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CHARACTERISTICS OF PROTEROZOIC LATE-/ POST-COLLISIONAL INTRUSIVES IN ARCHAEAN CRUST IN IISALMI – LAPINLAHTI AREA, CENTRAL FINLAND

by
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Introduction

The Iisalmi - Lapinlahti area in central Finland is located in the western margin of Archaean craton against the Svecofennian collision zone from the west (Fig. 1). The Archaean bedrock in the area is predominantly composed of amphibolite-banded tonalitic-trondhjemitic migmatites. The zircon U-Pb ages of the migmatite components vary from 3.2 Ga of the palaeosome to 2.63 Ga of the late metamorphism (Mänttäri et al. 1998; Hölttä et al. 2000). The study area is characterized by well-preserved Archaean granulite facies blocks with fresh mineral parageneses (Paavola 1984; Hölttä & Paavola 2000) despite strong Palaeoproterozoic overprint 1.9 – 1.8 Ga ago (Kontinen et al. 1992). The area is cut by numerous Palaeoproterozoic fractures, some of them bordering the granulite blocks.

In addition to numerous 2.3–2.1 Ga old diabase dykes (Hölttä et al. 2000; Toivola et al. 1991), a significant amount of later Palaeoproterozoic magmatism is also characteristic of the Archaean craton margin. The magmatism comprises intrusions of varying size, chemical composition varying from basic to acid. The very variable bimodal appearances between gabbro – diorite material together with younger granite – granodiorite material are most characteristic of the area (Paavola 1987, 1990, 2001; Lukkarinen 2000; Äikäs 2000). Intermediate intrusions are common, too. Also so-called microtonalite dykes (Huhma 1981; Rautiainen 2000) occur in the zone. According to the existing conventional zircon datings the age of the Palaeoproterozoic magmatism is distributed around 1.90–1.85 Ga (e.g. Paavola 1988). A comprehensive description of geotraverse crossing the area is given in Korsman et al. (1999). The area is characterized by an exceptionally thick crust, ca. 55 – 60 km (Grad & Luosto 1987).

This paper concentrates on the characteristics of some late- to post-collisional granitoids in the Iisalmi - Lapinlahti area. They are compared to a larger background material from a sample profile NW from the study area (Figs. 2 – 4) called 'Ladoga-Bothnian Bay' (LBZ) profile in the following.

From the regional magnetic and gravity maps in Figures 2–3 it can be seen that the Archaean-Proterozoic (AP-) border in the western part of the Iisalmi - Lapinlahti area is characterized by a strong magnetic and gravity minimum zone reflecting the loss of magnetite and density in the shearing associated with the collision processes.

In the low-altitude magnetic map in Figure 4 are shown in more detail the location of the samples considered in this paper. From the map it can be seen that the area is characterized by roundish magnetic anomalies, sometimes cut by numerous younger fractures, such as the anomaly between samples 1-3 and 11.

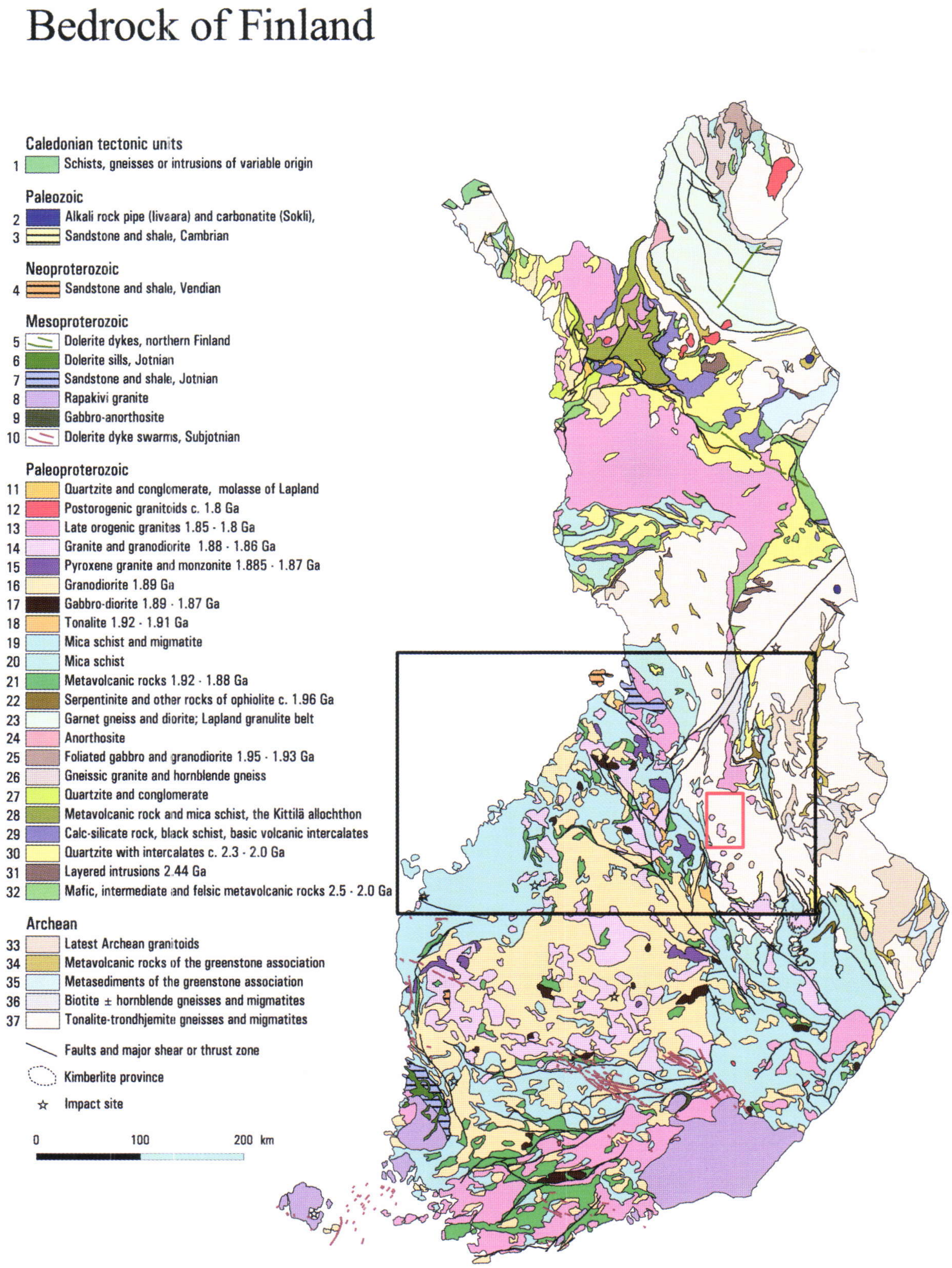

Fig. 1. A simplified geological map of of Finland after Korsman et al. 1997. The location of the geophysical maps in Figures 2–4 are shown by black and red rectangles.

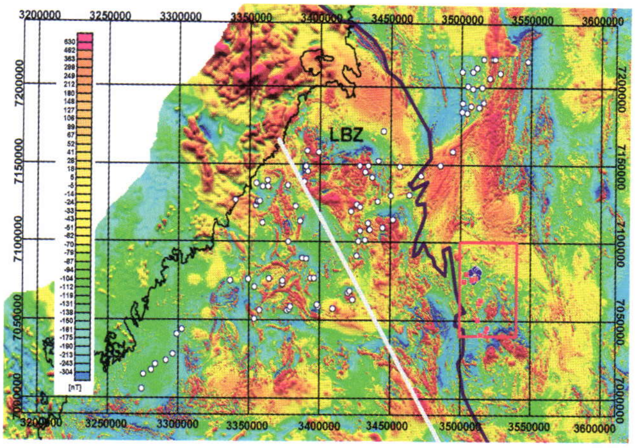

Fig. 2. The magnetic map of the study area. Compiled from high- and low-altitude magnetic data by Geological Survey of Finland. The red line borders the the Iisalmi - Lapinlahti area shown in more detail in Figure 4. The location of the study samples are shown as red and blue circles and red squares in the figure. The location of background 'Ladoga-Bothnian bay' profile samples are shown as white circles. Black line shows the approximate course of the Archaean-Proterozoic (AP-) border. The gray line gives the western border of the Ladoga-Bothnian zone (LBZ, eastern edge being roughly the AP-border).

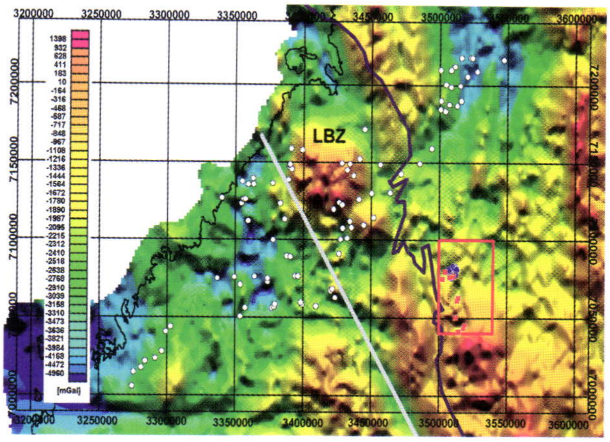

Fig 3. The regional gravity map of the survey area. Compiled from data by Geodetic Institute of Finland. For definitions, see caption of Figure 2.

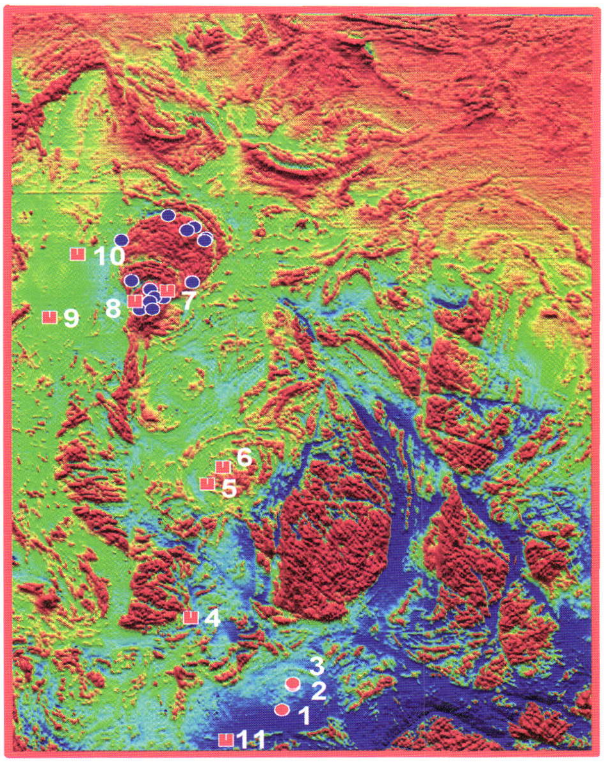

Fig. 4. The detailed low-altitude magnetic map of the Iisalmi - Lapinlahti area and location of the samples described below. The red dots and squares show the location of the samples ILa 1 – 11. The blue dots refer to samples (ILb) collected separately from the Kaarakkala intrusion. The map is compiled from low-altitude magnetic data of the Geological Survey of Finland.

Description of the samples

This work concentrates on sample groups ILa 1-11 and ILb, collected separately. The background material from felsic to mafic granitoids from the profile crossing the Ladoga-Bothnian Bay zone, is divided to Proterozoic and Archaean samples on basis of their geographical location. In the following is given a short description of the sample groups ILa and ILb.

The Palomäki quartz diorite (samples ILa 1-3) is a homogeneous and massive intrusion covering a large area and it contains commonly fine-grained dark fragments. The main minerals are plagioclase, quartz, biotite and hornblende. Epidote, titanite, apatite and opaques are conspicuously abundant. The Ohenmäki granite (sample ILa 11) cuts the Palomäki quartz diorite.

The Palosvuori granite – granodiorite (sample ILa 4) is homogeneous, grey and massive. The mineral composition is quartz, plagioclase, potassium feldspar and biotite. Epidote, titanite, carbonate, chlorite and opaques are the main accessory minerals.

The Ryhälänmäki granite (samples ILa 5-6) is reddish, massive and generally homogeneous, but includes dioritic and quartz dioritic xenoliths in certain areas. The granite is reddish or reddish grey and mainly medium grained. It is massive or very weakly foliated. The main minerals are quartz, plagioclase, potassium feldspar and biotite. Hornblende is rare. Varying amounts of epidote, muscovite, chlorite, titanite, apatite and opaque occur.

The Kaarakkala (leuco-) gabbroic ring intrusion (samples ILb) causes a strong zonal magnetic anomaly (Fig. 4). Excluding the contact zones it is undeformed and fresh. The rock is quite homogeneous but compositional banding is common. The main minerals are plagioclase, hornblende and biotite. Quartz is occasionally present. Titanite, apatite and magnetite are relatively abundant. The most basic inner part of the intrusion is nearly hornblenditic. Red medium grained homogeneous leucogranite crosscut the intrusion. It follows conformly the ring structure being an essential part of the appearance of the Kaarakkala intrusion. The Nieminen sample (ILa 7) represents the granite. The Ahvenlampi sample (ILa 8) is from a typical, homogeneous leucogabbroic zone of the main Kaarakkala intrusion.

Palosenmäki granite - granodiorite is a roundish intrusion causing a negative anomaly on the magnetic map (Fig. 4). The rock is relatively coarse-grained, reddish white and very homogeneous consisting of plagioclase, quartz, potassium feldspar and biotite. Plagioclase is distinguished in the texture as larger, subhedral and zoned crystals. The Pirttimäki sample (ILa 9) is from the southern border zone of the intrusion representing an anomalous, porphyric contact type while the Hallamäki sample (ILa 10) is most typical representative of the intrusion.

The Kiikkerinvuori granite (sample ILa 11) is reddish, massive and homogenious. It is a part of the Ohenmäki multistage granitic intrusion.

Petrophysical characteristics of the ILa samples

The major geophysical features of the study area are already evident from Figures 2 – 4. In Figure 5 is given a summary of the density and susceptibility of the ILa 1-11 sample groups. From the figure it can be seen that the Palomäki samples 1-3 have distinctly higher 'mafic' density compared to all other groups having lower densities characteristic of felsic intrusives. The susceptibility varies from ferri- to paramagnetic in both groups.

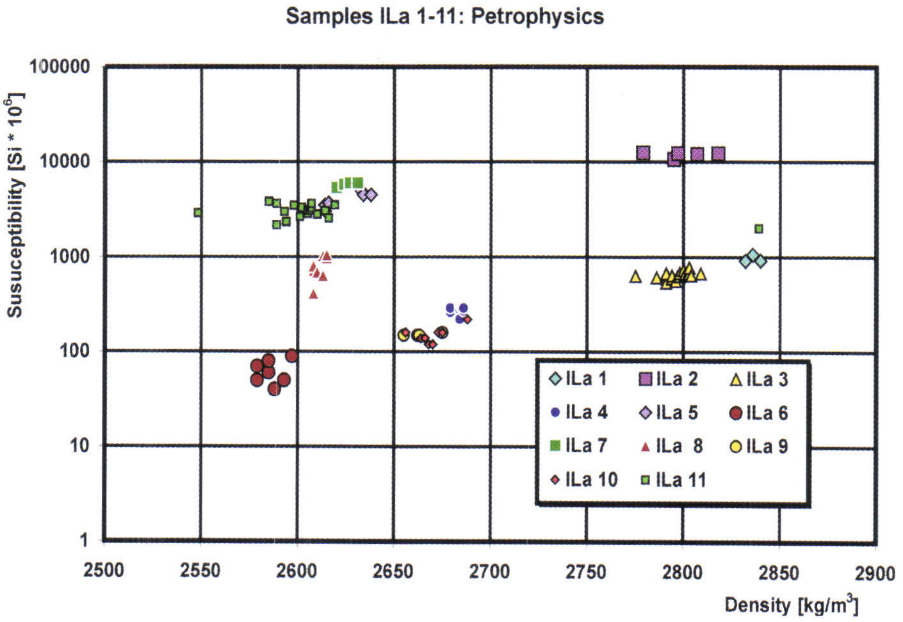

Fig. 5. Density – susceptibility variations of the samples ILa 1 - 11.

Isotopic characteristics of the samples

Conventional U-Pb dating

The decomposition of zircons and extraction of U and Pb for conventional isotopic age determination follows mainly the procedure described by Krogh (1973). Zircon fractions were ≤0.65 mg in weight (see Table 1), and the total procedural blank was ≤50 pg. ^{235}U-^{208}Pb-spiked and non-spiked isotopic ratios were measured using a VG Sector 54 thermal ionization multicollector mass spectrometer. The measured lead and uranium isotopic ratios were normalized according to accepted ratios of SRM 981 and U500 standards. The U-Pb age calculations were done using the PbDat-program (Ludwig 1991) and the fitting of

Table 1. Conventional U-Pb age data on zircons from samples A1512 Ahvenlampi diorite, A1516 Palomäki quartz diorite, A1517 Palosvuori quartz diorite, and A1518 Kiikkerinvuori granite.

Sample information	Sample	U	Pb	^{206}Pb/^{204}Pb	^{208}Pb/^{206}Pb	ISOTOPIC RATIOS$^{1)}$						Rho$^{2)}$	APPARENT AGES/Ma±2sigma		
Analysed mineral and fraction	weight/mg	ppm		measured	radiogenic	^{206}Pb/^{238}U	2SE%	^{207}Pb/^{235}U	2SE%	^{207}Pb/^{206}Pb	2SE%		^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb
ILb (A1512 Ahvenlampi, Kaarakkala)															
A) d>4.3, abraded 20h	0.65	757	284	11553	0.21	0.3282	0.60	5.157	0.60	0.1140	0.15	0.97	1830	1846	1864±1
B) d:3.6-4.0	0.52	827	315	1696	0.27	0.3112	0.60	4.888	0.60	0.1139	0.15	0.97	1747	1800	1863±2
C) d>4.3	0.52	485	179	1743	0.19	0.3200	0.60	5.017	0.60	0.1137	0.15	0.97	1790	1822	1860±2
D) d:4.0-4.2, +200mesh	0.58	543	213	1112	0.25	0.3190	0.60	5.002	0.60	0.1137	0.15	0.97	1785	1820	1859±2
E) d>4.3, abraded 40h	0.43	740	282	4687	0.21	0.3302	0.60	5.188	0.60	0.1139	0.15	0.97	1839	1851	1863±1
F) 4.2-4.3	0.46	645	253	1129	0.24	0.3223	0.60	5.075	0.60	0.1142	0.15	0.97	1801	1832	1867±2
ILa 3 (A1516 Palomäki)															
A) d>4.3,+200mesh, abraded 21h	0.48	817	274	5006	0.08	0.3234	0.38	5.066	0.39	0.1136	0.06	0.99	1806	1830	1858±1
B) d>4.3, +200mesh	0.48	733	242	2917	0.08	0.3167	0.38	4.958	0.39	0.1135	0.06	0.99	1774	1812	1857±2
C) d:4.2-4.3	0.46	796	266	1895	0.09	0.3146	0.39	4.923	0.40	0.1135	0.07	0.98	1764	1806	1856±2
D) d:3.6-4.0	0.48	1250	406	1408	0.12	0.2937	0.40	4.582	0.40	0.1132	0.08	0.98	1660	1746	1851±2
ILa 4 (A1517 Palosvuori)															
A) d>4.3, +200mesh, abraded 15h	0.34	320	110	5065	0.11	0.3233	0.60	5.109	0.60	0.1146	0.19	0.97	1806	1838	1874±4
B) d>4.3, +200mesh	0.57	324	102	5021	0.10	0.3000	0.60	4.709	0.60	0.1138	0.07	0.97	1691	1769	1862±2
C) d:4.2-4.3	0.30	*)	*)	2081	0.10	0.2406	0.60	3.718	0.60	0.1121	0.23	0.97	1390	1575	1833±4
D) d:4.0-4.2	0.29	672	171	2085	0.11	0.2358	0.60	3.684	0.60	0.1133	0.12	0.97	1365	1568	1853±2
E) d>4.3, -200mesh, abraded 4h	0.25	291	98	7061	0.11	0.3169	0.60	5.010	0.60	0.1147	0.07	0.97	1775	1821	1875±1
ILa 11 (A1518 Kiikkerinvuori)															
A) d>4.3, abraded 4h	0.31	408	129	1077	0.13	0.2829	0.60	4.396	0.60	0.1127	0.09	0.97	1606	1712	1843±2
B) d>4.3	0.27	626	175	408	0.12	0.2320	0.60	3.600	0.60	0.1126	0.22	0.87	1345	1550	1841±4
C) d:4.0-4.3, abraded 4h	0.49	580	182	1433	0.12	0.2846	0.60	4.462	0.60	0.1137	0.08	0.98	1614	1724	1860±2
D) d:4.0-4.3	0.24	684	184	945	0.12	0.2413	0.60	3.738	0.60	0.1123	0.11	0.96	1394	1580	1837±2
E) d:4.0-4.3, abraded 4h	0.37	156	49	1993	0.12	0.2898	0.60	4.518	0.60	0.1131	0.07	0.99	1640	1734	1849±1

1) Isotopic ratios corrected for fractionation, blank (50 pg), and age related common lead (Stacey and Kramers 1975).

2) Correlation between ^{207}Pb/^{235}U and ^{206}Pb/^{238}U errors.

the discordia lines using the Isoplot/Ex program (Ludwig 1998).

Results

ILb group sample, Ahvenlampi, Kaarakkala intrusion: Zircons are mainly long prismatic, brownish and dull. Typically zircons contain inclusions of unknown dark mineral. Brown and more rounded zircons most probably represent inherited material. Six analysed zircon fractions plot on a discordia line with intercept ages of 1864±8 and 76±330 Ma (MSWD=5.3; n=6) (Table 1, Fig. 6). The slightly high MSWD value indicates minor heterogeneity in zircon material and is caused mainly by zircon fractions F and B which plot slightly on the older side of the other four data points. However, the $^{207}Pb/^{206}Pb$ ages of 1863±1 and 1864±1 Ma from the two nearly concordant fractions E and A determine the emplacement age of the Ahvenlampi diorite independently.

ILa sample 3, Palomäki quartz diorite: Zircons from the Palomäki quartz diorite show extreme homogeneity. These morphologically typical magmatic zircons have long prisms and are translucent to transpar-

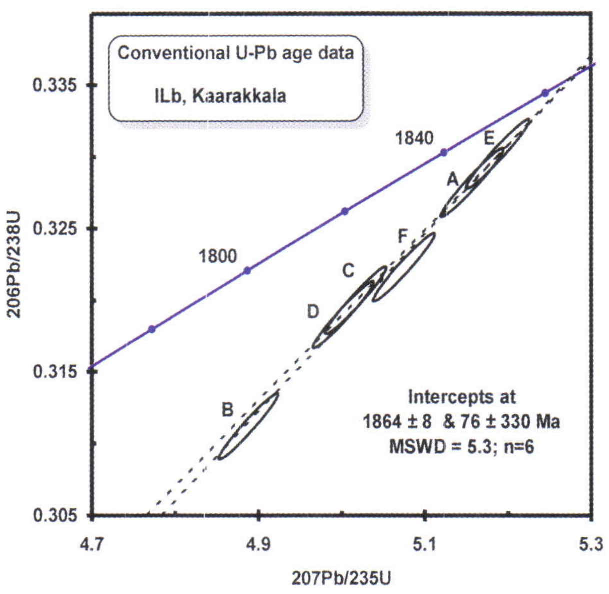

Fig. 6. U-Pb age data of ILb group sample from Ahvenlampi, Kaarakkala intrusion.

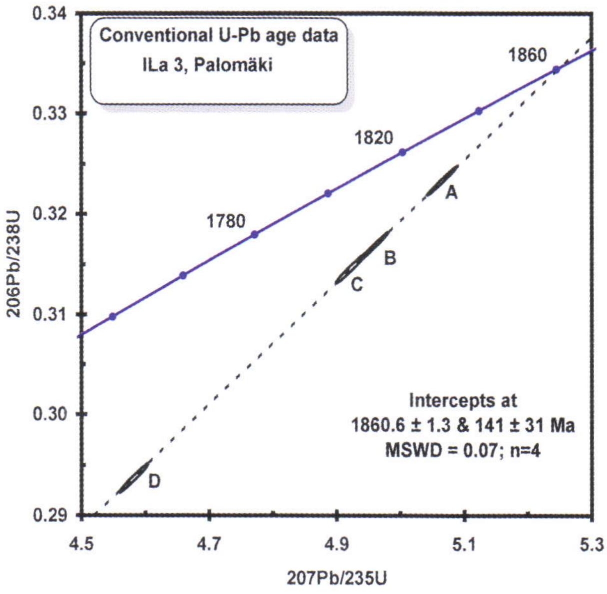

Fig. 7. U-Pb age data of ILa sample 3, Palomäki quartz diorite.

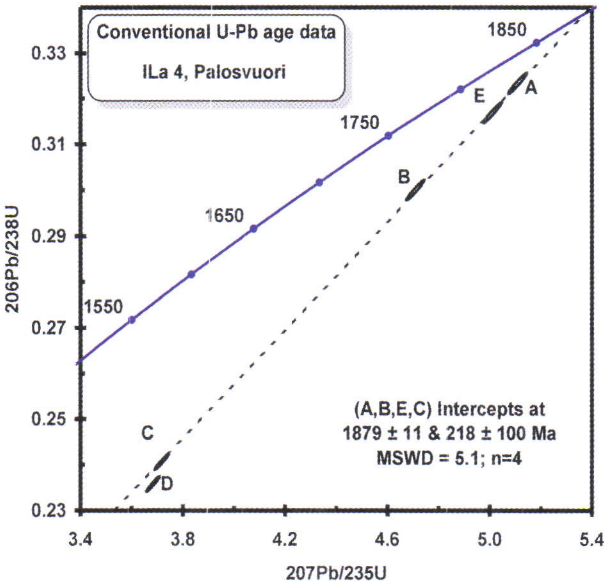

Fig. 8. U-Pb age data of ILa sample 4, Palosvuori quartz diorite.

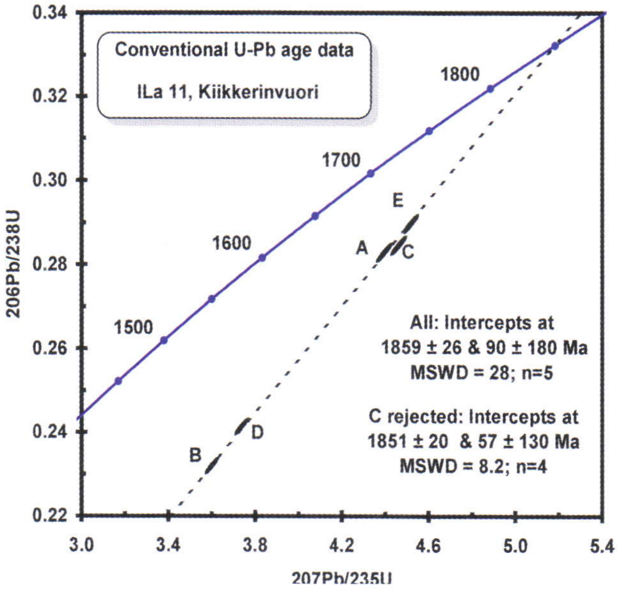

Fig. 9. U-Pb age data of ILa sample 11, Kiikkerinvuori granite.

ent and light brown in colour. Four analysed zircon fractions plot well on a same discordia line (Table 1, Fig. 7). The upper intercept age of 1861±1 Ma determines the age for the Palomäki quartz diorite.

ILa sample 4 Palosvuori, granite – granodiorite: In the Palosvuori sample the amount of the zircon was quite small and the zircon material quite heterogeneous. However, some zircons contain dark mineral inclusions. Among the clearly magmatic type, there are brown and dull zircon grains and fragments with varying morphologies.

Four of the five analysed zircon fractions plot on the same line. The most discordant analysis point D plots on the older side of this discordia (Table 1 and Fig. 8). These highly discordant data points are normally not very reliable, and can be rejected from the calculations. Although the slightly high MSWD value of 5.1 indicates some heterogeneity in the sample material, the upper intercept age 1879±11 Ma gives a good age estimate for the Palosvuori granite – granodiorite intrusion. This age, with the $^{207}Pb/^{206}Pb$ ages of 1874 and 1875 Ma for the most concordant data points (A and E) indicate that the Palosvuori granite – granodiorite belongs into the 1.88 Ga age group and not into the 1.86 Ga group represented by the Palomäki quartz diorite and Kaarakkala intrusion.

ILa sample 11, Kiikkerinvuori granite: This sample yielded a very small amount of prismatic, brownish, dull zircon. Among these, there are also some irregular shaped grains of zircons.

The analysed five zircon fractions indicate that the zircon material was heterogeneous, as the MSWD value for the five point discordia line would be as high as 28 (Fig. 9.). Rough age approximation can be done using the four data point discordia line. However, to reject the data point C an assumption that it contains clearly older zircon material is needed. Then the discordia line plotted through data points A, B, D, and E gives an upper intercept age of 1851±20 Ma with the MSWD value of 8.2. Although the age error and MSWD value are high, it is considered that the Kiikkerinvuori granite do not belong to the syncollisional age group. To ascertain this, few additional analysis should be done.

Sm-Nd-analyses

Hannu Huhma (Geological Survey of Finland) has analyzed Sm/Nd-ratios from the samples ILa 3, 4 and 11 and calculated their ε_{Nd} values and model ages (Table 2). The analytical procedures are described e.g. in Huhma (1986). From the ε_{Nd} values it can be seen that the Archaean crustal component is strongest (lowest ε_{Nd}) in Kiikkerinvuori (-6.5) increasing from Palosvuori (-3.4) to Palomäki (-2.2).

Geochemical characteristics of the samples

In Figure 10 is given the classification of the rocks on the diagram of Cox et al. (1979). From the figure it can be seen that the Palomäki (=ILa 1-3) and ILb samples from Kaarakkala are close to each other in the low-SiO_2 alkaline gabroic fields. The other ILa samples (ILa 4-11) and LBZ-Archaean samples plot in the sub-alkaline granite-quarz-diorite fields. The Proterozoic LBZ-samples have a wider spectrum from mainly sub-alkaline gabbros to diorite and granites.

In the Classification diagram by de la Roche et al. (1980, Fig. 11) and Batchelor and Bowden (1985) the ILb and ILa samples 1-3 plot maily in the fields of 'post-collison uplift' monzonites and syeno-gabbros. The Archaean LBZ and ILa samples 4-11 cluster mainly in the syn-collisional granodiorites and monzo- / syeno-granites. However, it is clear from tectonic and isotopic consideration above that ILa samples 4-11 are also late- to post-collisional. Their characteristics are possibly distorted by the strong Archaean crustal component which is evident from their isotopic and chemical compositions. The Proterozoic LBZ samples plot in a wider range of rock type fields having tectonic characteristics from pre-plate collision to syn-collision and post-collision uplift, which is reasonable for these rocks.

The diagram introduced by Pearce and Peate (1995, Fig. 12) originally for volcanic arc magmas gives in a compact form a wide spectrum of elements in order of their increasing compatibility. From the diagram it is evident that there is a close correlation between Archaean LBZ samples and felsic ILa samples 4-11. Moreover, the similarity between mafic rocks ILb (Kaarakkala) and ILa samples 1-3 (Palomäki) is striking. When considering the REE compositions it can be seen that the Archaean LBZ and ILa samples 4-11 are clearly depleted compared to the more mafic ILb and ILa 1-3 rock groups, which means that these rocks cannot be derivatives from each other. However, it is clear that the ILa 4-11 rocks can be derivatives of Archaean LBZ rocks. Moreover, ILb and ILa 1-3 rocks have apparently a similar or the same source.

The Proterozoic LBZ samples are more enriched compared to the Archaean LBZ and ILa samples 4-11 but has a flatter REE pattern (i.e. lower LREE and higher HREE) compared to the ILb and ILa samples 1-3. This means that the ILb and ILa 1-3 rocks could be contaminated by the Proterozoic LBZ component but they are probably not directly their derivatives

Table 2. Sm-Nd isotopic data for the granitoids from the Lapinlahti area.

Sample	Name	Rock type	Sm (ppm)	Nd (ppm)	^{147}Sm/^{144}Nd	^{143}Nd/^{144}Nd±2SE	epsNd(1.90 Ga) CHUR	T-DM (DePaolo 1981)
ILa 3 (A1516)	Palomäki	quartz diorite /WR	8.1	56.6	0.0868	0.511153±10	-2.2	2264
ILa 4 (A1517)	Palosvuori	granite – granodiorite /WR	4.2	26.6	0.0953	0.511199±10	-3.4	2369
ILa 11 (A1518)	Kiikkerinvuori	granite /WR	4.0	18.5	0.1309	0.511488±10	-6.5	2879

WR=whole rock powder; CHUR=evolution of undifferentiated Earth

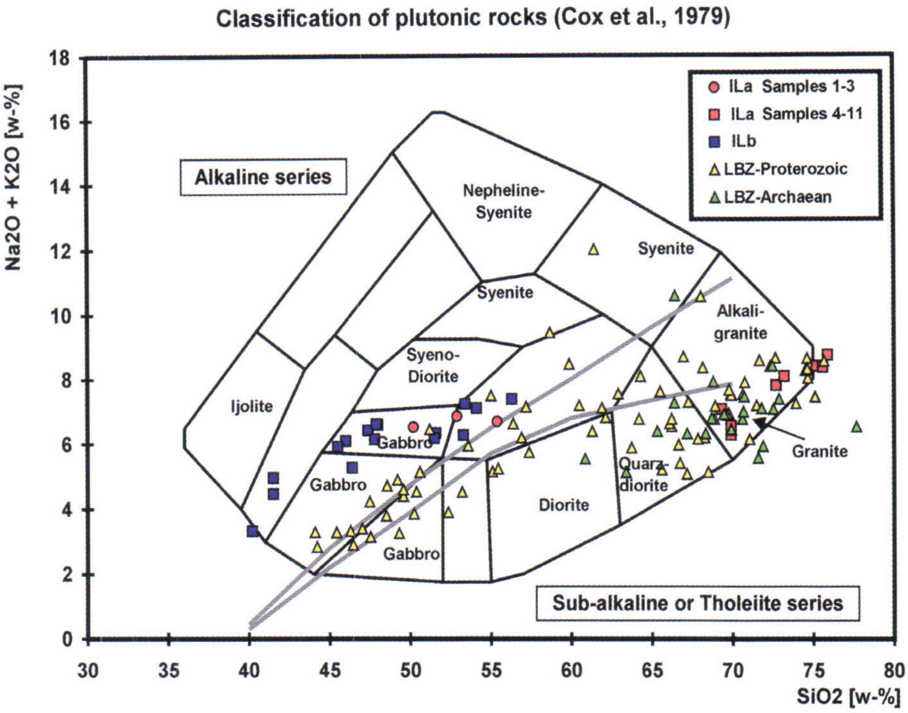

Fig. 10. Classification of the rocks on the diagram of Cox et al. (1979). The alkaline - sub-alkaline boundary lines (in gray) are adopted from Rickwood (1989). The area between them can be considered 'uncertain'. The nomenclature of igneous rocks is adopted from Wilson (1993).

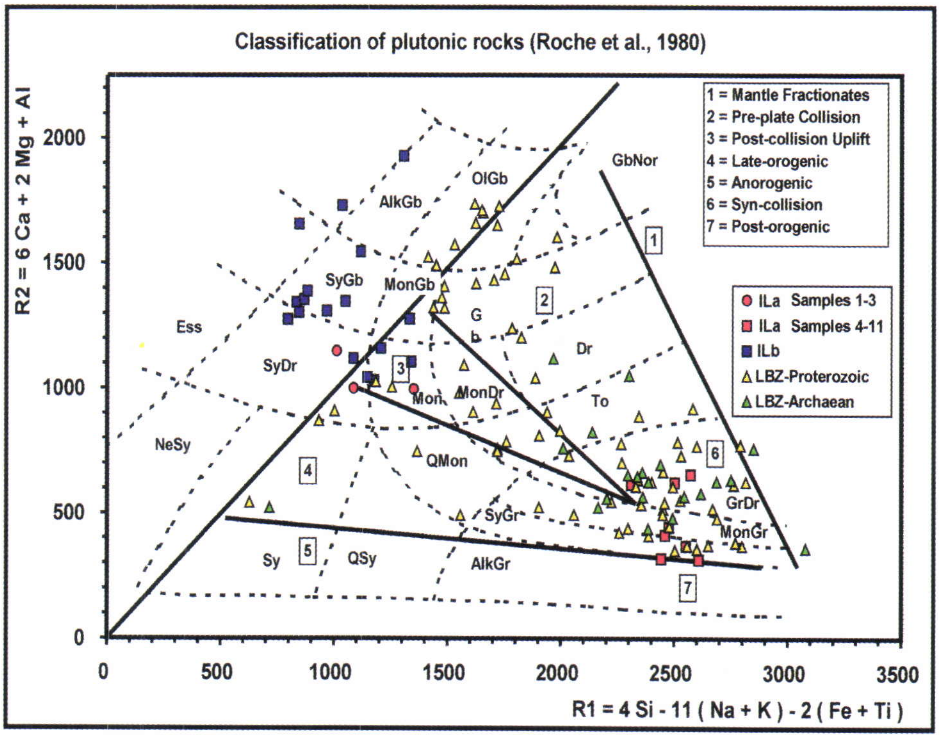

Fig. 11. Classification of the rocks by multicational diagram of de la Roche et al. (1980). The tectonomagmatic classification border lines have been adopted from Batchelor and Bowden (1985).

because of their lower SiO_2 -content.

Conclusions and evolution model

From the consideration above it can be seen that both, felsic and mafic rocks give ages from ca 1.88 – 1.86 indicating late- and post-collisional processes. From their chemical composition it can also be concluded that they have clearly a different source of origin. The ILa 4-11 rocks are less enriched in incompatibles, sample ILa 11 has low ε_{Nd} referring to strong Archaean crustal contamination and their geochemical composition is very similar to that of Archaean rocks in the LBZ-profile. Therefore, it is probable that the ILa 4-11 rocks are derivatives from melting of the Archaean crust with possibly a minor Proterozoic component.

In contrast, the Palomäki (ILa 1-3) and Kaarakkala (ILb) rocks are derivatives from a mafic source contaminated by incompatible elements. Moreover, the ε_{Nd} value measured from the ILa 1-3 rocks is highest referring to the smallest component of Archaean crustal contamination. From this it can be concluded that they have a strong component from the enriched upper mantle below the Archaean crust. The enrichment has apparently happened during and after the Svecofennian collision while no signs of such enrichment was observed in the older rocks (or their derivatives) as is evident from the Archaean LBZ and ILa 4-11 samples in Figure 12.

The observed features of the Iisalmi - Lapinlahti area rocks can be explained by a schematic model shown in Figure 13. adopted from Ruotoistenmäki (1996) which depicts the collision of Svecofennian crust against the Archaean craton. In the collision process, ca. 1.9–1.885 Ga ago, the Proterozoic (Pielavesi) crust and possibly wet sediments carried by subducting slab are thrusted against and below the Archaean (Iisalmi) block. In the collision the Archaean crust is broken into blocks, some of which still contain well-preserved granulite facies mineral assemblages. The block margins are evident as fracture zones in the geophysical maps shown above. The overthrust tectonics on the Archaean-Proterozoic boundary has been described in e.g. Pietikäinen and Vaasjoki (1999). Indications of fossilized subducting slab behind the Central Finland granite have been observed in the reflection seismic profile 'Babel' (Babel Working Group 1990).

After the Svecofennian collision the erosion of the Archaean crust has been close to 15-20 km (e.g. Kontinen et al. 1992; Pajunen, 1999) which means that after the collision the crust was possibly up to 80 km thick at its maximum. The lower parts of the thickened crust and mantle below were thus thrusted to depths where temperature and pressure are higher.

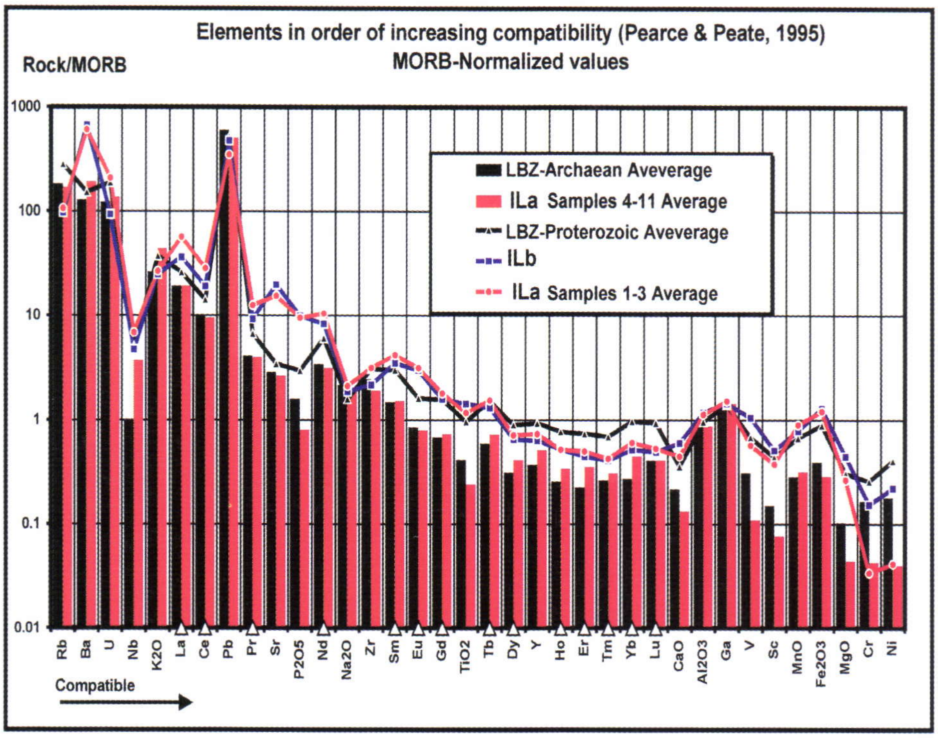

Fig. 12. Morb-normalized patterns of the average of the elements using diagram introduced by Pearce and Peate (1995). For sake of clarity the Archaean LBZ and ILa 4-11 values have been plotted with bars. The REE-elements have been emphasized by D:s in the horizontal axis.

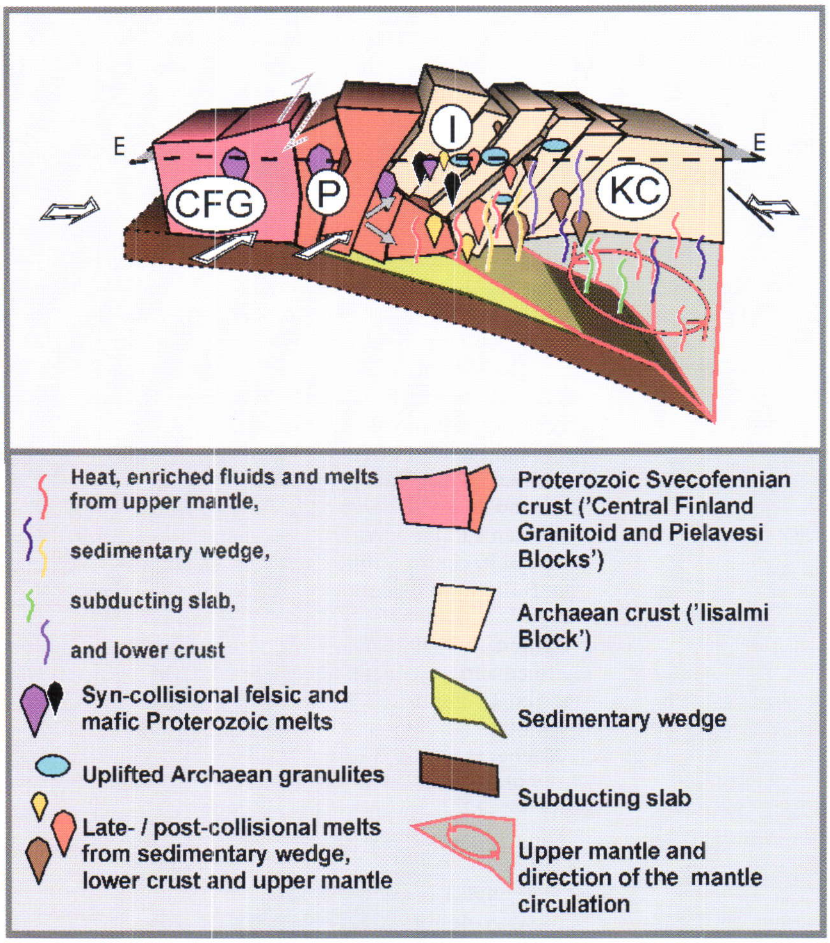

Fig. 13. A schematic model of the collision of Svecofennian crust against the Archaean craton and interconnected magmatic processes. Adopted and modified from Ruotoistenmäki (1996). P = Proterozoic (Pielavesi) block, I = Archaean (Iisalmi) block containing the Iisalmi - Lapinlahti area, E = present day erosion level.

Moreover, they were intruded and contaminated by fluids and melts from the subducting slab and sedimentary wedge. As a result, the lower crust and upper mantle were slowly heated and melted which resulted in late- / post-collisional magmatism observed in the Iisalmi-Lapinlahti area. The ILa 1-3 and ILb rocks have higher component from the upper mantle and sedimentary Proterozoic material, while the ILa 4-11 rocks represent components having higher proportion of the old Archaean crust. The increased component from the high density upper mantle raised the average density of the crust in the area making it possible to sustain the isostatic balance and a very thick crust even today.

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