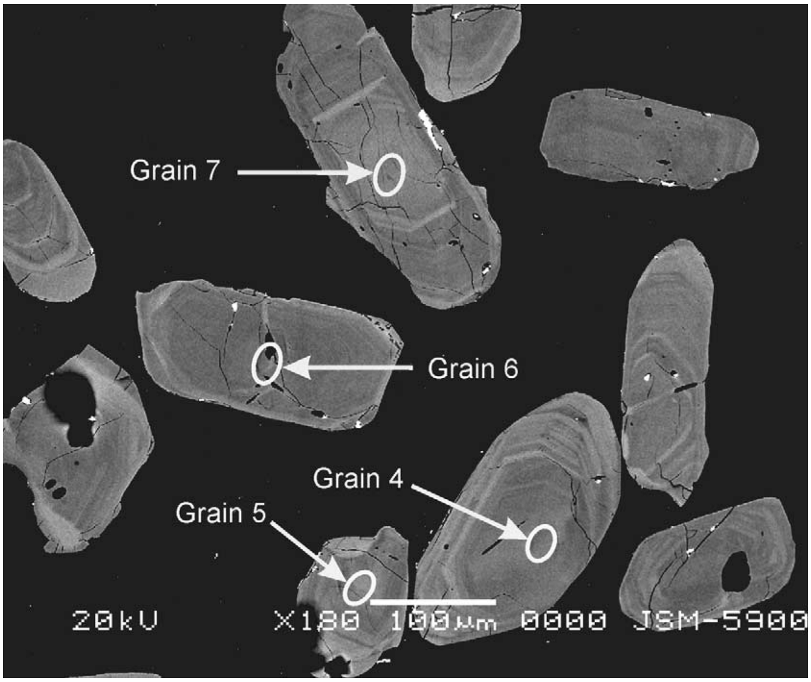

Fig. 2. A scanning electron microscope (SEM) back-scatter electron (BSE) image of zircons from sample A1075-Pyöreänsuonvuori. The ellipses correspond to the analyzed spots listed in Table 1.

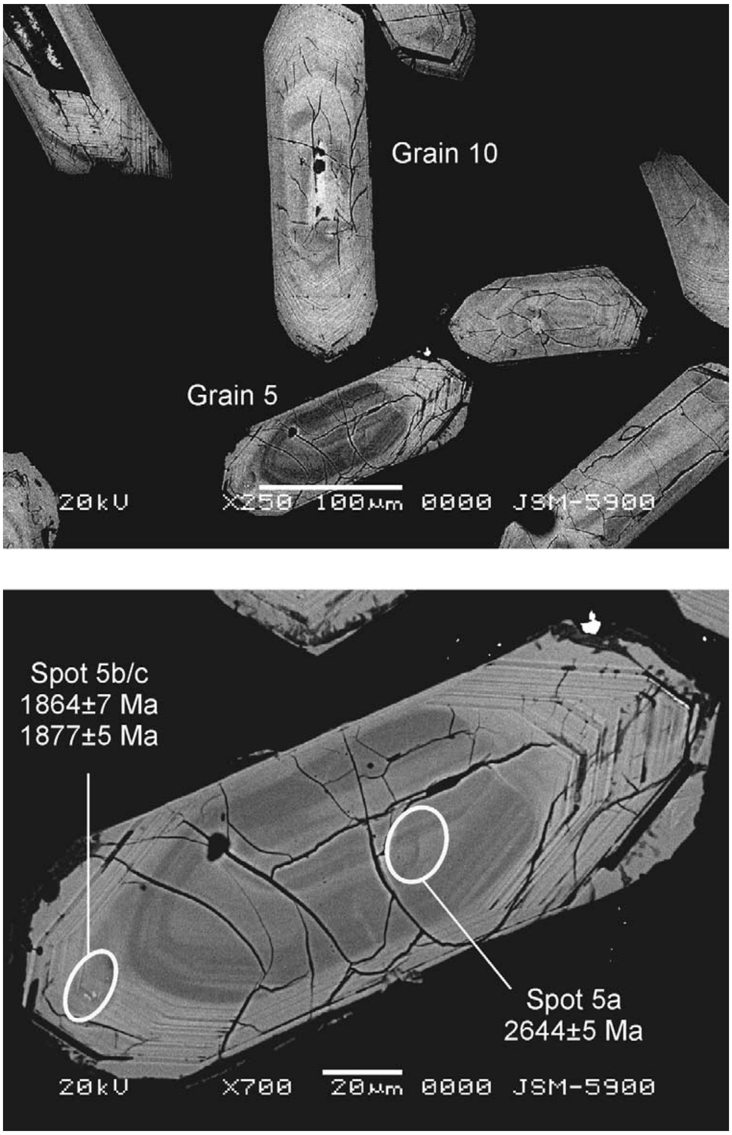

Fig. 3. SEM-BSE images of zircons from sample A1153-Kalliokangas. Grain 5 contains a darker core, which is markedly older than the rim exhibiting oscillatory zoning typical of magmatic zircons. The ^{207}Pb/^{206}Pb ages for the analyses from grain 5 are shown.

analyses, which define intercepts at 1894 (+13/−23) and 386 Ma with an MSWD of 0.67. Using the same regression program, the recalculated age for the bulk analyses is 1923 (+7/−6) Ma, i.e. the results differ from each just in excess of analytical error. However, the regression line for the four bulk analyses passes through the cluster of the eight best spot analyses, so the difference between the numeric results may arise from the relatively small sample populations for both methods.

2.2.2. A217-Rastinpää

One analysis exhibits a young age, but a second spot from the same grain (7) plots within the main cluster. Another grain (5) gives an analytically poor result with a low error correlation. The other crystals can be

Table 1
U–Pb ionp robe data from Svecofennian granitoid rocks in Finland

Analysis	Date	U (ppm)	Pb (ppm)	Th/U	^{206}Pb/^{204}Pb	^{207}Pb/^{206}Pb	±1σ %	^{206}Pb/^{238}Pb	±1σ %	^{207}Pb/^{235}Pb	±1σ %	Rho	^{207}Pb/^{206}Pb age (Ma)
A83-Laajamäki granodiorite (map sheet: 331408, northing: 7028.70, easting: 3481.00)													
N041-01A	24-02-97	431	181	0.346	8163	0.1165	0.84	0.3776	1.38	6.065	1.62	0.85	1903 ± 15
N041-02A	24-02-97	232	80	0.411	579	0.1087	1.82	0.3126	2.39	4.685	3.00	0.80	1778 ± 33
N041-02B	24-02-97	295	101	0.416	685	0.1064	4.76	0.3095	1.72	4.540	5.06	0.34	1739 ± 87
N041-03A	24-02-97	357	145	0.285	1554	0.1142	0.86	0.3649	2.35	5.747	2.50	0.94	1868 ± 15
N041-04A	24-02-97	255	103	0.428	6101	0.1160	0.76	0.3618	1.88	5.784	2.02	0.93	1895 ± 14
N041-05A	24-02-97	199	79	0.306	74239	0.1179	1.04	0.3574	2.18	5.807	2.41	0.90	1924 ± 19
N041-06A	24-02-97	399	149	0.398	1865	0.1147	0.92	0.3344	1.62	5.287	1.86	0.87	1875 ± 17
N041-07A	24-02-97	874	334	0.316	16134	0.1159	0.58	0.3426	1.09	5.474	1.23	0.88	1893 ± 10
N041-08A	24-02-97	368	149	0.251	11608	0.1173	0.59	0.3611	2.15	5.839	2.22	0.96	1915 ± 11
N041-09A	24-02-97	397	155	0.334	5552	0.1163	0.50	0.3499	1.60	5.608	1.68	0.95	1899 ± 9
N041-10A	24-02-97	296	108	0.268	5373	0.1160	0.93	0.3277	2.44	5.241	2.61	0.93	1895 ± 17
A217-Rastinpää gneissose tonalite (map sheet: 332404, northing: 6954.84, easting: 3478.21)													
N042-01A	06-02-97	409	164	0.334	16278	0.1165	0.66	0.3592	1.59	5.770	1.72	0.92	1903 ± 12
N042-02A	06-02-97	374	150	0.346	10345	0.1182	0.71	0.3583	2.10	5.840	2.22	0.95	1930 ± 13
N042-03A	06-02-97	416	164	0.268	9803	0.1173	0.40	0.3529	1.69	5.706	1.73	0.97	1915 ± 7
N042-04A	06-02-97	489	200	0.398	12653	0.1175	0.41	0.3653	0.79	5.920	0.89	0.89	1919 ± 7
N042-05A	06-02-97	371	141	0.285	8870	0.1159	1.15	0.3412	1.13	5.451	1.61	0.70	1894 ± 21
N042-06A	06-02-97	529	206	0.428	9321	0.1160	0.16	0.3492	1.29	5.584	1.30	0.99	1895 ± 3
N042-07A	06-02-97	331	107	0.273	1684	0.1034	2.18	0.2928	1.41	4.173	2.59	0.54	1685 ± 40
N042-07B	07-02-97	463	182	0.329	14695	0.1167	0.60	0.3524	1.81	5.669	1.90	0.95	1906 ± 11
N042-08A	07-02-97	908	345	0.343	13227	0.1145	0.41	0.3403	1.01	5.374	1.09	0.93	1872 ± 7
N042-09A	07-02-97	450	177	0.357	11873	0.1178	0.82	0.3523	1.27	5.723	1.52	0.84	1923 ± 15
N042-10A	07-02-97	423	171	0.299	8801	0.1178	0.53	0.3610	3.00	5.863	3.05	0.98	1923 ± 10
N042-11A	07-02-97	536	212	0.361	9308	0.1180	0.68	0.3541	1.47	5.759	1.62	0.91	1925 ± 12
N042-11B	07-02-97	678	266	0.326	7946	0.1181	0.44	0.3513	2.01	5.722	2.06	0.98	1928 ± 8
N042-12A	07-02-97	1802	615	0.327	1145	0.1168	0.34	0.3058	1.90	4.923	1.93	0.98	1907 ± 6
N042-13A	07-02-97	725	290	0.407	19032	0.1175	0.43	0.3584	2.03	5.803	2.07	0.98	1918 ± 8
N042-14A	07-02-97	1495	547	0.322	12562	0.1141	0.14	0.3284	2.74	5.168	2.74	0.99	1866 ± 3
N042-15A	07-02-97	818	313	0.339	4803	0.1139	0.43	0.3430	1.99	5.388	2.04	0.98	1863 ± 8
N042-15B	07-02-97	1113	434	0.279	9906	0.1180	0.57	0.3488	0.83	5.673	1.01	0.82	1926 ± 10
A1075-Pyöreänsuonvuori gneissose tonalite (map sheet: 322312, northing: 6945.40, easting: 3495.68)													
N043-01A	27-02-97	83	33	0.314	>100000	0.1184	1.24	0.3521	3.59	5.750	3.79	0.95	1933 ± 22
N043-02A	27-02-97	119	48	0.332	>100000	0.1156	3.62	0.3629	4.28	5.785	5.61	0.76	1890 ± 65
N043-03A	27-02-97	110	45	0.281	47574	0.1166	1.18	0.3634	5.03	5.842	5.17	0.97	1904 ± 21
N043-04A	27-02-97	168	70	0.365	>100000	0.1165	0.70	0.3709	2.80	5.957	2.89	0.97	1903 ± 13

Table 1 (*Continued*)

Analysis	Date	U (ppm)	Pb (ppm)	Th/U	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{206}Pb$	±1σ %	$^{206}Pb/^{238}Pb$	±1σ %	$^{207}Pb/^{235}Pb$	±1σ %	Rho	$^{207}Pb/^{206}Pb$ age (Ma)
N043-05A	27-02-97	210	84	0.345	>100000	0.1151	0.93	0.3586	2.15	5.690	2.34	0.92	1881 ± 17
N043-06A	27-02-97	150	61	0.271	4613	0.1147	1.29	0.3672	3.07	5.808	3.33	0.92	1875 ± 23
N043-07A	27-02-97	215	87	0.409	>100000	0.1183	0.82	0.3641	3.11	5.937	3.22	0.97	1930 ± 15
N043-08A	27-02-97	100	41	0.270	>100000	0.1191	2.51	0.3675	4.40	6.036	5.06	0.87	1943 ± 45
N043-09A	27-02-97	148	60	0.377	>100000	0.1144	0.80	0.3659	3.72	5.770	3.81	0.98	1870 ± 14
N043-10A	27-02-97	59	23	0.187	15903	0.1178	1.45	0.3514	4.71	5.709	4.93	0.96	1923 ± 26
N043-11A	27-02-97	63	26	0.292	49900	0.1154	0.50	0.3664	3.95	5.833	3.98	0.99	1887 ± 9
N043-12A	27-02-97	126	52	0.295	55556	0.1177	1.34	0.3668	2.89	5.951	3.19	0.91	1921 ± 24
N043-13A	27-02-97	93	36	0.361	1038	0.1124	4.25	0.3522	3.47	5.460	5.48	0.63	1839 ± 77
A1153-Kalliokangas tonalite (map sheet: 231405, northing: 7028.75, easting: 2470.44)													
N044-01A	25-02-97	496	184	0.360	66711	0.1170	0.30	0.3324	1.36	5.361	1.40	0.98	1910 ± 5
N044-02A	25-02-97	244	81	0.340	1467	0.1333	0.79	0.2935	2.53	5.395	2.66	0.95	2142 ± 14
N044-02B	14-04-97	1070	383	0.330	9259	0.1144	0.33	0.3209	0.57	5.060	0.66	0.86	1870 ± 6
N044-02C	14-04-97	964	274	0.264	816	0.1130	0.34	0.2557	0.72	3.985	0.79	0.90	1848 ± 6
N044-03A	25-02-97	257	93	0.236	1234	0.1128	1.31	0.3254	2.48	5.061	2.80	0.88	1845 ± 24
N044-04A	25-02-97	1825	593	0.720	4284	0.1135	0.16	0.2920	0.86	4.569	0.87	0.98	1856 ± 3
N044-05A	25-02-97	132	45	0.996	2177	0.1813	0.31	0.2914	2.33	7.281	2.35	0.99	2664 ± 5
N044-05B	14-04-97	659	246	0.225	29656	0.1140	0.36	0.3352	0.72	5.268	0.80	0.89	1864 ± 7
N044-05C	14-04-97	1104	345	0.396	1604	0.1148	0.28	0.2799	0.63	4.430	0.69	0.91	1877 ± 5
N044-06A	26-02-97	273	98	0.248	20064	0.1136	0.53	0.3233	2.29	5.064	2.35	0.97	1858 ± 9
N044-07A	26-02-97	442	147	0.210	4392	0.1137	0.52	0.2987	1.60	4.683	1.69	0.95	1860 ± 9
N044-08A	26-02-97	263	100	0.178	>100000	0.1129	1.03	0.3428	2.29	5.338	2.51	0.91	1847 ± 19
N044-09A	26-02-97	170	48	0.616	1107	0.1175	1.49	0.2521	3.33	4.086	3.65	0.91	1919 ± 27
N044-10A	26-02-97	555	151	0.242	2362	0.1131	0.50	0.2444	1.82	3.813	1.88	0.96	1850 ± 9
N044-11A	26-02-97	199	67	0.272	4760	0.1140	0.92	0.3031	2.18	4.765	2.36	0.92	1864 ± 17
N044-12A	26-02-97	165	57	0.161	1483	0.1133	1.26	0.3102	2.30	4.846	2.63	0.88	1853 ± 23
N044-13A	26-02-97	309	80	0.369	5089	0.1129	0.90	0.2310	1.86	3.594	2.06	0.90	1846 ± 16
N044-14A	26-02-97	49	18	0.248	>100000	0.1152	1.76	0.3299	5.54	5.240	5.81	0.95	1883 ± 32
N044-15A	26-02-97	196	62	0.573	681	0.1109	1.27	0.2830	3.37	4.327	3.60	0.94	1814 ± 23
N044-15C	26-02-97	265	84	0.390	4755	0.1119	1.27	0.2844	2.54	4.387	2.84	0.89	1830 ± 30
N044-16A	26-02-97	239	47	1.504	444	0.1110	1.10	0.1753	3.05	2.682	3.24	0.94	1815 ± 20
N044-17A	26-02-97	507	168	0.185	2361	0.1113	0.99	0.2982	2.28	4.575	2.48	0.92	1820 ± 18
N044-18A	26-02-97	546	178	0.259	25246	0.1131	0.85	0.2925	1.27	4.562	1.52	0.83	1850 ± 15
N044-19A	26-02-97	245	96	0.400	89847	0.1177	0.28	0.3528	2.32	5.725	2.34	0.99	1921 ± 5
N044-20A	26-02-97	291	112	0.440	446	0.1160	0.47	0.3444	2.78	5.510	2.82	0.99	1896 ± 8
N044-21A	26-02-97	345	98	1.213	871	0.1139	2.67	0.2554	5.46	4.012	6.08	0.90	1863 ± 48

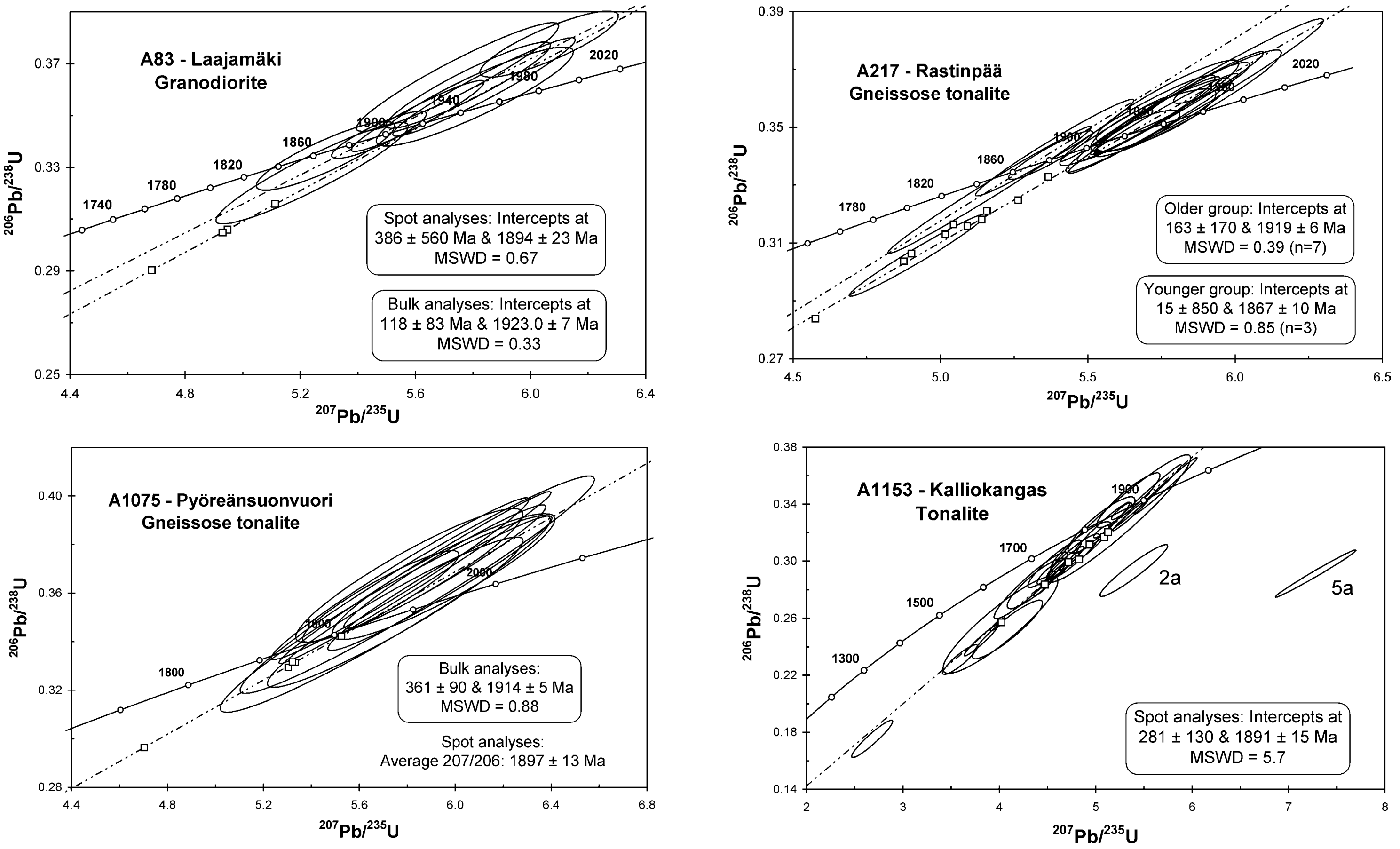

Fig. 4. Concordia diagrams for the U–Pb analyses from zircons of the samples A83, A217, A1075 and A1153. The results and 1σ error limits of individual NORDSIM analyses are indicated by the ellipses. The squares indicate the results of published bulk analyses (A83 and A1075, Vaasjoki and Sakko, 1988; A217, Korsman et al., 1984 and A1153, Vaasjoki et al., 1996). All age results have been calculated using the Isoplot/Ex toolkit (Ludwig, 1998).

divided into two groups: three grains (8, 14 and 15) are markedly younger than the others. This younger group defines an upper intercept of 1867 ± 10 Ma (MSWD = 0.85) and the older group 1909 ± 10 Ma (MSWD = 2.9). If three slightly deviating analyses (1, 6 and 7b) are omitted, the result for the older group becomes 1919 ± 3 Ma (MSWD = 1.5). The distribution of the conventional analyses is consistent with them representing mixtures of populations with two different ages, established by the ion probe data.

2.2.3. A1075-Pyöreänsuonvuori

The 13 analyses form a coherent group with an average $^{207}Pb/^{206}Pb$ age of 1897 ± 13 Ma, which, considering analytical errors, is marginally younger than the recalculated age of 1914 ± 5 Ma for the conventional analyses. However, the linear regression for the bulk analyses plots straight through the cluster of the spot analyses, and the apparent difference in the ages probably arises from insufficient statistics.

2.2.4. A1153-Kalliokangas

Of the 26 analyses 2 differ grossly from the rest. Both represent cores, and the elder (5a) has an Archean $^{207}Pb/^{206}Pb$ age. If these are omitted, the others define a regression line with the intercepts at 1891 ± 15 and 281 ± 130 Ma (MSWD = 5.7). However, three practically concordant analyses (1, 19 and 20) with an average $^{207}Pb/^{206}Pb$ age of 1909 Ma may be slightly older than the rest. If these, the analytically dubious point 14 (large errors) and point 9 with a high $^{207}Pb/^{206}Pb$ age are omitted from the calculation, the results become 1865 ± 10 and 75 ± 87 Ma (MSWD = 2.0). Thus, the spot analyses confirm the interpretation given for the data from the bulk samples.

3. Discussion and conclusions

The results from samples A83-Laajamäki, A217-Rastinpää and A1075-Pyöreänsuonvuori, representing the oldest granitoids within the Svecofennian primitive arc complex demonstrate that no zircons with $^{207}Pb/^{206}Pb$ ages in excess of 1950 Ma exist in these rocks. This is in concert with earlier geochemical and Sm–Nd isotopic results (Lahtinen, 1994; Lahtinen and Huhma, 1997), which clearly favor a mantle-derived origin for the source rocks of the earliest intrusive and extrusive rocks emplaced during the Svecofennian orogeny. Moreover, the results from A217-Rastinpää demonstrate a later zircon population formed during the Svecofennian culmination, which accounts for the slight heterogeneity observed in the conventional zircon data. Thus, the present results yield further credence to previous conclusions (Helovuori, 1979; Korsman et al., 1984; Vaasjoki and Sakko, 1988) that the Svecofennian magmatism observed at the Archean–Proterozoic craton margin commenced ca. 1.93 Ga ago at the earliest, when oceanic basalts were subducted under the Archean craton.

It seems that within the Fennoscandian Shield, the occurrence of the juvenile 1.92 Ga crust is almost entirely confined to Finland. In the two cases where similar age indications have been obtained in Sweden, one sample (Husum) has been in analogy to A217-Rastinpää, definitely reworked during the culmination of the Svecofennian orogeny, while Sm–Nd data from the other (Seltjärn) indicates a source differing from the depleted mantle (Lundqvist et al., 1998).

The ion probe measurements from sample A1153-Kalliokangas demonstrate the reason for the observed heterogeneity in the conventional zircon analyses: two of the 21 zircon grains analyzed contain clearly older cores, one being Archean in age. As the Kalliokangas tonalite is known to contain relatively abundant enclaves of mica schist, it would seem likely that some supracrustal material was totally absorbed during magma formation, and the observed old zircon cores stem from this source. However, the tonalite is geochemically clearly of I-type (Vaarma, 1990), so the amount of assimilated sediment cannot be volumetrically significant. In contrast, data from Sweden indicate that granitoid rocks with a marked S-type chemical signature (e.g. Njurunda) contain mixed zircon populations with apparent ages in excess of 2.0 Ga, while others (e.g. Oringen) contain clearly inherited cores in their zircons and exhibit slightly negative ε_{Nd} values (Welin et al., 1993).

These results enter some new evidence to the discussion on the problematics of the Svecofennian protocrust (e.g. Claesson et al., 1993; Vaasjoki et al., 1996; Lahtinen and Huhma, 1997). As the present data discard the last suspicions on the validity of the 1.92–1.93 Ga age for the earliest phases of

Svecofennian magmatism, they also rule out these rocks as a possible provenance for the Paleoproterozoic zircons abundantly encountered in the Svecofennian metaturbidites. The ca. 1.95 Ga old Jormua ophiolite in Finland (Peltonen et al., 1996) and the Knaften complex in Sweden (Wasström, 1993, 1996) are so small that they cannot serve as a viable source of detrital zircons found in the lower Svecofennian metasediments (Lahtinen et al., 2002). Thus, the source of this ca. 2 Ga old population remains enigmatic, and probably does not lie within the Fennoscandian Shield. In fact, the closest area to Fennoscandia with voluminous ca. 2 Ga old granitoids is the Ukrainian Shield of Sarmatia (e.g. Shcherbak, 1989).

The results from the Kalliokangas tonalite suggest that heterogeneous zircon populations within Svecofennian syntectonic granitoids cannot necessarily be taken as evidence of a Paleoproterozoic igneous precursor for the rock, as at least part of the zircons may be derived by assimilation of clastic material. Indeed, the concept of a Svecofennian protocrust, even as working hypothesis, needs rigorous constraining. Turbiditic sediments can be transported considerable distances and are even today deposited directly on oceanic crust, and thus, constitute no evidence for pre-existing continental crustal material in their immediate present environment. As the geographical provenance of their 2 Ga old zircons remains obscure and record of earliest Svecofennian magmatic activity is restricted to the primitive arc complex within the Raahe–Ladoga zone, the need for postulating a period of Paleoproterozoic crustal formation within the Fennoscandian Shield before the onset of the Svecofennian orogeny proper at 1.92 Ga arises solely from the geochemical nature and Sm–Nd characteristics of igneous rocks within the Central Finland granitoid complex.

Acknowledgements

We wish to thank Markku Väisänen (University of Turku) and an anonymous referee for comments which helped to improve the manuscript. This paper is NORDSIM contribution #80. The NORDSIM facility is funded and operated under an agreement with the Joint Nordic research councils and the Swedish Museum of Natural History.

References

Alviola, R., Mänttäri, I., Mäkitie, H., Vaasjoki, M., 2001. Svecofennian rare-element granitic pegmatites of the Ostrobothnia region, Western Finland; their metamorphic environment and time of intrusion. In: Mäkitie, H. (Ed.), Svecofennian Granitic Pegmatites (1.86–1.79 Ga) and Quartz Monzonite (1.87 Ga), and their Metamorphic Environment in the Seinäjoki Region, Western Finland. Geological Survey of Finland, Special Paper 30, pp. 9–29.

Claesson, S., Huhma, H., Kinny, P., Williams, I., 1993. Svecofennian detrital zircon ages—implications for the Precambrian evolution of the Baltic Shield. Precambrian Res. 64, 109–130.

Helovuori, O., 1979. Geology of the Pyhäsalmi ore deposit, Finland. Econ. Geol. 74, 1084–1101.

Huhma, H., 1986. Sm–Nd, U–Pb and Pb–Pb isotopic evidence for the origin of the early Proterozoic Svecokarelian crust in Finland. Geol. Surv. Finland Bull. 337, 52.

Huhma, H., Claesson, S., Kinny, P., Williams, I., 1991. The growth of early Proterozoic crust: new evidence from Svecofennian detrital zircons. Terra Nova 3, 175–179.

Kähkönen, Y., 1994. Shoshonitic and high-K metavolcanic rocks in the Southern part of the Paleoproterozoic Tampere schist belt, Southern Finland: evidence for an evolved arc-type setting. In: Nironen, M., Kähkönen, Y. (Eds.), Geochemistry of Proterozoic Supracrustal Rocks in Finland. Geological Survey of Finland Special Paper 19, pp. 101–116.

Korsman, K., Hölttä, P., Hautala, T., Wasenius, P., 1984. Metamorphism as an indicator of evolution and structure of the crust in Eastern Finland. Geol. Surv. Finland Bull. 328, 40.

Korsman, K., Niemelä, R., Wasenius, P., 1988. Multistage evolution of the Proterozoic crust in the Savo schist belt, Eastern Finland. In: Korsman, K. (Ed.), Tectono-Metamorphic Evolution of the Raahe–Ladoga Zone. Geological Survey of Finland Bulletin 343, pp. 89–96.

Korsman, K., Koistinen, T., Kohonen, J., Wennerström, M., Ekdahl, E., Honkamo, M., Idman, H., Pekkala, Y. (Eds.), 1997. Suomen kallioperäkartta-Berggrundskarta över Finland-Bedrock Map of Finland. 1:1,000,000. Geological Survey of Finland, Espoo.

Kousa, J., Marttila, E., Vaasjoki, M., 1994. Petrology, geochemistry and dating of Paleoproterozoic metavolcanic rocks in the Pyhäjärvi area, Central Finland. In: Nironen, M. and Kähkönen, Y. (Eds.) Geochemistry of Proterozoic Supracrustal Rocks in Finland. Geological Survey of Finland Special Paper 19, pp. 7–27.

Lahtinen, R., 1994. Crustal evolution of the Svecofennian and Karelian domains during 2.1–1.79 Ga, with special emphasis on the geochemistry and origin of 1.93–1.91 Ga gneissic tonalites and associated supracrustal rocks in the Rautalampi area, Central Finland. Geological Survey of Finland Bulletin 378, 128 pp.

Lahtinen, R., 1996. Geochemistry of Palaeoproterozoic supracrustal and plutonic rocks in the Tampere-Hämeenlinna area, Southern Finland. Geological Survey of Finland Bulletin 389, 113 pp.

Lahtinen, R., Huhma, H., 1997. Isotopic and geochemical constraints on the evolution of the 1.93–1.79 Ga Svecofennian crust and mantle in Finland. Precambrian Res. 82, 13–34.

Lahtinen, R., Huhma, H., Kousa, J., 2002. Contrasting source components of the Paleoproterozoic Svecofennian metasediments: detrital zircon U–Pb, Sm–Nd and geochemical data. Precambrian Res. 116, 81–109.

Lundqvist, Th., Vaasjoki, M., Persson, P.-O., 1998. U–Pb ages of plutonic and volcanic rocks in the Svecofennian Bothnian Basin, Central Sweden, and their implications for the Palaeoproterozoic evolution of the Basin. GFF 120, 357–363.

Ludwig, K., 1998. Using Isoplot/Ex. Berkeley Geochronology Center Special Publication 1, 43 pp.

Nironen, M., 1997. The Svecofennian orogen: a tectonic model. Precambrian Res. 86, 21–44.

Pääjärvi, A., 2000. Rautalammin ja Karttulan kartta-alueiden kallioperä. Summary: pre-quaternary rocks of the Rautalampi and Karttula map-sheet area. Suomen geologinen kartta 1:100,000: kallioperäkarttojen selitykset lehdet 3223 ja 3224. 81 pp.

Peltonen, P., Kontinen, A., Huhma, H., 1996. Petrology and geochemistry of metabasalts from the 1.95 Ga Jormua Ophiolite, Northeastern Finland. J. Petrol. 37 (6), 1359–1383.

Rämö, O.T., Vaasjoki, M., Mänttäri, I., Elliot, B., Nironen, M., 2001. Petrogenesis of the post-kinematic magmatism of the Central Finland granitoid complex I: radiogenic isotope constraints and implications for crustal evolution. J. Petrol. 42, 1971–1993.

Salli, I., 1983. Pielaveden kartta-alueen kallioperä. Summary: pre-quaternary rocks of the Pielavesi map-sheet area. Suomen geologinen kartta 1:100,000: kallioperääkarttojen selitykset lehti 3314, 29 pp.

Shcherbak, N., 1989. Geochronology of the Ukrainian Shield. Kiev, Naukova Dumka, 144 pp. (in Russian)

Sjöblom, B., 1990. Mäntän kartta-alueen kallioperä. Summary: pre-quaternary rocks of the Mänttä map-sheet area. Suomen geologinen kartta 1:100,000: kallioperäkarttojen selitykset lehti 2231, 64 pp.

Suominen, V., 1991. The chronostratigraphy of Southwestern Finland with special reference to Postjotnian and Subjotnian diabases. Geological Survey of Finland Bulletin 356, 100 pp.

Tiainen, M., Kähkönen, Y., 1994. Geochemistry of the Paleoproterozoic andesitic to rhyolitic arc-type metavolcanic rocks of Haukkamaa, Kuru, Central Finland. In: Nironen, M., Kähkönen, Y. (Eds.), Geochemistry of Proterozoic Supracrustal Rocks in Finland. Geological Survey of Finland Special Paper 19, pp. 29–44.

Vaarma, M., 1990. Pohjanmaan liuskevyöhykkeen geologia Evijärven alueella. Unpulished Lic. Phil. Thesis, Department of Geology, University of Helsinki, 101 pp.

Vaarma, M., Pipping, F., 1997. Alajärven ja Evijärven kartta-alueiden kallioperää. Summary: pre-quaternary rocks of the Alajärvi and Evijärvi map-sheet areas. Suomen geologinen kartta 1:100,000: kallioperäkarttojen selitykset lehdet 2313 ja 2314, 83 pp.

Vaasjoki, M., 1995. Rengon Rouvinmäen kvartsimontsodioriitti: uusi posttektoninen granitoidi. Summary: the Rouvinmäki quartzmonzodiorite at Renko: a new posttectonic granitoid. Geologi 47, 79–81.

Vaasjoki, M., 1996. Explanation to the geochronological map of Southern Finland: the development of continental crust with special reference to the Svecofennian orogeny. Geological Survey of Finland Report of Investigation 135, 30 pp.

Vaasjoki, M., Sakko, M., 1988. The evolution of the Raahe–Ladoga zone in Finland: isotopic constraints. In: Korsman, K. (Ed.), Tectonometamorphic evolution of the Raahe–Ladoga zone. Geological Survey of Finland Bulletin 343, pp. 7–32.

Vaasjoki, M., Pietikäinen, K., Vaarma, M., 1996. U–Pb zircon determinations from the Keikyä breccia and other sites in the Svecofennides: indications of a Svecokarelian protocrust. Bull. Geol. Soc. Finland 68, 3–10.

Väisänen, M., Mänttäri, I., Hölttä, P., 2002. Svecofennian magmatic and metamorphic evolution in Southwestern Finland as revealed by U–Pb zircon SIMS geochronology. Precambrian Res. 116, 111–127.

Wasström, A., 1993. The Knaften granitoids, Västerbotten County, Northern Sweden. Sveriges Geologiska Undersökning C 823, pp. 59–63.

Wasström, A., 1996. U–Pb zircon dating of a quartz-feldspar porphyritic dyke in the Knaften area, Västerbotten County, Northern Sweden. Sveriges Geologiska Undersökning C 828, 34–40.

Welin, E., Christiansson, K., Kähr, A.-M., 1993. Isotopic investigations of metasedimentary and igneous rocks in the Palaeoproterozoic Bothnian Basin, Central Sweden. Geologiska Föreningens i Stockholm Förhandlingar 115, 285–296.

Whitehouse, M., Claesson, S., Sunde, T., Vestin, J., 1997. Ion microprobe U–Pb zircon geochronology and correlation of Archaean gneisses from the Lewisian Complex of Gruinard Bay, Northwestern Scotland. Geochim. Cosmochim. Acta 61, 4429–4438.