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U-Pb ages and Nd isotope characteristics of the lateorogenic, migmatizing microcline granites in southwestern Finland

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Abstract

U-Pb ages and whole-rock Nd isotope data have been obtained from the Paleoproterozoic lateorogenic migmatizing microcline granites of southwestern Finland. Isotope dilution and ion microprobe U-Pb data on zircons and monazites show that the age spectrum of these granites is at least 1.85-1.82 Ga. Commonly, zircons and monazites record the same ages. The age variation in the Veikkola granite area is of the order of 25 Ma and indicates that this seemingly homogeneous granite consists of two separate intrusions. The zircons of the lateorogenic granites are pervasively altered and conventional U-Pb results are commonly discordant. The ion microprobe studies reveal that the granites contain very few inherited zircons with preserved original U-Pb isotope ratios, with the exception of the Oripää granite. Initial ε_{Nd} values, mostly in the range of -0.5 to -1.0, imply a moderate input of older crustal material into most of the lateorogenic granites. A shift from more juvenile to less radiogenic Nd isotope composition is observed from north to south, and the variation pattern of ε_{Nd} values of the lateorogenic granites is thus similar to that of the surrounding synorogenic granitoid rocks.

Keywords*:* granites, Svecofennian orogeny, absolute age, U/Pb, zircon, monazite, Sm/Nd, Paleoproterozoic, southwestern Finland

1. Introduction

J.J. Sederholm proposed in the early 20th century a fourfold classification for the Paleoproterozoic intrusive rocks of the Finnish Svecofennian (Sederholm, 1926). His first group consisted of granodioritic-tonalitic bodies, which intruded the Svecofennian supracrustal rocks. Both rock types were intensely metamorphosed by the microcline granites of the second group, and all these rocks were cut by largely undeformed granite stocks which formed the third group. On the basis of the contact relationships between a third group granite and the rapakivi granites in the archipelago of southwesternmost Finland, Sederholm (1926) concluded that the rapakivi granites were even younger and formed a fourth group of intrusive rocks. This classification is still colloquially used in field work within the Finnish Precambrian, although the current scientific nomenclature was cre-

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This paper deals with the lateorogenic migmatizing microcline granites of southern Finland that comprise Sederholm's original second group. We present new U-Pb mineral data (isotope dilution and ion microprobe) and whole-rock Nd isotope analyses on the lateorogenic granites in southwestern Finland.

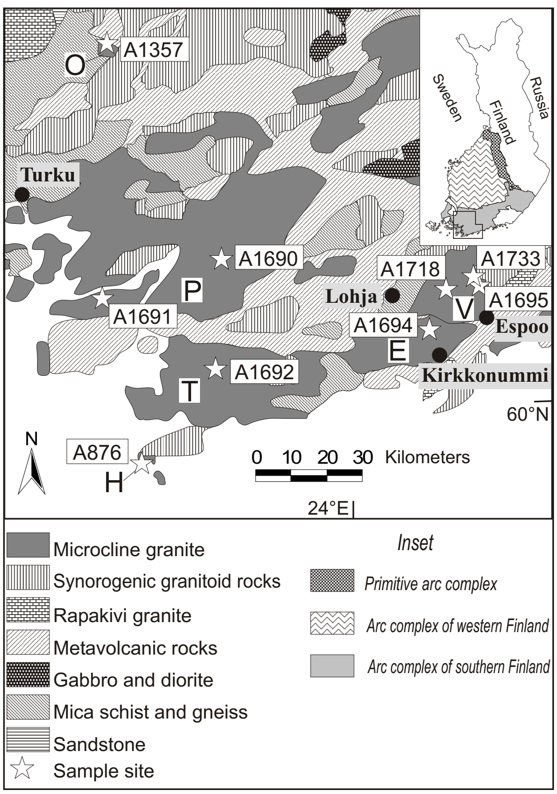

Fig. 1. Geological map of the study area with the locations of the dated samples. The three main crustal units of the Svecofennian domain of Finland are shown in the inset. Modified after Korsman et al. (1997). Capital letters mark the granites studied: E = Evitskog, H = Hanko, O = Oripää, P = Perniö, T = Tenhola and V = Veikkola granite.

2. Concepts of the evolution of the Svecofennian orogeny in Finland

The classification of plutonic rocks into syn-, late- and postorogenic by Simonen (1971) was associated with the classic geosynclinal orogenic concept. Several models for the Svecofennian orogeny based on plate tectonics have been presented subsequently. The latest published plate tectonic models are rather complex, involving several arc complexes (older nuclei and marginal arcs) that accreted to the Archean craton (Lahtinen, 1994; Nironen, 1997; Lahtinen et al., 2003). In line with these models, the Svecofennian crust is divided into three areas with different geological, geochronological and isotopic signatures (Korsman et al., 1997): the primitive arc complex in central Finland, the arc complex of western Finland and the arc complex of southern Finland (Fig. 1).

The main phase of tectonism seems to have been coeval within the arc complex of southern Finland. Early gabbros register ages of 1.89 Ga throughout the area (Hopgood et al., 1983; Patchett & Kouvo, 1986) and synorogenic granitoids yield zircon U-Pb ages from 1.89 to 1.87 Ga (Vaasjoki, 1996 and references therein). As shown by Huhma (1986), the synorogenic granitoids mainly consist of mantle derived (juvenile) material, which is also the case with the granites of central Finland (Rämö et al., 2001; Elliott, 2003). It is thus apparent that the culmination of the Svecofennian orogeny was roughly simultaneous everywhere in southern and central Finland. However, Väisänen et al. (2002) considered that the age of nearly 1.9 Ga of some granodiorites (of Sederholm's 1st group) in southwestern Finland reflects the time of initial arc-related magmatism. According to Väisänen et al. (2002), the synorogenic stage occurred somewhat later, i.e., 1.88–1.86 Ga ago and the peak of the metamorphism in SW Finland reached granulite facies at 1824±5 Ma, dating also the D_3 folding that deforms the lateorogenic microcline granites in that area (cf. Ehlers et al., 1993).

Although not many of the lateorogenic granites have been dated so far, it is evident that, in cases where multigrain zircon and/or monazite U-Pb data are available, the zircon results are heterogeneous with mean $^{207}Pb/^{206}Pb$ ages of about 1.84 Ga and monazites are consistently ~1.83 Ga old (Suominen, 1991). Vaasjoki (1996) noted the absence of igneous activity at 1.86–1.85 Ga and suggested that the Svecofennian orogeny may have terminated already by 1.87 Ga, and that the subsequent igneous activity in (the arc complex of) southern Finland might represent a separate tectonothermal event. Indeed, recent models on the Svecofennian evolution (e.g. Nironen, 1997; Korsman et al., 1999; Väisänen, 2002) suggest that the juvenile crustal components were assembled by ~1.87 Ga and that the emplacement of the migmatizing microcline granites was related either to transpressional intraplate tectonism (Ehlers et al., 1993) or extensional collapse after the cessation of the main compressive phase (Korja & Heikkinen, 1995; Korsman et al., 1999).

3. Sample description

3.1. Geologic setting

On the 1:1 000 000 bedrock map of Finland (Korsman et al., 1997), large bodies of lateorogenic, 1.84–1.82 Ga granites are indicated. The map picture is partly deceiving, as these rocks are not necessarily uniformly granitoid in composition. In places, they may contain up to 50% of nebulitic remnants and even xenoliths of supracrustal rocks and synorogenic intrusions, principally granodiorites and tonalites. The lateorogenic granites, although clearly intrusive in character, generally have no well-defined contacts with their country rocks. Rather, there is a gradation from granites through migmatites to metasedimentary rocks and synorogenic intrusive rocks. Nor do these granites form batholiths *sensu stricto*. It is generally thought that they are relatively thin undulating sheets within the country rocks (e.g. Fig. 7 in Ehlers et al., 1993), and their emplacement is attributed to mid-crustal levels (Selonen et al., 1996).

The late Svecofennian microcline granites are predominantly S-type, and thus, for example, their relatively high Al content is manifested by the ubiquitous occurrence of garnet. Other major minerals are microcline, quartz, plagioclase, biotite and cordierite. In many cases, the potassium feldspar phenocrysts give the granites a porphyritic texture, although even-grained types also exist. Petrographically, the lateorogenic granites are a heterogeneous group. The grain size varies from medium-grained to pegmatitic, and the color varies significantly, often in an outcrop scale, due to irregular distribution of dark minerals, mainly biotite. The accessory mineral parageneses are not consistent either, but in most cases muscovite, apatite, chlorite, monazite, zircon, and rutile or anatase are found.

3.2. Sample material and previous geochronological data

We have limited our sampling to purely granitic varieties of the aforementioned large granite bodies. Our targets (Fig. 1) were: (1) the *Perniö* granite south and southeast of Turku; (2) the *Tenhola* granite south of the Perniö granite; (3) the *Hanko (Hangö)* granite in the archipelago off the southwestern coast; (4) the *Veikkola* granite area north and northwest of Espoo; (5) the *Evitskog* granite south of the Veikkola area;

and (6) the *Oripää* granite stock and the synorogenic Pöytyä granodiorite about 50–60 km north-northeast of Turku.

(1) The *Perniö* granite covers the largest area of the studied granite bodies and is represented by two samples, A1690 and A1691. Both are medium- to coarse-grained, slightly porphyritic microcline granites. A slight magmatic orientation is present in both samples, but generally the rocks are rather massive. The principal difference between the two samples is in the habit of garnet. In sample A1691 garnet is abundant, euhedral and looks igneous in most places, whereas in A1690 garnet is scarce and most of it is heavily altered, appearing restitic in character. In a previous study, Suominen (1991) reported combined zircon and monazite regression ages of 1829±14 Ma for two samples close to the location of A1690 and 1840±8 Ma for a sample close to the location of A1691. The monazites in both cases are practically concordant ($^{207}Pb/^{206}Pb$ ages 1831±6 Ma and 1836±3 Ma, respectively) and thus determine the upper intercepts (Suominen, 1991).

(2) The *Tenhola* granite is an incipiently migmatized microcline granite with scattered nebulitic inclusions of gneissose composition. Our sample A1692 is taken from a purely granitic part of the rock. The rock is medium- to coarse-grained, and in places there is a vague undulating orientation. Pervasive iron oxide pigmentation gives the rock a reddish color. The microcline is commonly microperthitic and occasionally displays granophyric texture with quartz. Large xenomorphic garnet grains are present in minor amounts.

(3) The *Hanko* granite is a medium-grained, somewhat heterogeneous microcline granite with nebulitic structures resembling those of the Tenhola granite. Garnet is practically absent and the rock is richer in opaque minerals than the other samples of this study. The sample A876 is from the southernmost tip of the Finnish mainland (Fig. 1). The rock is relatively fresh and unaltered compared to our other dated samples. A previous conventional U-Pb study of the Hanko granite reveals rather discordant and heterogeneous zircon populations, which define a poor discordia line with an upper intercept age of 1842±34 Ma, while two nearly concordant monazite fractions yield ages of 1829±9 Ma (A875) and 1822±6 Ma (A876) (Suominen, 1991).

(4) The *Veikkola* granite is a light-colored microcline granite that has varying grain size. It is layered, yet there is no pervasive textural orientation. The layering is due to irregular pegmatitic zones that have gradational contacts to the medium-grained host rock. The layering is gently dipping, with varying strike. In places, euhedral garnets form bands along the lighter, coarse-grained strata, but generally the garnet is randomly dispersed. Our dated samples A1695, A1718, and A1733 are taken from the medium-grained parts of the granite.

(5) The *Evitskog* granite is a pink, coarse-grained and slightly porphyritic microcline granite. The minerals are largely altered and distributed inhomogeneously. Biotite and chlorite form irregular darker patches. Muscovite is also present in minor amounts. The rock has some altered remnants of garnet with chlorite as the most common alteration product. Zircon and monazite are particularly abundant in this granite and other accessory minerals (e.g. apatite and carbonate) are also present. Our sampling site (A1694 in Fig. 1) lies close to the contact of an intermediate supracrustal rock.

(6) The *Oripää* granite lies in the western part of the arc complex of southern Finland ~60 km north-northeast of Turku (Fig. 1). It is cross-cutting rather than migmatizing in character and thus it is somewhat different from the other granites studied in this paper. The Oripää stock is quite small (~20 km^2) and is surrounded by other migmatites and hornblende gneisses and is adjacent to the synorogenic Pöytyä granodiorite. The granite stock is heterogeneous with a very leucocratic, stromatic and coarse to pegmatitic appearance and abundant inclusions of gneissose rocks. Isotope dilution U-Pb data on zircons (Nironen, 1999) yield two overlapping upper intercept ages of 1850±27 and 1860±41 Ma from red and pale brown zircons, respectively. A concordant monazite yields an age of 1794±10 Ma (op. cit.).

4. Analytical methods

4.1. U-Pb dating

From each sample, an average of 15 kg of rock was crushed in a jaw mill and ground in a roller mill to <0.3 mm grain size. The heavy minerals were concentrated with a shaking table and the magnetic minerals were removed with a Carpco® induced roll magnetic separator. The zircons and monazites were separated according to a method described by Vaasjoki et al. (1991).

For multigrain ID-TIMS U-Pb dating, the decomposition of minerals and the extraction of U and Pb followed generally the procedure described by Krogh (1973, 1982). ^{235}U–^{208}Pb spike was used for zircon and ^{235}U–^{206}Pb spike for monazite. The spiked and unspiked isotope ratios were measured with a VG Sector 54 multicollector mass spectrometer. Mass fractionation correction of 0.15±0.05% per a.m.u. for Pb was estimated on the basis of repeated measurements of the SRM981 standard during the analyses. U-Pb age calculations were done using the PbDat program (Ludwig, 1991).

For ion microprobe dating, a range of zircon crystals representative of the whole sample was selected under the microscope and mounted in epoxy, polished and gold-coated. The ion microprobe analyses were performed using the Cameca IMS 1270 secondary ion mass spectrometer of the NORDSIM laboratory at the Swedish Museum of Natural History, Stockholm. The procedure was essentially similar to that described in detail by Whitehouse et al. (1997, 1999). The data were calibrated against a zircon standard (91500; Wiedenbeck et al., 1995) and corrected for modern common Pb (T=0; Stacey & Kramers, 1975).

The fitting of the discordia lines and calculation of the intercept and concordia ages were done using the Isoplot/Ex program (Ludwig, 2001). In the concordia diagrams, all error ellipses and bars are plotted at 2σ level, and the decay constant errors are ignored. Calculated age errors are at 2σ level, unless otherwise indicated.

4.2. Whole-rock Sm-Nd studies

About 150 mg of each sample powder, pulverized in a ring mill with a carbon steel head, was spiked with a ^{149}Sm–^{150}Nd tracer and subsequently dissolved in a Teflon bomb at 180 °C in HF-HNO_3. The extraction of Sm and Nd and the measurement procedure of their isotopic ratios followed that presented by Rämö et al. (2001).

5. Results

5.1. Multigrain ID-TIMS U-Pb chronology

Multigrain analyses (each fraction comprising of at least some tens of crystals, in most cases over 100) on zircons and monazites were carried out on the Tenhola granite (sample A1692), the Evitskog granite (A1694), and the Veikkola granite (A1695, A1718 and A1733). The U-Pb analytical data are summarized in Table 1 and the results are presented in concordia diagrams in Fig. 2. For the analyses, only zircons with magmatic appearance were selected from the heavy mineral separates.

The zircons from the *Perniö* granite (A1690 and A1691) were chosen for ion microprobe study (cf. section 5.2) and only monazites of these samples were dated with the ID-TIMS method. Both monazite results are concordant and the ages, 1829±3 and 1831±3 Ma, are identical within experimental error (Fig. 2a).

The zircons from the *Tenhola* granite (A1692) are euhedral, prismatic, and colorless to light brown. Only homogeneous, prismatic zircons from the density fraction above 4.2 g/cm³ were selected. The U-Pb isotopic ratios of the analyzed four zircon fractions define a linear trend (MSWD=2.3) with an upper intercept age of 1835±13 Ma (Fig. 2b). The concordant age for monazite is 1831±3 Ma.

The zircons from the *Evitskog* granite (A1694) are generally small, elongate and prismatic. They can be divided into nearly colorless and light brown subpopulations. The U-Pb results of two fractions from each

Table 1. TIMS U-Pb age data on zircons and monazites from migmatizing microcline granites in southwestern Finland.

Sample information / Analysed mineral and fraction[a]	Sample weight/ mg	U ppm	Pb ppm	$^{206}Pb/^{204}Pb$ measured	$^{208}Pb/^{206}Pb$ radio-genic	ISOTOPIC RATIOS[b] $^{206}Pb/^{238}U$	±2σ (%)	$^{207}Pb/^{235}U$	±2σ (%)	$^{207}Pb/^{206}Pb$	±2σ (%)	ρ[c]	APPARENT AGES / Ma ±2 σ $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
PERNIÖ GRANITE															
A1690 Kistolanperä															
MON d>4.3 g/cm³ Ø<75µm, equidimensional, yellow, abr. 20min	0.34	2209	6369	14700	8.67	0.329	0.65	5.074	0.65	0.112	0.15	0.97	1835	1832	1828±3
A1691 Pungböle															
MON d>4.3 g/cm³ Ø<75µm, elongated, yellow, variable grain size , abr. 20min	0.27	4582	6113	7725	3.56	0.329	0.65	5.084	0.65	0.112	0.15	0.97	1835	1833	1831±3
TENHOLA GRANITE															
A1692 Tenhola															
A) Zr d>4.2 g/cm³ Ø<75µm, prismatic, brown, translucent, l/w=3-5,abr. 12h	0.12	924	296	2677	0.11	0.298	0.65	4.591	0.65	0.112	0.15	0.97	1685	1748	1824±3
B) Zr d>4.2 g/cm³ Ø<75µm, prismatic, light brown, translucent-transparent, l/w=3-5, abr. 2h	0.18	829	245	1605	0.11	0.272	0.65	4.174	0.65	0.111	0.15	0.97	1552	1669	1819±3
C) Zr d>4.2 g/cm³ Ø<75µm, prismatic, nearly colourless, transparent, l/w=3-4, abr. 2h	0.07	1588	518	966	0.11	0.293	0.65	4.518	0.65	0.112	0.15	0.97	1658	1735	1829±3
D) Zr d>4.2g/cm³ Ø=75-150µm, stubby, plenty of crystal faces, light brown, translucent, l/w=1.5-3, abr. 21h	0.22	678	225	4249	0.11	0.311	0.65	4.797	0.65	0.112	0.15	0.97	1745	1784	1830±3
MON d>4.3 g/cm³ Ø<75µm, equidimensional, yellow, translucent, minor inclusions, abr. 20 min	0.20	4435	5383	109160	3.16	0.328	0.65	5.071	0.65	0.112	0.15	0.97	1831	1831	1831±3
EVITSKOG GRANITE															
A1694 Evitskog															
A) Zr d>4.2g/cm³ Ø<75µm, prismatic, brownish, nearly colourless, transparent, l/w=4-5, abr. 6h	0.25	889	308	707	0.13	0.301	0.65	4.596	0.65	0.111	0.15	0.97	1696	1749	1812±3
B) Zr d>4.2 g/cm³ Ø=75-150 µm, prismatic, colourless, transparent, minor inclusions, l/w≈4, abr. 12h	0.47	679	224	2605	0.12	0.306	0.65	4.678	0.65	0.111	0.15	0.97	1719	1763	1816±3
D) Zr d=4.0-4.2 g/cm³ Ø<75µm, prismatic, brown, translucent-transparent, l/w=4-5, abr. 16h	0.56	1035	312	2409	0.07	0.289	0.65	4.410	0.65	0.111	0.15	0.97	1637	1714	1810±3
E) Zr d=4.0-4.2 g/cm³ Ø<75µm, prismatic, brown, translucent-transparent, l/w=4-5, abr. 1.5h	0.34	1367	410	1082	0.08	0.278	0.65	4.225	0.65	0.110	0.15	0.97	1583	1679	1801±3
MON d>4.3 g/cm³ Ø<75µm, flat, yellow, transparent, abr. 20min	0.18	4679	5549	79556	3.09	0.326	0.65	5.013	0.65	0.111	0.15	0.97	1821	1821	1822±3

VEIKKOLA GRANITE															
A1695 Hyppykallio															
A) Zr d>4.2 g/cm³ Ø<75µm, prismatic, reddish brown, pigmented, transparent, l/w=3-4, abr. 6h	0.34	1341	380	779	0.05	0.265	0.65	4.036	0.65	0.111	0.15	0.97	1515	1642	1808±3
B) Zr d>4.2 g/cm³ Ø<75µm, prismatic, thin, colourless, transparent, l/w>5, abr. 3h	0.27	1706	528	796	0.05	0.289	0.65	4.446	0.65	0.111	0.15	0.97	1639	1721	1822±3
C) Zr d>4.2 g/cm³ Ø>75µm, stubby, variable grain size, pigmented, translucent, l/w=2-4, abr. 4 h	0.36	1123	341	1022	0.04	0.290	0.65	4.481	0.65	0.112	0.15	0.97	1639	1728	1836±3
D) Zr d=4.0-4.2 g/cm³ Ø<75µm, prismatic, elongate,light-coloured, some pigment, transparent, l/w>5, abr. 2 h	0.29	1687	528	773	0.05	0.291	0.65	4.468	0.65	0.111	0.15	0.97	1649	1725	1819±3
E) Zr d=4.0-4.2 g/cm³ Ø<75µm, thin, prismatic, colourless, transparent, l/w≈5	0.15	2131	601	627	0.04	0.260	0.65	3.936	0.65	0.110	0.15	0.97	1491	1621	1794±3
F) Zr d>4.2 g/cm³ Ø<75µm, stubby, reddish brown, translucent, l/w=2-4, abr. 42h	0.24	1719	539	1205	0.04	0.301	0.65	4.664	0.65	0.112	0.15	0.97	1698	1761	1836±3
MON d>4.3 g/cm³ Ø<75µm, flat, round, yellow, abr. 20 min.	0.34	2714	5848	9133	6.30	0.335	0.65	5.229	0.65	0.113	0.15	0.97	1863	1857	1851±3
A1718 Veikkola															
A) Zr d>4.2g/cm³ Ø<75µm, stubby, brown, transparent, slightly pigmented, l/w≈2, abr.6h	0.54	1785	529	1814	0.07	0.283	0.65	4.360	0.65	0.112	0.15	0.97	1609	1705	1825±3
B) Zr d=4.0-4.2 g/cm³ Ø<75µm, prismatic, brownish, transparent, some inclusions, l/w≈4, abr. 7h	0.31	1842	566	2504	0.07	0.296	0.65	4.553	0.65	0.117	0.15	0.97	1669	1741	1828±3
C) Zr d=4.0-4.2 g/cm³ Ø>75µm, stubby, light brown, some pigment, transparent, l/w≈2, abr. 5h,	0.28	1655	493	1915	0.07	0.285	0.65	4.385	0.65	0.112	0.15	0.97	1611	1709	1830±3
F) Zr d=3.8-4.0 g/cm³ Ø<75µm, prismatic, brownish, translucent, l/w=3-4, abr. 2 h	0.45	2428	678	4090	0.06	0.272	0.65	4.190	0.65	0.111	0.15	0.97	1558	1672	1819±3
MON d>4.3 g/cm³ Ø<75µm, flat, euhedral, yellow, transparent, abr. 25 min	0.29	3675	5579	30175	4.24	0.327	0.65	5.036	0.65	0.112	0.15	0.97	1826	1825	1825±3
A1733 Solvalla															
A) Zr d>4.2 g/cm³ Ø>75µm, prismatic, light brown, pigmented, translucent-transparent, l/w=4-5, abr. 22 h	0.54	943	303	3105	0.05	0.316	2.05	4.926	2.05	0.113	0.15	0.99	1771	1807	1848±3
B) Zr d>4.2 g/cm³ Ø<75µm, prismatic, colourless, transparent, l/w=3-5, abr. 20 h	0.16	1270	409	3589	0.04	0.320	0.65	4.984	0.65	0.113	0.15	0.97	1790	1817	1847±3
C) Zr d>4.2 g/cm³ Ø<75µm, prismatic, colourless, transparent, partly pigmented, l/w=3-5	0.57	936	295	1877	0.04	0.308	0.65	4.780	0.65	0.113	0.15	0.97	1729	1781	1843±3
D) Zr d=4.0-4.2 g/cm³ Ø<75µm, prismatic, light brown, transparent, l/w=2-3, abr. 8 h	0.24	1743	541	2519	0.05	0.305	0.65	4.728	0.65	0.113	0.16	0.97	1715	1772	1841±3
MON d>4.3 g/cm³ Ø<75µm, yellow, flat, round, transparent, abr. 25 min.	0.50	2672	5899	14917	6.46	0.336	0.65	5.249	0.65	0.113	0.26	0.92	1869	1861	1851±5

a) abr. refers to the duration of air-abrasion and l/w to the length-width ratio of the zircon crystals.
b) Isotopic ratios corrected for fractionation, blank (50 pg), and age related common lead (Stacey and Kramers, 1975; $^{206}Pb/^{204}Pb$±0.2; $^{207}Pb/^{204}Pb$±0.1; $^{208}Pb/^{204}Pb$±0.2).
c) Error correlation of $^{207}Pb/^{235}U$ versus $^{206}Pb/^{238}U$

of the two colour types define a relatively good linear trend (MSWD=1.4) with an upper intercept age of 1824±5 Ma (Fig. 2c). Monazite is concordant at 1822±3 Ma.

The sample A1695 from the eastern part of the *Veikkola* granite area has monazite with a concordia age of 1852±3 Ma (Fig. 2d). Zircons are colorless to reddish brown, and many of the crystals have bright red iron oxide pigmentation. The six analyzed zircon fractions show considerable scatter on the concordia diagram, suggesting zircon heterogeneity (Fig. 2d). However, they indicate a coeval or slightly older crystallization age as the monazite result, yielding an upper intercept age of 1858±29 Ma (MSWD=18).

Because of the inferior precision of the dating of sample A1695, a second sample from the eastern part of the Veikkola granite was taken. This sample A1733, ~2 km northwest from the location of A1695, is in every way very similar to the sample A1695. Extreme care was taken in the selection of zircons and only transparent, homogeneous crystals with well developed prism and pyramid faces were used for analysis. U-Pb isotopic ratios from four zircon fractions of the sample A1733 define a discordia line with an upper intercept age of 1854±7 Ma (MSWD=1.9) (Fig. 2e). The nearly concordant monazite is consistent with this, having a $^{207}Pb/^{206}Pb$ age of 1851±5 Ma.

In the sample from the central part of the Veikkola granite area (A1718), ~10 km west of A1695, the magmatic zircons are light brown, pigmented and generally stubbier than those from the eastern part of the Veikkola granite. The discordant results of four zircon fractions define a discordia line, which intercepts the concordia curve at 1829±7 and 18±82 Ma (MSWD=1.3) (Fig. 2f). Monazite is concordant at 1825±3 Ma and thus consistent with the zircon result.

5.2. Ion microprobe U-Pb zircon chronology

Many of the earlier bulk analytical data on zircons from the migmatizing microcline granites exhibit scatter considerably in excess of analytical uncertainty and thus suggest zircon heterogeneity (cf. Suominen, 1991). Therefore, ion microprobe studies on several samples were deemed necessary. Two samples from the Perniö granite (A1690 and A1691), one from the Hanko granite (A876) and one from the Oripää granite (A1357) were chosen for ion microprobe dating. The U-Pb analytical data are presented in Table 2. This set of samples was chosen because two of them (A876 and A1357) had been previously dated with ID-TIMS method and resulted in heterogeneous ages (Suominen, 1991 and Nironen, 1999, respectively). As for the Perniö granite, the sample A1691 had too few zircons to be dated with multigrain analysis and in the sample A1690 the zircons, although sufficient in number, were too altered and heterogeneous for a reliable selection of magmatic fractions to be recovered. Another reason for these particular samples to be chosen for ion microprobe study was that they traverse the lateorogenic granite belt from north to south and their whole-rock Nd isotope composition shifts from rather juvenile in the north to less radiogenic in the south (cf. chapter 5.3). The inferred differences in crustal residence ages were expected to manifest themselves in the zircon inheritance patterns of these granites.

5.2.1. Perniö granite

The magmatic zircons from the sample A1690 are generally stubby, reddish due to a pigment overlay and almost invariably zonally altered (Fig. 3). The BSE images show that many of the crystals have a distinct core that has lost its original internal structure. Of the 18 dated spots, 9 hit an altered part and are extremely discordant. In addition, one analysis of a rounded core domain gave a strongly reversely discordant result. The remaining 8 spots, representing the healthy parts of the grains, cluster close to the concordia curve. They define an upper intercept age of 1844±8 Ma (MSWD=1.0). When also the slightly reversely discordant data points 01b and 02a are excluded, a concordia age of 1835±12 Ma from the remaining six analyses can be calculated (Fig. 3). Monazites from this sample (Fig. 2a and Table 1) as well as from the nearby sample A399 Kisto-

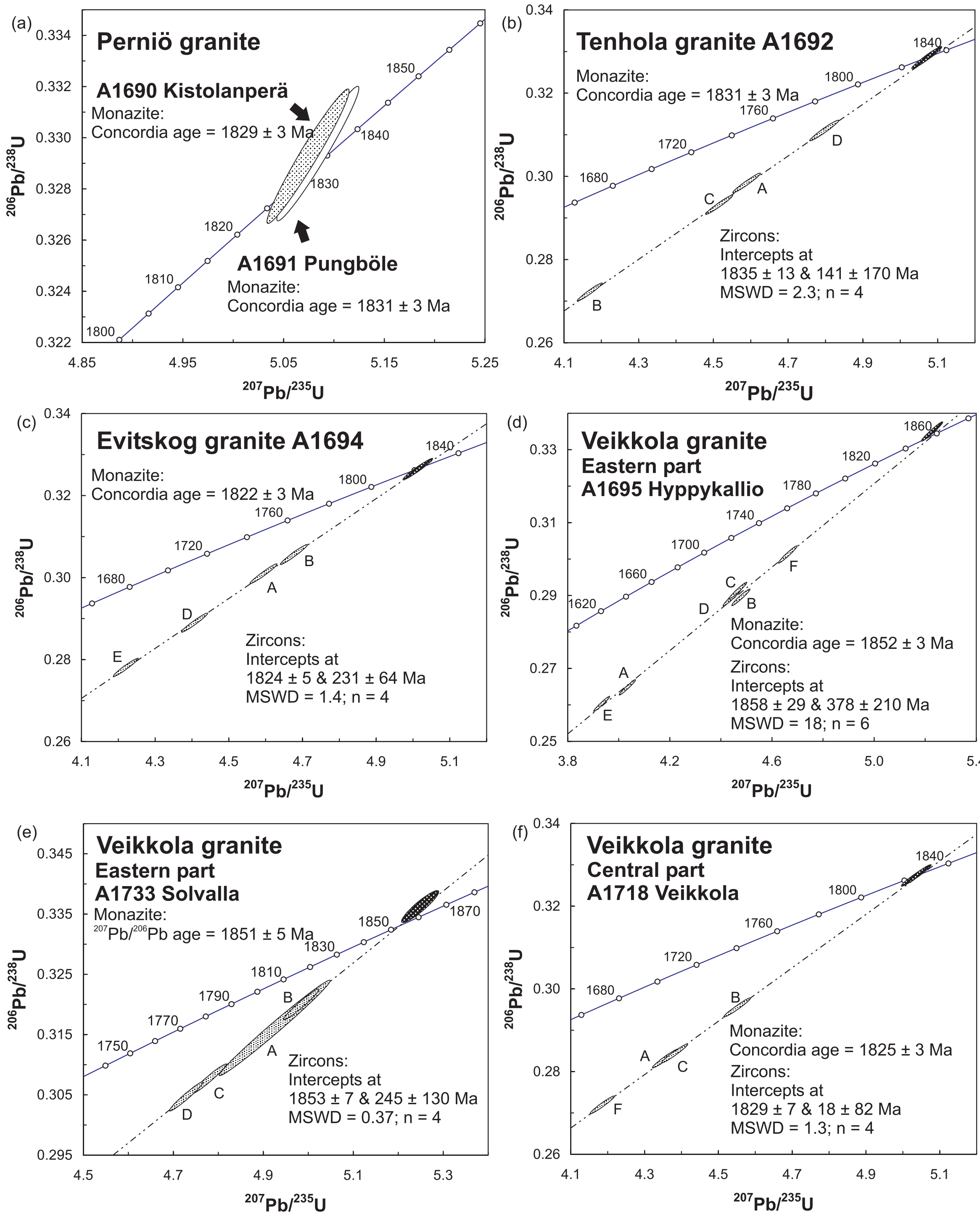

Fig. 2. Concordia diagrams of the TIMS U-Pb data. Fraction notation refers to the first column of Table 1. a) Monazites from the Perniö granite. b) Zircon and monazite results from the Tenhola granite. c) Zircon and monazite results from the Evitskog granite. d) Heterogeneous zircon and concordant monazite results from the eastern part of the Veikkola granite area. e) Another sample of the eastern Veikkola granite. The zircon and monazite results confirm the concordant monazite age of the nearby sample A1695 Hyppykallio. f) Zircon and monazite results from the central part of the Veikkola granite area.

Table 2. U-Pb NORDSIM zircon analyses

Sample/ spot #	Derived ages (Ma)						Corrected ratios								Elemental data		$^{206}Pb/^{204}Pb$
	$^{206}Pb/^{238}U$	±1σ	$^{207}Pb/^{235}U$	±1σ	$^{207}Pb/^{206}Pb$	±1σ	$^{206}Pb/^{238}U$	±1σ (%)	$^{207}Pb/^{235}U$	±1σ (%)	$^{207}Pb/^{206}Pb$	±1σ (%)	ρ [a]	Disc. [b] (%)	[U] (ppm)	[Pb] (ppm)	(meas.)
PERNIÖ GRANITE																	
A1690-Kistolanperä																	
n1231-01a	**1783**	**43**	**1805**	**24**	**1830**	**8**	**0.319**	**2.73**	**4.914**	**2.77**	**0.112**	**0.46**	**0.98**		**408**	**149**	**5.41E+3**
n1231-01b	**1952**	**47**	**1904**	**24**	**1853**	**5**	**0.354**	**2.76**	**5.522**	**2.77**	**0.113**	**0.28**	**0.99**	**0.2**	**603**	**252**	**2.47E+5**
n1231-02a	**1931**	**70**	**1890**	**65**	**1845**	**79**	**0.349**	**2.91**	**5.430**	**2.92**	**0.113**	**0.14**	**0.99**		**2398**	**938**	**2.38E+4**
n1231-02a#2	1014	49	1276	25	1749	3	0.170	7.45	2.513	8.66	0.107	4.43	0.85	-22.6	3467	671	7.36E+2
n1231-02b	**1709**	**57**	**1759**	**32**	**1819**	**10**	**0.304**	**3.07**	**4.654**	**3.23**	**0.111**	**0.98**	**0.95**		**399**	**145**	**5.22E+2**
n1231-02b#2	**1783**	**46**	**1805**	**27**	**1830**	**18**	**0.319**	**3.65**	**4.916**	**3.70**	**0.112**	**0.58**	**0.98**		**466**	**176**	**1.58E+3**
n1231-03a	**1757**	**44**	**1801**	**24**	**1853**	**4**	**0.313**	**2.83**	**4.893**	**2.84**	**0.113**	**0.23**	**0.99**	**-0.5**	**738**	**269**	**1.65E+4**
n1231-03b	656	18	893	19	1538	19	0.107	2.95	1.410	3.11	0.095	0.99	0.94	-54.3	4219	538	1.90E+2
n1231-04a	**1739**	**44**	**1784**	**25**	**1838**	**6**	**0.310**	**2.89**	**4.796**	**2.90**	**0.112**	**0.31**	**0.99**	**-0.6**	**213**	**80**	**1.25E+5**
n1231-04b	524	16	682	19	1245	41	0.085	3.16	0.957	3.81	0.082	2.12	0.83	-46.7	7333	744	2.05E+2
n1231-05a	2425	56	2118	25	1833	5	0.457	2.73	7.055	2.75	0.112	0.30	0.99	31.2	3383	8976	2.75E+3
n1231-05b	1318	34	1524	23	1823	11	0.227	2.80	3.485	2.86	0.111	0.59	0.97	-25.9	1993	516	1.09E+3
n1231-06a	1139	42	1373	38	1757	52	0.193	4.05	2.864	4.97	0.107	2.88	0.81	-23.8	1585	356	6.76E+2
n1231-07a	1615	39	1700	23	1807	4	0.285	2.73	4.336	2.73	0.110	0.19	0.99	-7.1	2136	687	1.21E+4
n1231-08a	673	18	913	19	1548	26	0.110	2.88	1.457	3.19	0.096	1.37	0.90	-51.6	3986	524	2.19E+2
n1231-09a	**1752**	**42**	**1790**	**24**	**1835**	**7**	**0.312**	**2.75**	**4.828**	**2.78**	**0.112**	**0.37**	**0.99**		**373**	**135**	**1.15E+4**
n1231-10a	770	38	1039	36	1659	35	0.127	5.16	1.782	5.49	0.102	1.88	0.93	-46.0	1483	227	1.66E+2
n1231-11a	1476	36	1633	23	1843	9	0.257	2.75	3.996	2.80	0.113	0.50	0.98	-17.4	1757	522	9.93E+3
A1691 Pungböle																	
n1233-01a	1752	42	1837	24	1936	6	0.312	2.73	5.107	2.75	0.119	0.33	0.99	-5.8	205	83	2.89E+4
n1233-01b	1996	55	1944	37	1889	48	0.363	3.19	5.784	4.19	0.116	2.71	0.76		162	79	3.78E+2
n1233-02a	1555	40	1674	24	1826	6	0.273	2.90	4.199	2.91	0.112	0.32	0.99	-11.6	255	86	8.99E+4
n1233-03a	1739	44	1792	24	1854	5	0.310	2.84	4.841	2.86	0.113	0.26	0.99	-1.7	415	155	9.34E+4
n1233-04a	2390	13	2132	15	1891	21	0.449	3.11	7.161	4.12	0.116	2.69	0.75	15.8	278	155	1.20E+2
n1233-05a	1040	43	1314	24	1794	5	0.175	2.97	2.647	3.48	0.110	1.82	0.85	-36.2	879	192	1.17E+3
n1233-06a	**1791**	**46**	**1816**	**25**	**1846**	**6**	**0.320**	**2.92**	**4.983**	**2.94**	**0.113**	**0.34**	**0.99**		**318**	**126**	**9.85E+4**
n1233-07a	**1737**	**29**	**1785**	**26**	**1841**	**33**	**0.309**	**2.84**	**4.800**	**2.85**	**0.113**	**0.25**	**0.99**	**-1.0**	**360**	**137**	**2.19E+4**
n1233-08a	444	63	620	37	1330	48	0.071	2.99	0.842	3.18	0.086	1.08	0.94	-61.8	5277	411	7.84E+3
n1233-09a	1498	67	1629	42	1802	15	0.262	4.97	3.974	5.03	0.110	0.82	0.98	-10.0	304	95	6.02E+2
n1233-10b	1661	41	1740	24	1837	7	0.294	2.81	4.549	2.83	0.112	0.36	0.99	-5.6	278	97	8.94E+3
n1233-11b	1859	45	1873	32	1889	44	0.334	2.76	5.328	3.71	0.116	2.48	0.74		344	140	2.92E+2
n1233-12a	**1753**	**43**	**1795**	**24**	**1843**	**7**	**0.313**	**2.79**	**4.855**	**2.82**	**0.113**	**0.41**	**0.98**		**171**	**65**	**9.17E+4**
n1233-13a	1404	44	1585	24	1835	5	0.243	3.11	3.765	3.12	0.112	0.29	0.99	-21.3	1413	443	2.41E+4
n1233-14a	**1775**	**33**	**1810**	**22**	**1850**	**7**	**0.317**	**2.89**	**4.945**	**2.92**	**0.113**	**0.36**	**0.99**		**470**	**182**	**2.89E+3**
n1233-15a	1296	45	1489	25	1776	7	0.223	2.78	3.334	2.80	0.109	0.36	0.99	-25.5	342	91	6.33E+4
n1233-16a	**1844**	**39**	**1842**	**25**	**1839**	**5**	**0.331**	**2.73**	**5.132**	**2.74**	**0.112**	**0.26**	**0.99**		**470**	**189**	**1.32E+4**

Table 2. cont.

Sample/ spot #	Derived ages (Ma)						Corrected ratios								Elemental data		$^{206}Pb/^{204}Pb$
	$^{206}Pb/^{238}U$	±1σ	$^{207}Pb/^{235}U$	±1σ	$^{207}Pb/^{206}Pb$	±1σ	$^{206}Pb/^{238}U$	±1σ (%)	$^{207}Pb/^{235}U$	±1σ (%)	$^{207}Pb/^{206}Pb$	±1σ (%)	ρ [a]	Disc. [b] (%)	[U] (ppm)	[Pb] (ppm)	(meas.)
HANKO GRANITE																	
A876 Tulludden																	
n1232-01a	**1743**	**42**	**1787**	**23**	**1839**	**5**	**0.310**	**2.73**	**4.812**	**2.74**	**0.112**	**0.26**	**0.99**	**-0.7**	**1106**	**402**	**4.01E+3**
n1232-02a	802	21	1051	20	1611	15	0.132	2.84	1.814	2.94	0.099	0.78	0.96	-48.4	1057	179	6.29E+2
n1232-03a	747	48	985	46	1563	44	0.123	6.77	1.639	7.18	0.097	2.37	0.94	-41.3	927	137	5.51E+2
n1232-04a	1552	38	1713	24	1915	10	0.272	2.75	4.402	2.80	0.117	0.55	0.98	-16.3	139	47	2.34E+3
n1232-04b	593	16	749	16	1248	19	0.096	2.84	1.090	3.00	0.082	0.96	0.94	-48.4	6571	850	2.47E+2
n1232-05a	1350	37	1516	26	1756	21	0.233	3.04	3.450	3.25	0.107	1.15	0.93	-18.6	707	197	8.57E+2
n1232-06a	481	17	597	19	1068	36	0.077	3.64	0.801	4.05	0.075	1.79	0.89	-44.3	6986	709	2.39E+2
n1232-07a	1544	56	1568	53	1599	90	0.271	4.07	3.682	6.41	0.099	4.96	0.63		1473	577	2.58E+2
n1232-07b	469	12	570	13	999	27	0.075	2.74	0.753	3.06	0.072	1.36	0.89	-44.9	8293	796	2.87E+2
n1232-08a	**1684**	**41**	**1759**	**24**	**1850**	**7**	**0.299**	**2.79**	**4.656**	**2.81**	**0.113**	**0.37**	**0.99**	**-4.9**	**2012**	**700**	**6.14E+4**
n1232-09a	907	28	1074	26	1431	41	0.151	3.28	1.881	3.93	0.090	2.17	0.84	-26.8	3848	757	3.13E+2
n1232-09b	835	23	964	20	1271	17	0.138	2.98	1.583	3.10	0.083	0.87	0.95	-30.3	1030	184	3.98E+2
n1232-10a	**1777**	**43**	**1814**	**23**	**1855**	**2**	**0.317**	**2.74**	**4.966**	**2.74**	**0.113**	**0.12**	**0.99**		**5461**	**1998**	**4.99E+3**
n1232-11a	838	22	1048	19	1516	11	0.139	2.80	1.808	2.85	0.094	0.56	0.98	-43.4	2383	427	4.57E+2
ORIPÄÄ GRANITE																	
A1357 Oripää																	
n1234-01a	1523	37	1677	23	1875	8	0.266	2.74	4.213	2.78	0.115	0.43	0.98	-16.3	1687	534	1.91E+4
n1234-02a	**1659**	**40**	**1755**	**23**	**1872**	**6**	**0.294**	**2.75**	**4.632**	**2.77**	**0.114**	**0.31**	**0.99**	**-7.9**	**852**	**298**	**1.01E+4**
n1234-02b	1390	34	1532	22	1735	4	0.241	2.73	3.521	2.74	0.106	0.24	0.99	-17.7	3240	907	8.44E+3
n1234-03a	**1696**	**42**	**1778**	**24**	**1876**	**4**	**0.301**	**2.79**	**4.760**	**2.80**	**0.115**	**0.24**	**0.99**	**-5.8**	**2442**	**895**	**2.02E+4**
n1234-04a	**1640**	**40**	**1741**	**23**	**1865**	**5**	**0.290**	**2.76**	**4.555**	**2.78**	**0.114**	**0.27**	**0.99**	**-8.7**	**1989**	**696**	**4.16E+4**
n1234-04b	1056	27	1273	20	1661	7	0.178	2.73	2.502	2.76	0.102	0.38	0.99	-35.7	4535	939	4.17E+3
n1234-05a	**1681**	**41**	**1772**	**23**	**1881**	**7**	**0.298**	**2.74**	**4.725**	**2.77**	**0.115**	**0.39**	**0.99**	**-7.0**	**1097**	**391**	**1.80E+5**
n1234-06a	**1658**	**40**	**1748**	**24**	**1857**	**9**	**0.293**	**2.74**	**4.592**	**2.78**	**0.114**	**0.50**	**0.98**	**-6.9**	**1195**	**410**	**7.74E+4**
n1234-07a	**1762**	**42**	**1810**	**24**	**1866**	**6**	**0.314**	**2.73**	**4.945**	**2.75**	**0.114**	**0.31**	**0.99**	**-1.1**	**1782**	**680**	**1.90E+5**
n1234-08a	**1720**	**41**	**1778**	**24**	**1847**	**10**	**0.306**	**2.73**	**4.759**	**2.79**	**0.113**	**0.56**	**0.98**	**-2.2**	**576**	**199**	**6.02E+4**
n1234-09a	**1777**	**45**	**1824**	**25**	**1879**	**9**	**0.317**	**2.86**	**5.028**	**2.90**	**0.115**	**0.48**	**0.98**	**-0.4**	**447**	**169**	**5.26E+3**
n1234-10a	**1799**	**43**	**1831**	**24**	**1868**	**7**	**0.322**	**2.74**	**5.070**	**2.77**	**0.114**	**0.36**	**0.99**		**895**	**324**	**1.41E+5**
n1234-11a	**1683**	**41**	**1753**	**23**	**1838**	**7**	**0.298**	**2.73**	**4.620**	**2.76**	**0.112**	**0.40**	**0.98**	**-4.3**	**1463**	**502**	**4.03E+4**
n1234-12a	1226	31	1452	22	1800	6	0.209	2.73	3.178	2.75	0.110	0.33	0.99	-31.1	3108	767	1.08E+3
n1234-12b	**1714**	**41**	**1779**	**24**	**1856**	**8**	**0.305**	**2.73**	**4.769**	**2.76**	**0.114**	**0.44**	**0.98**	**-3.3**	**1021**	**353**	**1.75E+3**
n1234-13a	1597	39	1719	23	1870	9	0.281	2.73	4.435	2.77	0.114	0.49	0.98	-11.4	1110	358	1.09E+3
n1234-14a	**1824**	**44**	**1837**	**24**	**1851**	**6**	**0.327**	**2.78**	**5.104**	**2.79**	**0.113**	**0.31**	**0.99**		**1075**	**419**	**1.13E+4**
n1234-15a	**1905**	**45**	**1890**	**24**	**1875**	**4**	**0.344**	**2.73**	**5.435**	**2.74**	**0.115**	**0.20**	**0.99**		**2354**	**982**	**3.85E+4**

[a] Rho, error correlation for $^{207}Pb/^{235}U$ versus $^{206}Pb/^{238}U$ ratios.
[b] Degree of discordance is calculated at the closest 2 σ limit. Empty cells mark concordant data.
Only data in bold are included in age calculations. Other data are rejected due to high common Pb and/or discordance.

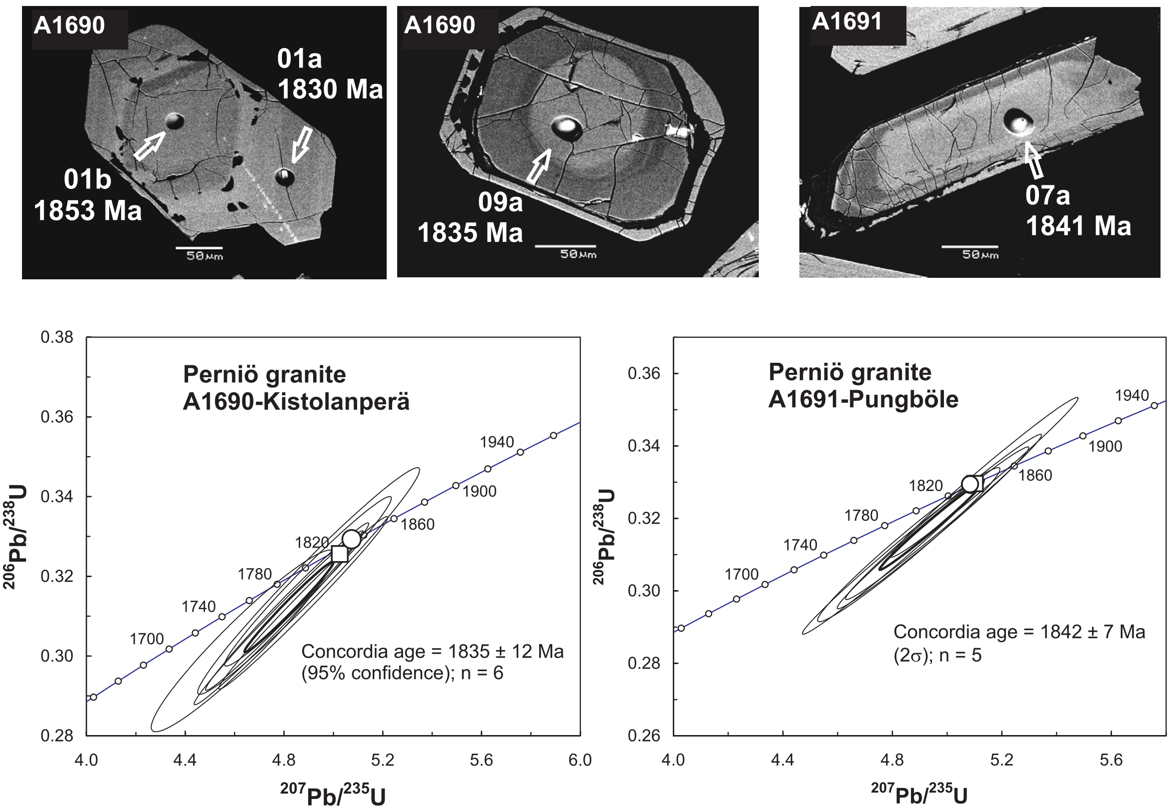

Fig. 3. Perniö granite (samples A1690 and A1691). *Upper part*: Back-scattered electron (BSE) images of some of the zircon crystals studied with ion microprobe. Analysis numbers and $^{207}Pb/^{206}Pb$ ages of the analysis spots are indicated (cf. Table 2). Bright white areas are remnants of gold coating. Zircon crystal 01 (A1690) is relatively healthy, with slightly older center. Crystals 09 from the same sample and 07 from A1691 are more typical for the Perniö granite, prismatic and zonally altered. *Lower part*: Concordant U-Pb data yields an age of 1835±12 Ma for the sample A1690 and 1842±7 Ma for the sample A1691. The white circles are monazites from the same samples (Table 1 and Fig. 2a) and the white squares are monazites from the same sites reported by Suominen (1991) (samples A399 and A389).

la (Suominen, 1991) (1829±3 Ma and 1831±6 Ma, respectively) are coeval with the zircon concordia age (Fig. 3).

Most zircons from the sample A1691 are prismatic and generally longer than those of A1690, but the inner structure is very similar with cracking and alteration rims (Fig. 3). The U-Pb ion microprobe analysis of this sample comprises 17 spots, of which 9 hit an altered zone and were discarded. When the results from the remaining 8 healthy spots are considered, it is evident that one of them (near the edge of a homogeneous crystal 01a), though discordant, represents an inherited zircon with a $^{207}Pb/^{206}Pb$ age of 1936 Ma. If the slightly discordant analysis spots 03a and 10b are omitted, a concordia age of 1842±7 Ma (n=5/17) can be calculated (Fig. 3). The monazite from this sample (Fig. 2a and Table 1) is slightly younger (1831±3 Ma) than the zircon age. From the same outcrop, Suominen (1991) reported a monazite concordia age of 1836±3 Ma (Fig. 3), which overlaps with our new zircon result.

5.2.2. Hanko granite

Sample A876 from the Hanko granite has mostly prismatic, stubby and brown zircon. In the Hanko granite, most of the zircon is heavily altered and therefore only three out of 14 obtained ages are concordant or

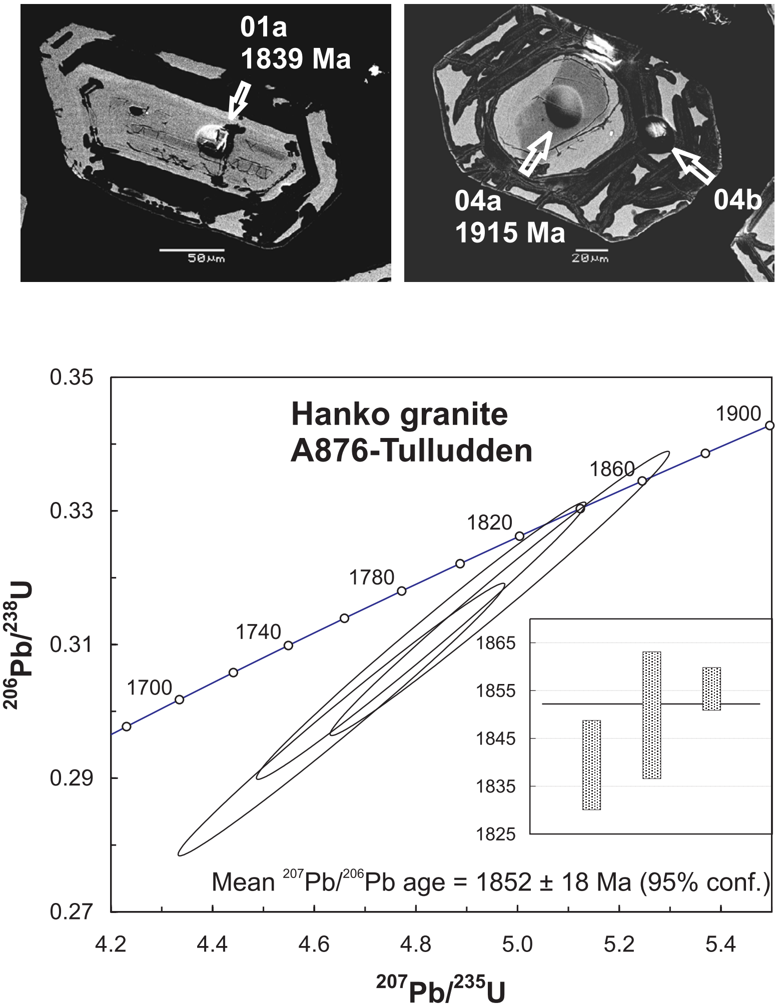

Fig. 4. Hanko granite (sample A876). *Upper part*: BSE image of a stubby magmatic zircon 01 with strongly altered dark zones. Crystal 04 shows lighter, healthy areas and darker altered zones. The analysis 04b tapped an altered zone and the result is grossly discordant (Table 2). Analysis result of the spot 04a from the center is also discordant, but indicates an older age (1915 Ma) than the bulk of the zircons, implying inheritance. *Lower part*: Near-concordant U-Pb data. The inset displays a weighted average $^{207}Pb/^{206}Pb$ age of the three near-concordant spots. Error bars are at $\pm 2\sigma$ level.

nearly concordant (Fig. 4). The near-concordant spots of the magmatic zircons have a mean $^{207}Pb/^{206}Pb$ age of 1852±18 Ma (n=3/14). This age result should be treated with caution because of insufficient statistics. Evidence of inheritance is given by spot 04a (Fig. 4) that hit the core of an altered zircon crystal (a discordant result with a $^{207}Pb/^{206}Pb$ age of 1915±10 Ma). Previous ID-TIMS monazite analyses (Suominen, 1991; Huhma, 1986) from two samples representing the Hanko granite (1829±9 Ma and 1822±6 Ma) point to a slightly younger age than the nearly concordant zircons.

5.2.3. Oripää granite

Sample A1357 from the Oripää granite contains only a small amount of zircon and it can be divided into two morphological types: (1) prismatic, stubby and light brown and (2) more rotund, anhedral and colorless (Fig. 5). The BSE study shows that zircons of this sample are less altered than those of the other samples. Hence, only five of 18 analysis spots had to be discarded. The prismatic zircons display a weak magmatic zoning. An upper intercept age of 1872±10 Ma (MSWD=0.96) for the prismatic zircons (n=9/18) can be calculated. The small, more anhedral zircons have a metamorphic appearance, no zoning and also lower U contents than the prismatic ones. These apparently metamorphic crystals yield a result of 1850±16 Ma (MSWD=1.00; n=4) (Fig. 5). Thus, the two types are coeval within analytical error limits.

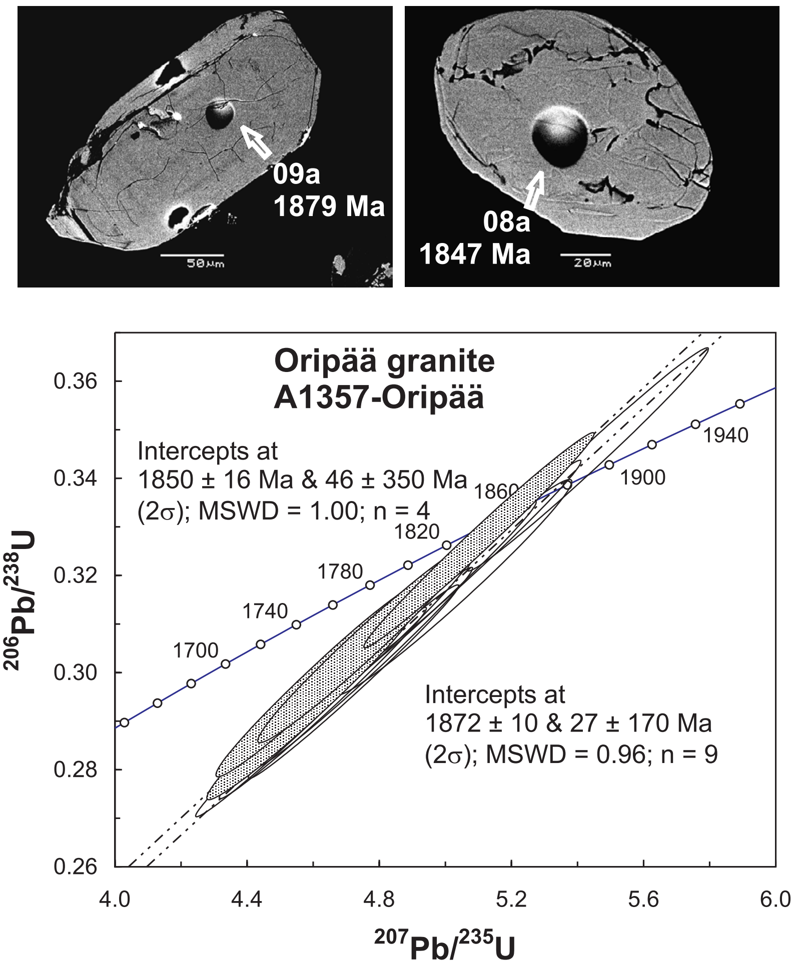

Fig. 5. Oripää granite (sample A1357) *Upper part*: BSE images of a prismatic zircon 09 displaying a weak magmatic zoning. The crystal 08 is a homogenized, recrystallized anhedral zircon. *Lower part*: Upper intercept ages of the near-concordant data for the Oripää granite imply different ages for the two morphological zircon types, although the ages overlap within analytical error. Open ellipses represent the prismatic zircons and the dotted ellipses the anhedral variety.

5.2.4. Rejected data – a note on discordance

A total of 67 spots of the zircons were analyzed, but only 29 of them yielded concordant or nearly concordant age data with low concentration of common lead. The reason for the low profitability was that the choice of zircon spots to be dated was based solely on cathodoluminescence (CL) images. In later back-scattered electron (BSE) observations it turned out that the CL images do not show well the abundant cracks and the often pervasive alteration of zircons from the lateorogenic microcline granites. EDS analyses of these metamict parts reveal increased H_2O, Ca, Al, U and common Pb concentrations, and the U-Pb analyses are extremely discordant. An example of a typical metamict zircon is shown in the BSE image of zircon 04 from the Hanko granite (sample A876) in Fig. 4. The alteration of the zircon domains offers an explanation to the strong discordance of the ID-TIMS U-Pb results reported for the Perniö and Hanko granites by Suominen (1991) and for the Oripää granite by Nironen (1999). Plotted together (Fig. 6), all of the ion microprobe data for the Perniö granite (sample A1690) and the previous multigrain analysis results of the nearby samples A55 and A399 (Suominen, 1991) form identical discordance patterns. The situation is similar with the sample A1691 and samples from the Hanko (A876) and Oripää (A1357) granites.

5.3. Whole-rock Nd isotopes

Neodymium isotope compositions of the eight dated lateorogenic microcline granites and the synorogenic Pöytyä granodiorite are shown in Table 3 and Figs.

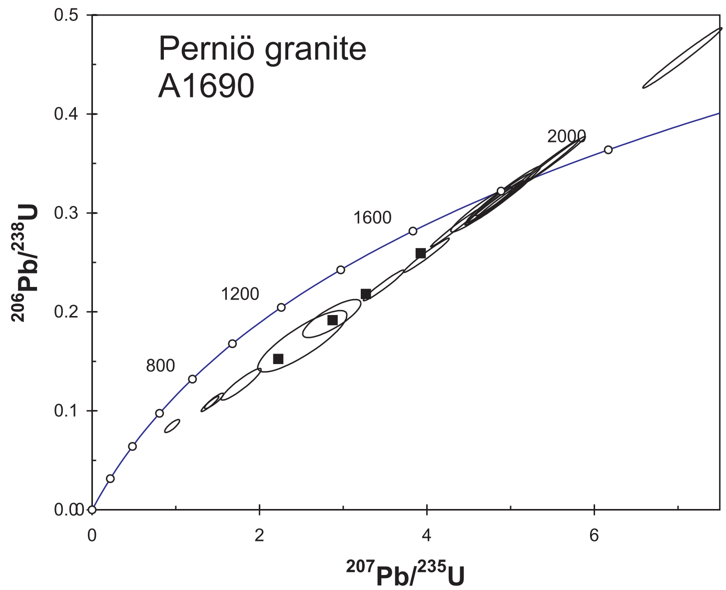

Fig. 6. Concordia diagram showing an example of the effect of the zircon metamictization. All ion microprobe data of the current study for the Perniö granite sample A1690 (Table 2) is plotted as ellipses. Black squares display conventional ID-TIMS data from the same site (samples A55 and A399; Suominen, 1991). The discordance patterns arising from metamict zircons are identical.

7 and 8. The lateorogenic samples show considerable variation in the elemental concentrations of Sm and Nd (1.4 to 15.7 ppm and 8.9 to 83.5 ppm, respectively) but a relatively small range in Sm/Nd (^{147}Sm/^{144}Nd=0.093 to 0.119). In a Sm-Nd isochron diagram (not shown), the samples show rather substantial scatter and, combined with the small range in Sm/Nd, do not yield meaningful age information. This is reflected also in the initial composition of the samples: the ε_{Nd} values range from -1.1 to +2.5, which is about five times the maximum experimental error (±0.35 units) on ε_{Nd}. The depleted mantle model ages (DePaolo, 1981) similarly show a rather large range, from 1940 to 2232 Ma.

The initial ε_{Nd} values of the dated samples fall into three groups (Fig. 7; Table 3). The sample A876 representing the Hanko granite is the most unradiogenic (ε_{Nd} at 1852 Ma=-1.1, T_{DM} model age 2232 Ma) and the Perniö, Tenhola, Evitskog and Veikkola granites with ages of the order of 1850–1820 Ma form a tight group with initial ε_{Nd} of -0.6 to -0.3 and T_{DM} model ages between 2133 and 2193 Ma. The Oripää granite (A1357) has the most juvenile Nd (ε_{Nd} +2.5 at 1.85 Ga; T_{DM} model age 1940 Ma). The adjacent synorogenic Pöytyä granodiorite is rather juvenile with ε_{Nd} (at 1870 Ma) of +1.8 and a model age of 2028 Ma. Fig. 8 shows that the ε_{Nd} values shift from positive in the north to increasingly negative towards the south, whereas in E-W direction, the values remain constant.

6. Discussion

6.1. General implications

A general feature of the U-Pb age determinations of the lateorogenic granites of southwestern Finland is that in most cases the zircons and monazites record similar ages. Some zircon U-Pb results also point to heterogeneous zircon populations. Because of this, combined with the relatively high average uranium content of the zircons (cf. Tables 1, 2) and their consecutive metamictization, the monazites often provide more meaningful age data than the zircons.

Age results from this study as well as data from earlier publications are summarized in Table 4 and shown graphically in Fig. 9. With the exception of the ion microprobe results, only high precision data, i.e., with age errors less than ±10 Ma have been considered. Where ID-TIMS zircon and monazite ages are identical (within experimental error), the more precise of the two, usually the monazite age, has been used. As shown in Fig. 9, the majority of the ages fall in the

Table 3. Nd isotope data for the migmatizing microcline granites and the Pöytyä granodiorite in southern Finland

Sample	Granite	Age (Ma)	Sm (ppm)	Nd (ppm)	$^{147}Sm^a/^{144}Nd$	$^{143}Nd^b/^{144}Nd$	$\varepsilon_{Nd\,(t)}{}^c$	$T_{DM}{}^d$ (Ma)
A1690	Perniö granite, Kistolanperä	1835 ± 12	9.76	58.25	0.1013	0.511465 ± 11	-0.4	2133
A1691	Perniö granite, Pungböle	1842 ± 7	8.59	45.92	0.1131	0.511597 ± 8	-0.6	2184
A1692	Tenhola granite	1833 ± 6	15.67	83.53	0.1134	0.511603 ± 15	-0.6	2183
A1694	Evitskog granite	1823 ± 3	11.22	57.21	0.1185	0.511670 ± 9	-0.6	2193
A1695	Veikkola granite, Hyppykallio	1852 ± 3	7.08	36.07	0.1186	0.511672 ± 10	-0.3	2191
A1718	Veikkola granite, Veikkola	1825 ± 3	9.27	51.56	0.1086	0.511559 ± 7	-0.4	2146
27-MAN-02	Hanko granite, Tulludden	1852 ± 18	6.87	36.89	0.1126	0.511559 ± 10	-1.1	2232
A1357[e]	Oripää granite	1850 ± 16	1.36	8.85	0.09263	0.511500 ± 16	+2.5	1940
136-MN-90	Pöytyä granodiorite	1870 ± 5 [f]	3.43	17.87	0.1159	0.511737 ± 9	+1.8	2028

[a] Estimated error is better than 0.5%.
[b] Normalized to $^{146}Nd/^{144}Nd = 0.7219$, within-run precision expressed as $2\sigma_m$ in the last significant digits.
[c] Initial ε_{Nd} values calculated using chondritic ratios of $^{143}Nd/^{144}Nd = 0.512638$ and $^{147}Sm/^{144}Nd = 0.1966$, maximum error is ± 0.35 ε-units.
[d] Depleted mantle model age, calculated according to the model of DePaolo (1981).
[e] Nd isotope data from Rämö & Nironen (2001).
[f] Age from Nironen (1999).

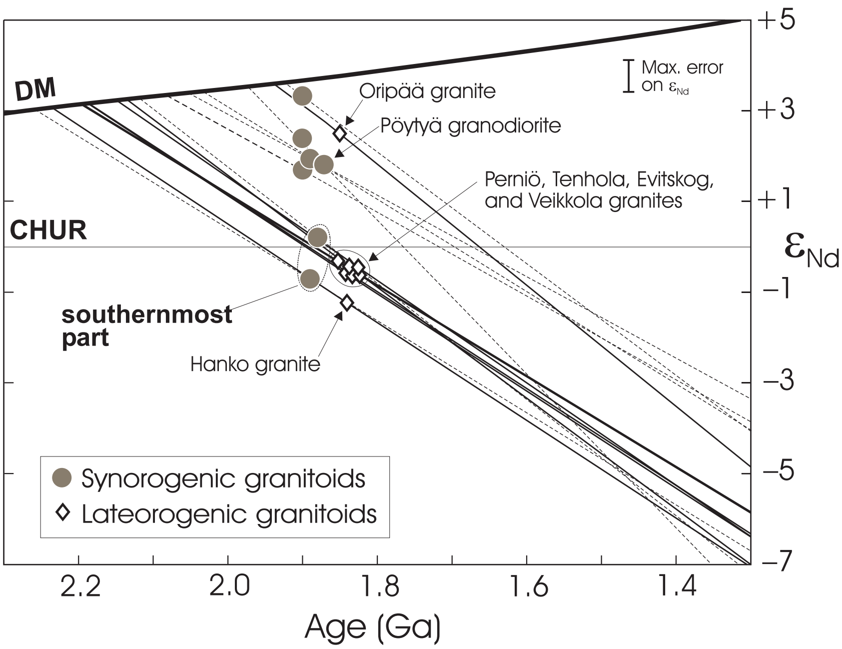

Fig. 7. Nd versus age diagram showing the initial Nd isotope composition of the eight lateorogenic microcline granites dated by the U-Pb method in this study. Also shown is the composition of the Pöytyä granodiorite and that of six previously analyzed synorogenic granitoids from the surrounding crust (arc complex of southern Finland; cf. Korsman et al., 1999) according to Huhma (1986) and Patchett & Kouvo (1986). Solid and dashed lines denote the evolution of the individual samples. DM is the depleted mantle of DePaolo (1981), CHUR is bulk earth evolution (DePaolo & Wasserburg, 1976).

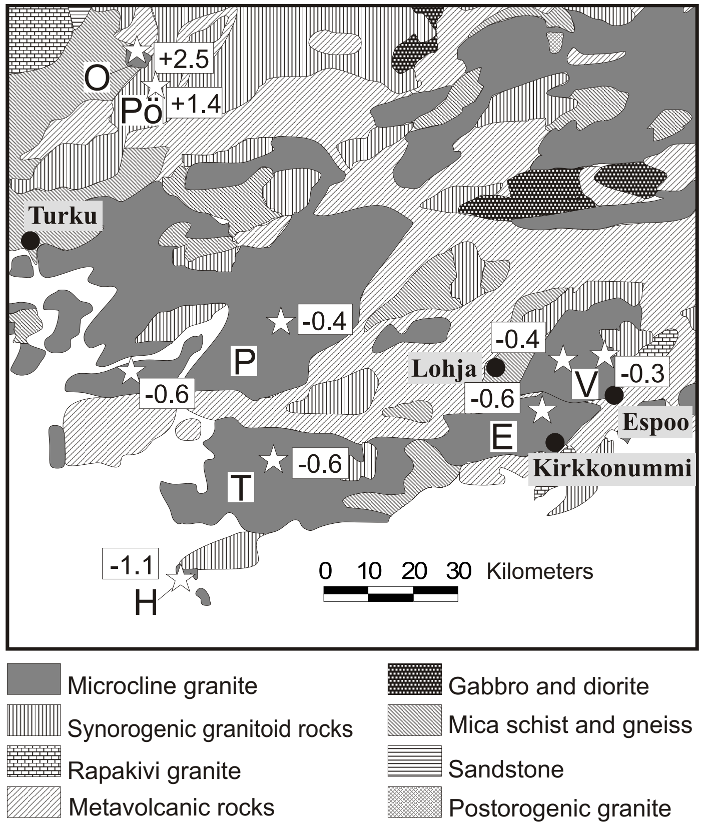

Fig. 8. Geological map of southwesternmost Finland showing the geographic position and initial ε_{Nd} values of the eight lateorogenic granite samples dated in this study, and that of the synorogenic Pöytyä granodiorite (Pö). Other symbols and the map area are the same as in Fig. 1.

range of ~1840–1820 Ma, a result already anticipated on the basis of earlier studies. Fig. 9 also shows that the ages of granulite facies metamorphism in southern Finland record roughly the same time span.

Among the lateorogenic granites, the most notable deviations from the general age distribution are the Veikkola and Oripää areas, and their U-Pb age results are discussed in more detail below.

6.2. The Veikkola area

Earlier studies of the lateorogenic, migmatizing microcline granites of southern Finland have indicated that their emplacement took place in a series of magmatic pulses during the time interval of 1.84–1.82 Ga (e.g. Hopgood et al., 1983; Huhma, 1986; Suominen, 1991). However, our new results on the Veikkola granite area (Fig. 2) show an age difference of 20–30 Ma between the eastern and the central parts of the granite. The scattered zircon age data of the sample A1695 from the eastern part implies zircon heterogeneity, but concordant monazite age of 1852±3 Ma from the same sample indicates older emplacement age compared to the previous studies and also compared to the central part of the same granite area. On careful selection of zircon crystals to be dated, we succeeded to get a meaningful age result for the sample A1733 from the eastern margin of the Veikkola granite that verifies the ≥1.85 Ga age for that part of the area. The central part (sample A1718) in turn displays a fairly good zircon upper intercept age of 1829±7 Ma (MSWD=1.3), and the result is backed up by the concordant monazite age of 1825±3 Ma. The selected zircons of the samples, especially in A1733, but also in A1718, are small, clear, homogeneous, prismatic and clearly of magmatic origin, and show no traces of later reworking (e.g. etched surfaces, growth nuclei or turbidity). Therefore, the ages are obviously real emplacement ages, as inheritance, metamorphosis or hydrothermal activity in only one

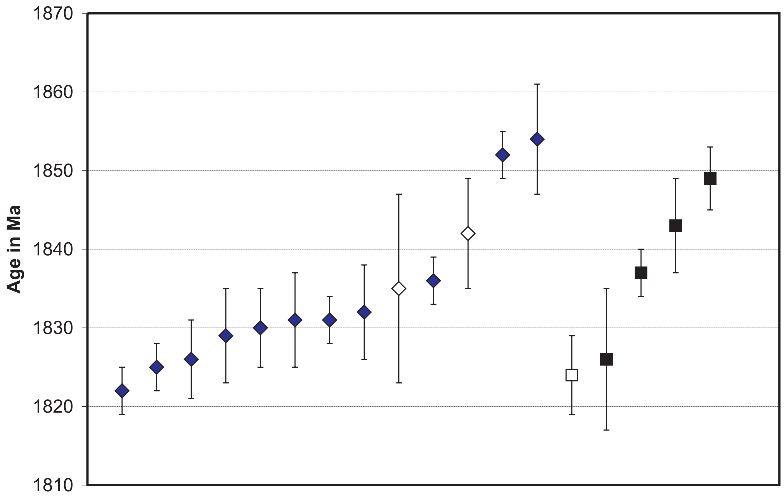

Fig. 9. A "chronogram" of previously published and current zircon and monazite age data for migmatizing microcline granites (diamonds) and rocks associated with granulite facies metamorphism (squares) in southwestern Finland, summarized in Table 4. Open symbols refer to ion microprobe (NORDSIM) data. Error bars are at ±2σ level. For references, see Table 4.

of the two localities less than 10 km apart is not likely to occur. Also, inherited monazite would hardly preserve in a thermal event such as a granite emplacement. The Veikkola granite thus most likely consists of two different intrusions that so far have been recognized by isotopic dating alone.

6.3. The Oripää granite

The Oripää granite was included in this study mainly because previous conventional work indicates a zircon population that is heterogeneous in terms of age (Nironen, 1999). In that study, however, the ages of the red and pale brown zircon varieties overlap within analytical error limits. Parallel results are obtained with ion microprobe in this study as the older, prismatic Oripää zircons (n=9/18) define an age of 1872±10 Ma, indicating crystallization close to the culmination of the Svecofennian orogeny. This is roughly the same as the emplacement age of the nearby Pöytyä granodiorite (1870±5 Ma; Nironen, 1999). The younger, anhedral and colorless zircons (n=4/18) from Oripää have an age of 1850±16 Ma. All the zircon data deviates clearly from the considerably younger monazite age of 1794±10 Ma (op. cit.).

Considering the very low REE concentration of the rock, combined with the low Zr content (Rämö & Nironen, 2001), it is evident that the rock represents a low-temperature (minimum) melt. In such conditions, zircon crystals remain solid in the anatectic magma (Chappell, 2005), and are likely to keep their original U-Pb isotopic ratios. Moreover, on the basis of careful examination of the BSE images, there is a possibility that some of the prismatic zircons bear a growth rim that escaped the ion microprobe dating. Thus, the obtained zircon ages may not represent the emplacement age of the batholith.

The Oripää granite is undeformed and entrains blocks of the surrounding ~1.87 Ga gneisses, implying later emplacement. The granite stock even seems to post-date the EW-trending D_3 structures, dated at 1824±5 Ma near Turku, more than 50 km southwest of Oripää (Väisänen et al., 2002). However, Nironen (1999) considers the D_3 in Oripää area as a separate event, tied with the emplacement of the Pöytyä granodiorite, i.e., 1.87 Ga. Therefore, we conclude that the 1872±10 Ma zircon population is inherited. As no older inherited zircon ages typical of Svecofennian detrital material (cf. Claesson et al., 1993; Lahtinen et al., 2002) were encountered, and yet the composition of the granite is characteristic of a low-temperature melt, indicating that no significant new zircon crystallization took place, it is possible that the adjacent synorogenic granitoid rocks constitute the principal source for the Oripää granite, instead of sedimentary source rocks suggested earlier (Rämö & Nironen, 2001).

The origin of the minor 1850±16 Ma zircon population is somewhat ambiguous. Nironen (1999) obtained a comparable ID-TIMS age (1850±27 Ma) and Rämö & Nironen (2001) suggest that it marks the thrust-induced melting after the accretion of the arc complex of southern Finland. Then, the monazite age of 1794±10 Ma (Nironen, 1999) could be the emplacement age of the granite. Alternatively, the younger zircon age might represent the original emplacement age of the granite pluton. In that case, the monazite age could be related to a wider regional metamorphic event, as similar indications are given by several granitoid rocks throughout southern Finland with titanites or monazites in the 1780–1790 Ma bracket (Hopgood et al., 1983; Vaasjoki, 1995; Nironen, 1999; Ehlers et al., 2004). However, on the basis of the current data set, unequivocal age determination of the Oripää granite is not possible.

6.4. Regional implications

The concordant 1852±3 Ma monazite age obtained from the eastern part of the Veikkola area necessitates an adjustment of the upper limit of the traditional 1.84–1.82 Ga time span for the emplacement of the lateorogenic migmatizing microcline granites in southwestern Finland. The eastern Veikkola granite is the only lateorogenic granite dated so far with age over 1850 Ma. Thus, while the migmatizing microcline granite activity in southwestern Finland apparently lasted from ~1.85 to ~1.82 Ga, it most likely occurred in several distinct pulses, and future models dealing with the tectonic evolution of the arc complex of southern Finland after its accretion should account for this quite large age distribution. It seems that the rocks associated with high-grade metamorphism in southerwestern Finland also record about the same time span as the lateorogenic granites (Table 4 and Fig. 9). The data suggest that metamorphic peak was attained in the eastern half of the present study area (1837±3 Ma monazite age from a charnockite in Lohja; K. Korsman, pers. comm.) earlier than in the Turku area to the west (metamorphic zircon growth age 1824±5 Ma; Väisänen et al., 2002) (Table 4). Similar metamorphic ages (≤1.83 Ga) are also reported from monazites farther west from the present study area (e.g. Ehlers et al., 2004).

The Nd isotope composition of the lateorogenic microcline granites in southwesternmost Finland reveals a homogeneous zone in an east-west direction across the main lateorogenic belt (Fig. 8). However, the source of the lateorogenic magmatism appears to have been slightly more juvenile in the north than in the south (Figs. 7, 8). Although the Nd isotope data are relatively few, the pattern of the initial ε_{Nd} values of the lateorogenic granites is not in favor of a simple depleted mantle–Paleoproterozoic crust mixing model. Rather, the range in the initial Nd isotope composition of the lateorogenic granites complies with the variation shown by the synorogenic granitoids of the surrounding orogenic crust (the arc complex of southern Finland; cf. Korsman et al., 1999). The available data on the synorogenic granitoids show a bimodal distribution with the southwesternmost part of the terrane having the least radiogenic ε_{Nd} values (Fig. 7; cf. Lahtinen & Huhma, 1997; Rämö et al., 2001). Of the lateorogenic granites in this study, sample A876 from the Hanko granite is the least radiogenic (initial ε_{Nd} value of -1.1). The Perniö, Evitskog, and Veikkola granites (initial ε_{Nd} values between -0.6 and -0.3) are similar to the analyses of the Hanko granite and also similar to the southernmost synorogenic granitoid samples. The Oripää granite, the northernmost of the eight dated samples, is much more radiogenic (highest ε_{Nd}) than the other granites and is, in this regard, similar to the synorogenic granitoids in the northern part of the arc complex of southern Finland (Fig. 7).

The southward shift to less radiogenic initial ε_{Nd} values in both the late- and synorogenic granitoid rocks may reflect the presence of terrane boundaries within the arc complex of southern Finland. Regarding the notable differences in their initial ε_{Nd} values, it is surprising that the four samples from the Hanko, Perniö and Oripää granites studied by ion microprobe do not reveal any substantial variation in zircon inheritance

Table 4. U-Pb ages in ascending order from migmatizing granites and rocks associated with granulite facies metamorphism (in italics), southwestern Finland.

Sample	Basic-X	Basic-Y	Locality	Min	Rock type	Age (Ma)	±2σ (Ma)	N	R	Reference	Comment
A1694	6676850	2520540	Evitskog Kirkkonummi	MZ	Microcline granite	1822	3	1	C	this study	C Mz coeval
A1718	6684370	2524900	Veikkola Kirkkonummi	MZ	Microcline granite	1825	3	1	C	this study	Zr UI at 1829 ± 7
A0389	6677400	2450960	Haarla Perniö	MZ	Microcline granite	1826	5	1	C	Suominen, 1991	Zr discordant
A0875	6634330	2442550	Märaskär Hanko	MZ	Microcline granite	1829	6	1	NC	Huhma, 1986	Zr heterogeneous
A0997	6669200	1573680	Tammo Parainen	MZ	Microcline granite	1830	5	1	C	Suominen, 1991	Zr UI at 1829 ± 31 Ma
A0399	6693300	2458550	Kistola Muurla	MZ	Microcline granite	1831	6	1	NC	Suominen, 1991	Zr reference line 1830 & 190 Ma
A1692	6662850	2459200	Olsböle Tenhola	MZ	Microcline granite	1831	3	1	C	this study	C Mz coeval
A0876	6633450	2439080	Tulludden Hanko	MZ	Microcline granite	1832	6	1	C	Suominen, 1991	Zr heterogeneous
A1690	6693160	2459590	Kistolanperä Muurla	ZR	Microcline granite	1835	12	6	C	this study	NORDSIM data
A0390	6679740	2424340	Pungböle Kemiö	MZ	Microcline granite	1836	3	1	C	Suominen, 1991	Zr *reference line 1835 & 230 Ma*
A1691	6679750	2424360	Pungböle Kemiö	ZR	Microcline granite	1842	7	5	NC	this study	NORDSIM data
A1695	6685000	2533960	Hyppykallio Espoo	MZ	Microcline granite	1852	3	1	C	this study	Zr UI at 1858+/-29 Ma
A1733	6687248	2531035	Solvalla Espoo	ZR	Microcline granite	1854	7	4	UI	this study	NC Mz 1851 ± 5 Ma
PSH16	*6716100*	*1552700*	*Lemu*	*ZR*	*Garn-cord. gneiss, leucosome*	*1824*	*5*	*6*	*C*	*Väisänen et al., 2002*	*NORDSIM data*
A0064	*6704280*	*1568740*	*Kakola Turku*	*MZ*	*Garn-cord. granite*	*1826*	*9*	*1*	*NC*	*Suominen, 1991*	*Zr reference line 1840 & 320 Ma*
A1335	*6690600*	*2500500*	*Maikkala Lohja*	*MZ*	*Charnockite*	*1837*	*3*	*1*	*C*	*K. Korsman, pers. comm.*	*Zr UI at 1860 ± 5 Ma*
A0948	*6633700*	*2467250*	*Innerskär Tammisaari*	*ZR*	*Aplite*	*1843*	*6*	*3*	*UI*	*Hopgood et al., 1983*	*C Mz 1807 ± 12 Ma*
DU91	*6705900*	*1566100*	*Naantali*	*ZR*	*Hypersthene tonalite*	*1849*	*4*	*5*	*UI*	*van Duin, 1992*	*recalculated by M. Vaasjoki*

N = number of the mineral fractions.

R = type of the age data, UI = Upper intercept, C = concordant, NC = nearly concordant.

pattern. Provided that the less radiogenic granites are, at least partly, derived from material that was separated from the mantle considerably longer ago, it would seem likely that the zircons exhibited traces of earlier crystallization ages. Even more so, as the BSE images of the zircon crystals from the Perniö and Hanko granites show some distinct cores. However, the cores are generally thoroughly homogenized and only occasionally there are vestiges of magmatic zoning left. As a result, only few spots of the entire data set stand out as notably older than the bulk of the analysis spots. This indicates that the U-Pb systematics of the inherited zircon populations were at least partially reset in the course of the granite emplacement.

Our data extend the length of the period for the emplacement of the lateorogenic granites in southwestern Finland. Previously, ages of about 1.80 Ga for lateorogenic granites farther east have been reported (e.g. Nykänen, 1983; Korsman et al., 1984), while parts of the Veikkola granite here yield an emplacement age of about 1.85 Ga. Considering that some synorogenic Svecofennian granitoids exhibit ages from 1.88 to 1.85 Ga (e.g. Vaasjoki & Kontoniemi, 1991; Väisänen et al., 2002) and that postorogenic intrusions in southern Finland record ages between ~1.815 and 1.77 Ga (Vaasjoki, 1995; Väisänen et al., 2000; Suominen, 1991), there seem to be no temporal limits for the classically defined stages of syn-, late- and postorogenic igneous activities. The overlapping age intervals of these types of granite magmatism indicate that the nature of igneous activity is tied with processes rather than time. Combined isotopic and structural evidence (Nironen, 1997; Korsman et al., 1999) show that the various Svecofennian terranes had been assembled by 1.87 Ga ago. This also marks the end of the culmination of the Svecofennian orogeny. However, in contrast to some earlier opinions (e.g. Vaasjoki, 1996), orogenic movements did not cease simultaneously everywhere in southern Finland.

7. Conclusions

The results from the multi-grain ID-TIMS and SIMS U-Pb studies as well as whole-rock Nd isotope analyses of the lateorogenic granites of southwestern Finland suggest the following:

1. The age spectrum of the migmatizing microcline granites in southwestern Finland seems to be wider than thought before, ranging from ~1.85 Ga determined from the eastern part of the Veikkola granite area to ~1.82 Ga obtained from the Evitskog granite. Rocks associated with granulite facies metamorphism record a roughly similar time span within the same area.
2. In most cases, zircons and monazites of individual samples record similar ages. The most notable exception to this is the Oripää granite that has seemingly only inherited zircon. The monazite age is 1794±10 Ma, which either represents the age of the granite, or a wider regional thermal event that postdates the emplacement of the Oripää granite stock.
3. The diminishing proportion of radiogenic Nd in the lateorogenic granites towards the south of the study area reflects an increase in crustal residence ages. The initial ε_{Nd} values range from +2.5 of the Oripää granite to -1.1 of the Hanko granite, and the corresponding depleted mantle model ages range from 1940 Ma to 2232 Ma, respectively. Geographically, the variation pattern is very similar to that shown by the synorogenic Svecofennian granitoid rocks.
4. The U-Pb ages obtained with the ion microprobe cluster close to the granite emplacement in all cases except for the Oripää granite, i.e., the U-Pb system of inherited zircon cores is predominantly reset during the granite emplacement. Thus the concept of potential terrane boundaries derived from the Nd isotope results cannot be verified on the basis of single zircon age data.

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