Pukala intrusion, its age and connection to hydrothermal alteration in Orivesi, southwestern Finland.

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Abstract

The Pukala intrusion is situated in the Paleoproterozoic Svecofennian domain of the Fennoscandian Shield in the contact region between the Central Finland Granitoid Complex and the Tampere Belt. The acid subvolcanic intrusion, which is in contact or close to several altered domains, mainly consists of porphyritic granodiorite and trondhjemite. The Pukala intrusion was emplaced into volcanic sequence in an island-arc or fore-arc setting before or during the early stages of the main regional deformation phase of the Svecofennian orogeny. On the basis of the geochemical data, the Pukala intrusion is a peraluminous volcanic-arc granitoid. After crystallisation at 1896±3 Ma, multiphase deformation and metamorphism caused alteration, recrystallisation, and orientation of the minerals, and tilted the intrusion steeply towards south. The 1851±5 Ma U-Pb age for titanite is connected to the late stages of the Svecofennian tectonometamorphic evolution of the region.

Several hydrothermally altered domains are located in the felsic and intermediate metavolcanic rocks of the Tampere Belt within less than one kilometre south of the Pukala intrusion. Alteration is divided into three basic types: partial silica alteration, chlorite-sericite±silica alteration, and sericite alteration in shear zones. The first two types probably formed during the emplacement and crystallisation of the Pukala intrusion, and the third is linked to late shearing. Intense sericitisation and comb quartz bands in the contact of the intrusion and the altered domain at Kutemajärvi suggest that the hydrothermal system was driven by the Pukala intrusion.

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1. Introduction

In orogenic belts, hypabyssal intrusions form from residual of liquids in magma chambers of volcanoes or crystallise from magma chambers that did not erupt. The intrusions often create hydrothermal systems that may carry constituents to and cause mineralisation in the intrusions and their country rocks. For example, epithermal gold±telluride±silver deposits form as a result of hydrothermal activity during a period of volcanism and/or magmatism at subvolcanic depths (Heald et al., 1987; Hedenquist et al., 1996).

The study area, located in a Paleoproterozoic orogenic belt, contains a subvolcanic intrusion, volcanic rocks of island arc type, and a metamorphosed epithermal gold deposit (Seitsaari, 1951; Laitakari, 1986; Kähkönen, 1989; Kähkönen et al., 1989; Luukkonen et al., 1992; Kojonen et al., 1999; Talikka, 2003; FINGOLD database, www.gtk.fi/explor/, 20.2.2005). The purpose of this paper is to provide information of the relation between the subvolcanic intrusion and altered domains from the area inves-

tigated by presenting petrological, geochemical, and age data on the Pukala intrusion. With emphasis on the Kutemajärvi area, we also discuss the tectonometamorphic history of the area studied.

2. Geologic setting

The study area is in Orivesi, southwestern Finland, in the centre of the Svecofennian domain, which formed 1920–1870 Ma ago as a result of accretion of several island-arcs and microcontinents against the Archaean craton (Lahtinen et al., 2005). Several separate, in places concurrent, collisions took place producing a number of orogenic events and extensional phases between them (Lahtinen et al., 2005). The Svecofennian domain is divided in three main regions: the primitive arc complex, the arc complex of western Finland, and the arc complex of southern Finland (Korsman et al., 1997). The study area is located in the southern part of the arc complex of western Finland (Fig. 1).

The Svecofennian domain is predominantly composed of Paleoproterozoic metasedimentary rocks,
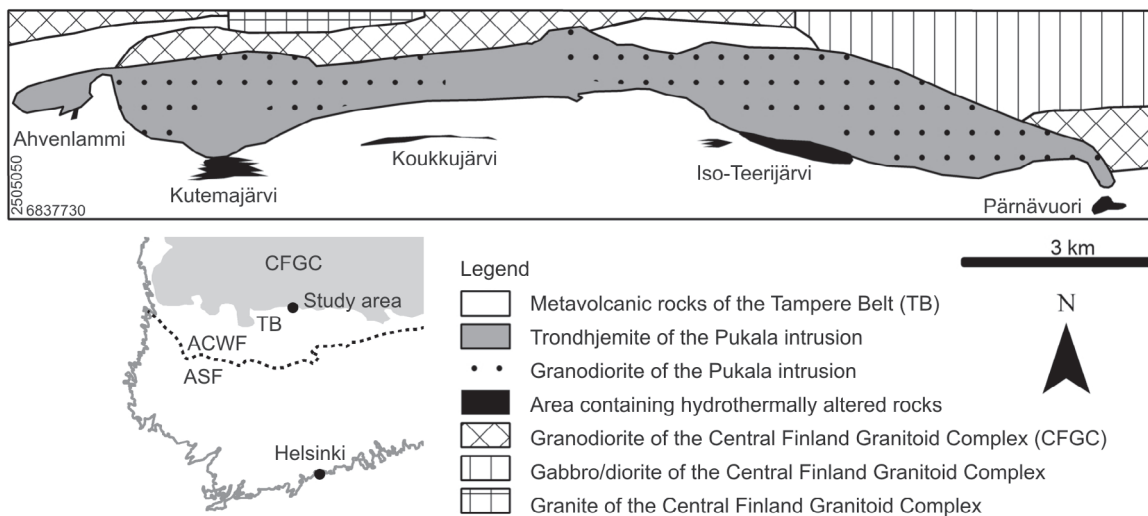

Fig 1. Generalised geological map of the study area. The Pukala intrusion is located in Orivesi, southwestern Finland, in the contact region between the Central Finland Granitoid Complex (CFGC) and the Tampere Belt (TB). Several small hydrothermally altered domains are situated in the metavolcanic rocks immediately to the south of the Pukala intrusion. ASF = arc complex of southern Finland, ACWF = arc complex of central and western Finland. Modified from Seitsaari (1951), Laitakari (1986), and Talikka (2003). Inset after Korsman et al. (1997).

metavolcanic rocks of island-arc type, and granitoids, which have intruded into the supracrustal rocks (Gaál & Gorbatschev, 1987; Korsman et al., 1997; Nironen, 1997; Kilpeläinen, 1998). The sedimentary and volcanic rocks were metamorphosed under high-temperature and low-pressure conditions (Korsman, 1977; Korsman et al., 1984; Schreurs, 1984; Schreurs & Westra, 1985; Hölttä, 1986; Kilpeläinen, 1998). The supracrustal rocks are mostly 2000–1880 Ma and the I-type granitoids 1890–1880 Ma old (Nurmi et al., 1984; Huhma, 1986; Kähkönen et al., 1989; Nironen, 1989; Kilpeläinen, 1998).

The Pukala intrusion lies between the Central Finland Granitoid Complex (CFGC) and the Tampere Belt (TB; Nironen et al., 2002) (Fig. 1). The country rocks on the northern side of the intrusion comprise granite, granodiorite, and gabbro of the CFGC. The northern edge of the Pukala intrusion follows a chain of lakes, which may indicate a presence of a shear zone along the contact between the CFGC and the Pukala intrusion. To the south of the intrusion, there are intermediate metavolcanic rocks of the TB with some felsic and mafic strata. The zircon U-Pb ages of the metavolcanic rocks in the TB are 1904–1889 Ma (Kähkönen et al., 1989). The structure of the TB is a large synform whose northern limb mainly comprises metavolcanic rocks and the southern limb metasedimentary rocks. Several large east-west striking fault zones cut the TB (Kähkönen, 1989). In the area mapped in the present study, the strike of the main schistosity is in east-west direction and the dip is 70-90º, more commonly to north than south.

3. Pukala intrusion

3.1. General aspects

The east-west striking Pukala intrusion is roughly 20 km long and 1–2 km wide. The intrusion consists of porphyritic granodiorite and trondhjemite (Fig. 2a-c) with minor granitic, tonalitic, and aplitic parts. The contacts between the rock types are gradual. The orientation of the weak foliation observed within the intrusion is the same as the orientation of the main regional schistosity in the metavolcanic rocks.

A number of mafic and intermediate rock enclaves are found within the intrusion, particularly in its southwestern part (Fig. 2b-c). These most likely are xenoliths from the adjoining metavolcanic rocks. The shape of the inclusions varies from oval to ragged, and their size is commonly 10–30 cm, although inclusions up to several meters in length exist. The inclusions are oriented in east-west direction, but the mineral grains in them lack an orientation.

Two mafic dyke swarms cut through the study area. East-west striking metamorphosed dykes are commonly uralite-phyric and their paleomagnetic age is Svecofennian (Pesonen & Neuvonen, 1981). Unmetamorphosed 1650–1600 Ma diabases strike N 50°W (Laitakari, 1987).

3.2. Petrology

All the rock types of the Pukala intrusion are porphyritic. In the granodiorite and trondhjemite, the plagioclase and potassium feldspar phenocrysts are 1–5 mm in diameter and commonly sericitised and saussuritised (Fig. 2a). Quartz phenocrysts (Ø 2–5 mm), of which some are recrystallised, also exist in places. The granodiorite has more phenocrysts than the trondhjemite. The fine-grained (grain size 0.01–0.2 mm) matrix is predominantly quartz with some plagioclase and biotite. The only abundant mafic mineral is biotite (3–8 vol. %), which defines the foliation. The modal compositions of the two main rock types are shown in Table 1 and in Fig. 3a. Accessory minerals include chlorite, muscovite, epidote, fluorite, apatite, carbonate, titanite, allanite, and zircon.

The intrusion is heterogeneous, with the tonalitic and granitic parts intimately intermingled. Aplite is found at few locations near the southern margin of the intrusion. In the contact of the intrusion and the outer rim of the altered domain at Kutemajärvi, comb quartz bands are present in the aplite.

Two types of rock inclusions have been identified: mafic, hornblende-biotite bearing and intermediate, biotite bearing. Both types are fine-grained and porphyritic in places. The plagioclase and/or hornblende phenocrysts are under 5 mm in diameter.
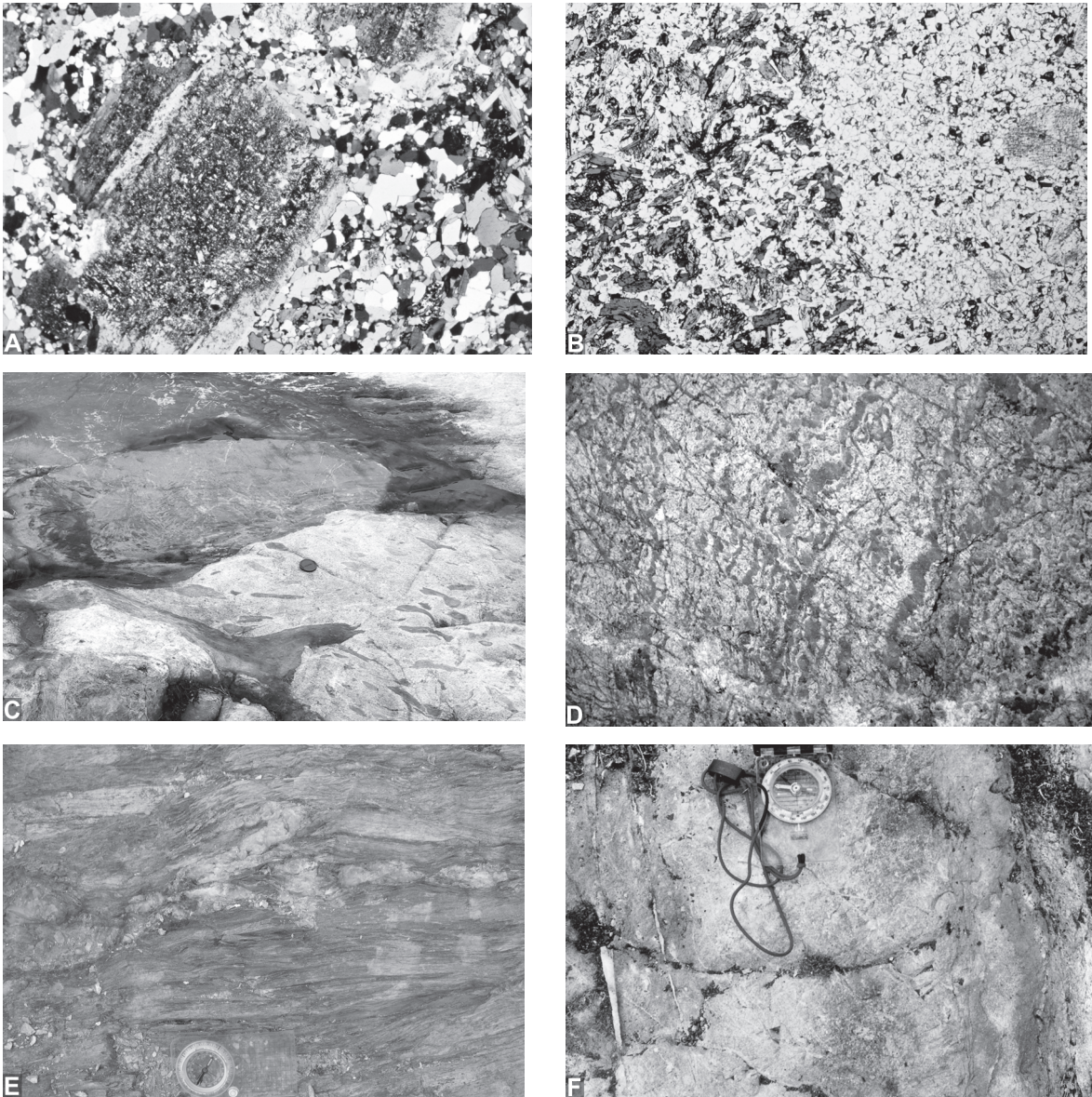
Fig. 2. a) Trondhjemite of the Pukala intrusion. Sericitised and saussuritised plagioclase phenocryst in fine-grained matrix comprising mainly quartz and biotite. The width of the view corresponds 5 mm. b) Contact of amphibole bearing xenolith and trondhjemite (Pukala intrusion). The width of the view corresponds 5 mm. c) Xenoliths in trondhjemite (Pukala intrusion). The diameter of the lens cap is 7.5 cm d) Comb quartz bands at Kutemajärvi. The width of the view corresponds 15 cm. Photo by Aulis Kinnunen. e) Chlorite-sericite schist few tens of meters south of the Pukala intrusion at Kutemajärvi. The diameter of the compass wheel is 6 cm. f) Partially silicified metavolcanic rock at Pärnävuori. A narrow sericitised shear on the right side.

3.3. Chemical composition

On the basis of their chemical composition, samples from the Pukala intrusion can be divided into two groups that correlate with the petrographic and field observations. The analytical methods and the geochemical data are presented in Table 2. The high SiO_2 and Na_2O contents are distinct. All rock samples are peraluminous with aluminium saturation index (ASI) values greater than 1.0 (Table 2). In the (FeO_t/MgO)-

Table 1. Modal composition of the Pukala intrusion.

	GRDR, N=3 average (%)	TR, N=3 average (%)
quartz	43.2	59.6
plagioclase	24.8	31.9
alkali-feldspar	21.8	0.2
biotite	7.2	5.0
chlorite	0.8	1.7
hornblende	0.1	x
muscovite	1.1	1.0
epidote, clinozoisite	0.6	0.2
fluorite	x	0.0
apatite	0.2	0.1
carbonate	0.3	0.1
titanite	x	0.0
allanite	x	0.0
zircon	x	x
opaques	0.3	0.2

Point-counting method, 1000 points/sample
x = mineral present in thin sections
GRDR = granodiorite, TR = trondhjemite
Alteration to sericite/saussurite is ignored

(Zr+Ce+Nb+Y) plot (Fig. 3b), the granodiorite represents fractionated and the trondhjemite unfractionated melts (Whalen et al., 1987). On the basis of the Nb-Y (Fig. 3c) and the Rb-(Nb+Y) (Fig. 3e) plots, the Pukala intrusion falls into the field of volcanic arc granites as defined by Pearce et al. (1984). In the R2-R1 plot (Fig. 3d), the granodiorite and some of the analysed trondhjemites fall in the syn-collision field; some trondhjemites, however, show the characteristics of mantle fractionates (Batchelor & Bowden, 1985).

The Pukala intrusion has been subjected to hydrothermal activity and metamorphism, which have caused changes to its chemical composition. The effects of the hydrothermal activity are seen in the varying contents of mobile elements such as barium, potassium, and silica. The contents of immobile elements, e.g., aluminium, zirconium, and titanium, vary only slightly within the intrusion.

When compared with the synkinematic (Lahtinen, unpublished data) and the postkinematic granitoids (Nironen et al., 2000) of the CFGC, and the rapakivi granites of Finland (Vorma, 1976; Rämö, 1991), the Pukala intrusion does not correlate well

with any of these granitoid types (Table 3). The closest relation is seen with the synkinematic granitoids in the Ba-Rb-Sr plot (Fig. 3f) and with syn- and post-kinematic granitoids of the CFGC in the Rb-(Nb+Y) diagram (Fig. 3e).

3.4. Age

For U-Pb age dating, zircon and titanite were separated from a granodiorite sample (A1675) of the Pukala intrusion. The U-Pb analytical data and methods are presented in Table 4. A total of five zircon fractions comprising yellowish to brownish, transparent, prismatic (l:w ~2–4) zircons were analysed. Despite the different abrasion times and grain-size fractions, the data practically forms a three point discordia line. It intercepts the concordia curve at 1896±3 Ma and 193±29 Ma (MSWD=1.3; n=5) (Fig. 4).

The titanite fraction E#1 gave a slightly discordant age result with $^{207}Pb/^{206}Pb$ age of 1849±5 Ma (Table 4). The concordia age for the other titanite fraction (E#2) is 1851±5 Ma (Fig. 4). Consequently, both sphene fractions are coeval.

The emplacement age of the Pukala intrusion is 1896±3 Ma. The clearly younger age of 1851±5 Ma for the titanite may imply local cooling under ~500 ºC after intrusion and metamorphic events. The peak metamorphism in the Svecofennian Tonalite-Trondhjemite Migmatite Belt occurred at ca. 1880 Ma (Mouri et al., 1999). According to Nironen (1989), the uraninite U-Pb age of ca. 1.86 Ga from a tourmaline breccia of the Ylöjärvi Cu-W deposit, 35 km to the west of the Pukala intrusion, dates local D_2 deformation and represents a retrogressive tectonothermal stage. Furthermore, the whole rock Rb-Sr isochron age of 1847±92 Ma (Kähkönen et al., 1989), although with large errors, may reflect the waning stages of the Svecofennian tectonothermal activity.

3.5. Depth of crystallisation

According to our interpretation, the Pukala intrusion was emplaced as a sheet-like intrusion between the volcanic strata at 1896 Ma and tilted gently to the
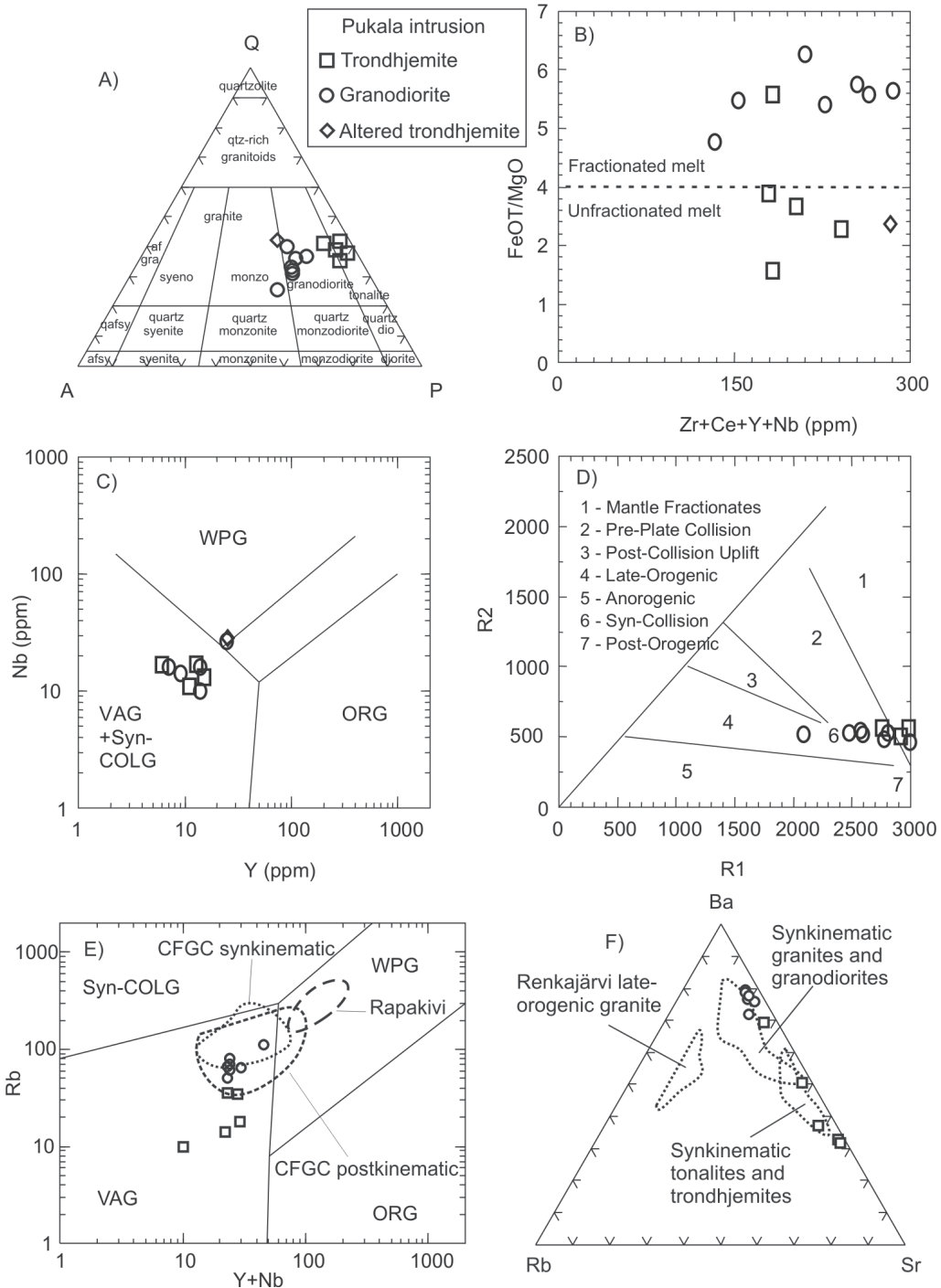
Fig. 3. a) Modal composition of the Pukala intrusion plotted in the QAP diagram introduced by Streckeisen (1974). b) (FeOt/MgO) vs. (Zr+Nb+Ce+Y) plot after Whalen et al. (1987). c) Nb vs. Y plot by Pearce et al. (1984). VAG = volcanic arc granite, Syn-COLG = syn-collisional granites, WPG = within plate granites, ORG = ocean ridge granites. d) R2 vs. R1 plot by Batchelor and Bowden (1985). R1 = 4Si-11(Na+K)-2(Fe+Ti), R2 = 6Ca+2Mg+Al. e) Rb vs. (Nb+Y) plot by Pearce et al. (1984). CFGC synkinematic and CFGC postkinematic, type 1 (Nironen et al., 2000), rapakivi (Vorma, 1976; Rämö, 1991) f) Ba-Rb-Sr diagram. Synkinematic granitoids (Nurmi et al., 1984), Renkajärvi late-orogenic granite (unpublished data; Nurmi & Haapala, 1986).

Table 2. Geochemical data on the Pukala intrusion.

Sample	120A	163	31	349	143	153	220	229	244	36A	355	391	409
Rock type	TR	TR	TR	TR	GRDR	GRDR	GRDR	GRDR	GRDR	GRDR	TR	GRDR	TR
X-coord	6839255	6839750	6839440	6840130	6840270	6839830	6839556	6839365	6839157	6839790	6840432	6840180	6839732
Y-coord	2517630	2514019	2505960	2513487	2516850	2515770	2519420	2519186	2521511	2510920	2512742	2508860	2512707
SiO_2	73.00	74.10	76.70	76.41	69.50	72.40	73.31	71.98	75.09	74.20	75.64	72.00	75.33
TiO_2	0.23	0.21	0.12	0.18	0.27	0.21	0.21	0.25	0.19	0.18	0.17	0.19	0.23
Al_2O_3	14.80	14.30	13.10	13.30	15.70	14.60	13.70	14.30	12.90	14.20	13.80	15.00	13.00
FeOt	2.50	2.25	1.38	1.31	3.03	2.40	2.27	2.57	2.16	1.98	1.03	2.19	2.16
MnO	0.07	0.06	0.04	0.03	0.07	0.06	0.07	0.08	0.06	0.04	0.02	0.05	0.05
MgO	0.47	0.67	0.50	0.42	0.56	0.39	0.41	0.48	0.42	0.45	0.56	0.42	0.81
CaO	2.38	2.32	0.92	2.43	1.77	2.05	2.26	2.29	1.84	1.69	1.90	2.04	1.72
Na_2O	5.08	4.73	3.57	4.83	3.94	3.87	3.72	3.80	3.47	4.35	5.59	4.04	4.59
K_2O	0.97	0.88	3.31	0.49	4.50	3.36	2.93	3.38	3.05	2.40	0.42	3.51	1.25
P_2O_5	0.09	0.07	0.02	0.04	0.11	0.07	0.05	0.07	0.05	0.06	0.04	0.07	0.07
Total	99.59	99.59	99.66	99.44	99.45	99.41	98.93	99.20	99.23	99.55	99.17	99.51	99.21
Rb	36	18	59	14	110	64	62	80	70	50	10	67	35
Nb	17	17	28	11	24	16	10	10	10	14	10	16	13
Y	6	12	25	11	22	14	14	14	14	9	b.d.l.	7	15
Zr	120	120	150	118	180	120	131	144	119	110	117	100	136
Ce	40	30	8	63	60	60	100	97	84	b.d.l.	56	3	77
Ba	280	360	670	244	1260	1410	1518	1452	1405	1270	183	1450	651
Sr	437	333	135	485	379	304	364	362	312	355	386	348	255
La	20	40	80	30	30	40	30	30	30	20	30	40	30
ASI	1.26	1.30	1.15	1.24	1.06	1.10	1.07	1.05	1.07	1.18	1.25	1.09	1.22

The geochemical data was determined by the XRF-method at the VTT Technical Research Centre of Finland and at the Geological Survey of Finland. Data source: Talikka (2003). Oxide values wt%. Others ppm. GRDR = granodiorite, TR = trondhjemite, ASI [Al/(Ca-1.67P+Na+K)] = aluminium saturation index, b.d.l. = below detection limit.

west and steeply to the south along with the metavolcanic rocks of the TB during the Svecofennian orogeny. This is supported by slightly coarser grain size of matrix in the northern and eastern parts of the intrusion. Furthermore, the xenoliths, which formed during the emplacement as a result of magmatic stoping and commonly appear near the edges and roof of the intrusion (Pitcher, 1997), are abundant near the southern margin in the western side of the intrusion. Consequently, the current erosion level exposes a shallower level of the intrusion in the south and west and a deeper level in the north and east.

In aeromagnetic map the metavolcanic rocks of the TB show a distinct magnetic anomaly pattern with stripes of positive magnetic anomalies, and similar pattern with lower intensity is seen in the area of the Pukala intrusion (GTK Active Map explorer, http://maps.gtk.fi/gtk/eexpert.asp, map sheet 2142). This implies that the metavolcanic rocks of the TB underlie the intrusion. On the basis of the geophysi-

cal and drilling data, the estimated depth of the intrusion is 1–2 km in the west and a bit less in the east.

4. Hydrothermally altered rocks

Several hydrothermally altered domains are located in the metavolcanic rocks of the TB less than one kilometre south of the Pukala intrusion. The largest of the hydrothermally altered areas, Kutemajärvi, hosts a gold deposit, which was mined (Orivesi mine) during 1994–2003 by Outokumpu Mining Oy and Polar Mining Oy. During its lifetime the mine produced 380 000 ounces of gold at an average grade of ~9.1 g/t Au (Dragon Mining NL, 2005). Previous studies on the Kutemajärvi area include contributions from Nurmi et al. (1984), Grönholm (1992), Luukkonen et al. (1992), Luukkonen (1994), Poutiainen and Grönholm (1996), Kojonen et al. (1999), and Poutiainen et al. (1999). In addition Pihlaja (1974), Kähkönen (1989), Luodes (1989), and Papunen (1990) have

Table 3. Geochemical data on selected Svecofennian granitoids.

	Pukala intrusion TR			Pukala intrusion, GRDR			CFGC, synkinematic			CFGC, postkinematic, type 1			Rapakivi		
	5 samples			7 samples			127 samples			9 samples			71 samples		
	mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max
SiO_2	74.9	73.0	76.4	72.6	69.5	75.1	67.7	56.4	77.2	66.2	61.5	72.7	71.4	65.1	77.0
TiO_2	0.20	0.17	0.23	0.21	0.18	0.27	0.46	0.05	1.23	0.65	0.32	0.82	0.41	0.20	0.96
Al_2O_3	13.8	13.0	14.8	14.3	12.9	15.7	15.1	12.2	18.6	15.4	13.6	16.8	13.1	11.5	16.2
FeOt	1.85	1.03	2.50	2.37	1.98	3.03	3.82	0.07	8.64	4.97	2.74	7.10	3.55	1.65	9.36
MnO	0.05	0.02	0.07	0.06	0.04	0.08	0.08	0.02	0.18	0.08	0.05	0.11	0.05	0.01	0.17
MgO	0.59	0.42	0.81	0.45	0.39	0.56	1.24	0.07	3.76	1.11	0.55	1.45	0.29	0.04	0.60
CaO	2.15	1.72	2.43	1.99	1.69	2.29	3.08	0.23	6.69	2.23	1.38	2.89	1.45	0.74	3.17
Na_2O	4.96	4.59	5.59	3.88	3.47	4.35	3.48	2.61	4.53	2.90	2.71	3.40	2.70	1.83	3.23
K_2O	0.80	0.42	1.25	3.30	2.40	4.50	3.69	1.83	5.92	4.31	3.56	4.86	5.72	4.23	7.12
P_2O_5	0.06	0.04	0.09	0.07	0.05	0.11	0.14	0.01	0.40	0.27	0.12	0.36	0.08	0.01	0.20
Rb	23	10	36	72	50	110	125	53	281	158	112	202	290	148	466
Nb	14	10	17	14	10	24	10	2	22	22	14	37	41	23	67
Y	9	b.d.l.	15	13	7	22	24	6	61	35	24	46	90	12	164
Zr	122	117	136	129	100	180	167	68	525	360	205	589	415	81	1160
Ba	344	183	651	1395	1260	1518	781	203	1470	1050	556	1403	909	90	2090
Sr	379	255	485	346	304	379	403	40	984	268	147	385	96	13	191
A/CNK	1.07	1.03	1.10	1.06	1.02	1.10	0.99	0.83	1.11	1.14	1.01	1.28	0.99	0.82	1.22

Oxide values wt%. Others ppm. b.d.l. = below detection limit. A/CNK = $Al_2O_3/(CaO+Na_2O+K_2O)$ mol.

CFGF, synkinematic (Lahtinen, unpublished). CFGF, postkinematic, type 1 (Nironen et al., 2000). Rapakivi (Vorma, 1976; Rämö, 1991).

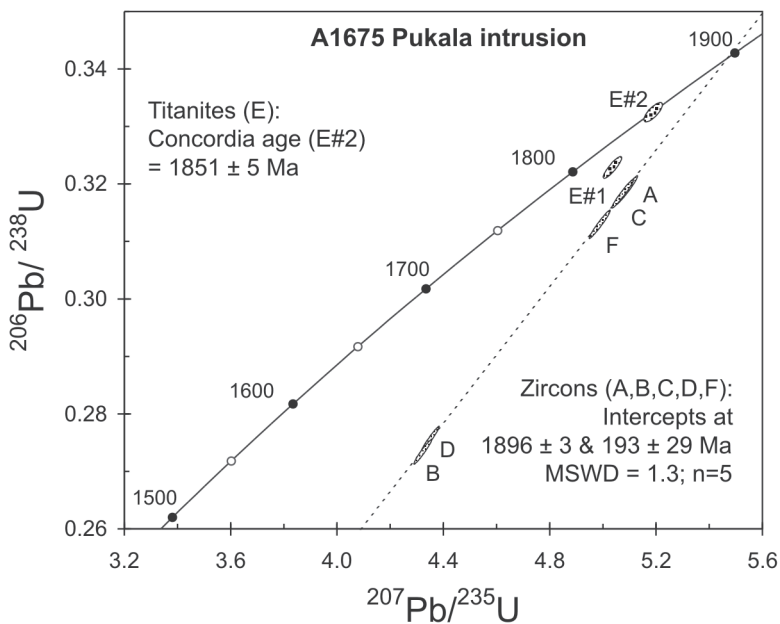TR = trondhjemite, GRDR = granodiorite, CFGC = Central Finland Granitoid Complex.

Fig. 4. Concordia plot for U-Pb age data on zircon and titanite from sample A1675 Pukala intrusion.

Table 4. ID-TIMS U-Pb age data on zircons and titanite from A1675 Pukala intrusion.

Analysed mineral and fraction	Sample weight/mg	U ppm	Pb ppm	measured $^{206}Pb/^{204}Pb$	radiogenic $^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	±2σ%	$^{207}Pb/^{235}U$	±2σ%	$^{207}Pb/^{206}Pb$	±2σ%	Rho	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
A1675 Pukala intrusion															
A) zircon d>4.2 g cm⁻³, >75 μm, transparent to translucent prismatic, abraded 23h	0.16	528	181	6083	0.12	0.3189	0.65	5.082	0.65	0.1156	0.15	0.97	1784	1833	1889±2
B) zircon d>4.2 g cm⁻³, >75 μm, transparent to translucent prismatic	0.57	513	153	2564	0.12	0.2754	0.65	4.343	0.65	0.1143	0.15	0.97	1568	1702	1870±2
C) zircon d>4.2 g cm⁻³, <75 μm, translucent prismatic, abraded 23h	0.46	516	176	8006	0.12	0.3182	0.65	5.069	0.65	0.1155	0.15	0.97	1781	1831	1888±2
D) zircon d>4.2 g cm⁻³, <75 μm, translucent prismatic	0.53	447	132	3579	0.12	0.2731	0.65	4.313	0.65	0.1146	0.15	0.97	1556	1696	1873±2
F) zircon d>4.2 g cm⁻³, <75 μm, translucent prismatic, abraded 10h	0.53	409	137	5126	0.12	0.3129	0.65	4.982	0.65	0.1155	0.15	0.97	1755	1816	1888±2
E#1) titanite, abraded 10 min	2.35	67	23	1012	0.05	0.3229	0.48	5.031	0.55	0.1130	0.26	0.88	1804	1825	1849±5
E#2) titanite, abraded 15 min	1.29	68	24	821	0.06	0.3325	0.42	5.187	0.55	0.1131	0.35	0.77	1851	1851	1850±6

1) Isotopic ratios corrected for fractionation, blank (50 pg), and age related common lead (Stacey & Kramers 1975; $^{206}Pb/^{204}Pb$ ± 0.2, $^{207}Pb/^{204}Pb$ ± 0.2, $^{207}Pb/^{204}Pb$ ± 0.1, $^{208}Pb/^{204}Pb$ ± 0.2).

Analytical methods: U-Pb analyses were performed at the Geological survey of Finland, Espoo. The decomposition of zircons and extraction of U and Pb for multigrain isotopic age determinations follows mainly the procedure described by Krogh (1973). $^{235}U-^{208}Pb$-spiked and unspiked isotopic ratios were measured using a VG Sector 54 thermal ionisation multicollector mass spectrometer. The measured lead and uranium isotopic ratios were normalised to the 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 the discordia lines using the Isoplot/Ex 3 program (Ludwig, 2003). Data-point error ellipses are 2σ. All ages are calculated on 2σ level and decay-constant errors are ignored.

studied the metavolcanic and/or hydrothermally altered rocks in the vicinity of the Pukala intrusion.

4.1. Main alteration types

On the basis of field observations, the hydrothermal alteration can be divided into three basic types (Talikka, 2003).

1. *Partial silica alteration* is present in the Koukkujärvi, Kutemajärvi, Iso-Teerijärvi, and Pärnävuori areas (Fig. 1). Domains of partially silicified rocks can be found in an area corresponding to the length of the Pukala intrusion. The degree of silicification varies from weak to medium and the primary structures of the metavolcanic rocks are still commonly visible. Partially silicified rocks have a sugary appearance and they lack schistosity (Fig. 2f). The main ore mineral is pyrite; other sulphides present are chalcopyrite, pyrrhotite, and galena. The amount of ore minerals increases along with the degree of silicification.

2. *Chlorite-sericite±silica alteration* exists in the Ahvenlammi, Koukkujärvi, Kutemajärvi, and Iso-Teerijärvi areas (Fig. 1). The altered rocks commonly are foliated, pervasively altered chlorite±sericite schist and found as thin (<2 m) layers within apparently unaltered metavolcanic strata. The alteration probably proceeded along shear zones and/or permeable layers of the volcanic rocks.

At Kutemajärvi, chlorite-sericite±quartz schist (Fig. 2e) form the outer rim of the continuous hydrothermally altered domain and the proportion of silicification increases towards the centre of the altered area, which is dominated by sericite-quartz schist and hosts the pipe-shaped ore deposits (Grönholm, 1992). In addition, massive andalusite, quartz, and topaz rocks are present in the centre of the altered domain (Grönholm, 1992; Luukkonen, 1994). The typical ore minerals detected at Kutemajärvi are pyrite, chalcopyrite, pyrrhotite, galena, sphalerite, gold, and Te-Bi minerals (Luukkonen, 1994). Partial silica alteration of the metavolcanic rocks is found outside the halo of the chlorite-sericite schist in places.

Andalusite-muscovite breccia, which is a retrograde type of rock, exists in a limited area (pipe 3, levels +200 – +310; pipe 5, level +256 – 490) in the Orivesi mine (Kutemajärvi). The brecciated appearance is due to blocks (⌀ 5–20 cm) of andalusite rich material and matrix between them. The matrix is mainly composed of muscovite and pyrophyllite. Diaspore, gem-grade topaz, apatite, lazulite, and thucholite are also present in the matrix. The andalusite-muscovite breccia bodies are lens-shape (thickness 1–1.5 m, length ⁓10 m), subvertical (tens of meters), and without any cleavage.

3. *Sericite alteration in shear zones* is found in the Pärnävuori area. The subvertical, NE-trending shear zones deform partially silicified and unaltered metavolcanic rocks and the main foliation. The shearing and alteration resulted in narrow bands of sericite schist on both sides of the shears (Fig. 2f). Ore minerals are few in the sericite schist. A megabreccia structure, in which sericitised shear zones separate blocks of partially silicified and metavolcanic rocks, may exist. According to Grönholm (1992), shear zones and fold structures that deform the main foliation of the hydrothermally altered rocks and unaltered metavolcanic rocks are found at Kutemajärvi.

4.2. Previous age constraints on Kutemajärvi alteration

Previous U-Pb datings and Pb-isotopic studies from the Kutemajärvi area have been published by Mänttäri et al. (1997). Monazite from the strongly hydrothermally altered mafic volcanic rock (chlorite schist) hosting the ore (pipe 3) has a U-Pb concordia age of 1879 ± 2 Ma (recalculated from previous data from Mänttäri et al., 1997). Thus, it post-dates the volcanic activity in the area. Additionally, the turbid zircons with outstandingly low $^{206}Pb/^{204}Pb$ ratios indicate a strong post-crystallisation hydrothermal effect at ca. 1.81 Ga.

4.3. Comb quartz layering

Comb quartz layers are commonly located beneath and adjacent to hydrothermal ore deposits, and associated with porphyry deposits e.g. Henderson Mo
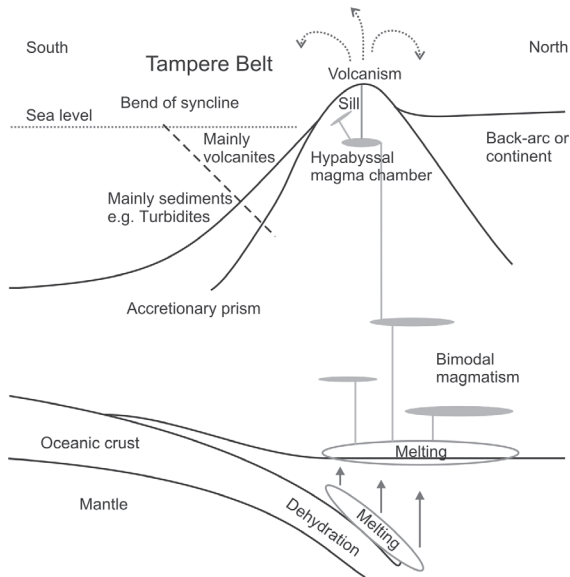
Fig. 5. Tectonic setting during the formation of the Pukala intrusion at ~1.9 Ga. Oceanic crust is subducting under island-arc or active continental margin resulting to bimodal magmatism and volcanism. The Pukala intrusion represents a hypabyssal magma chamber. Modified from Talikka (2003).
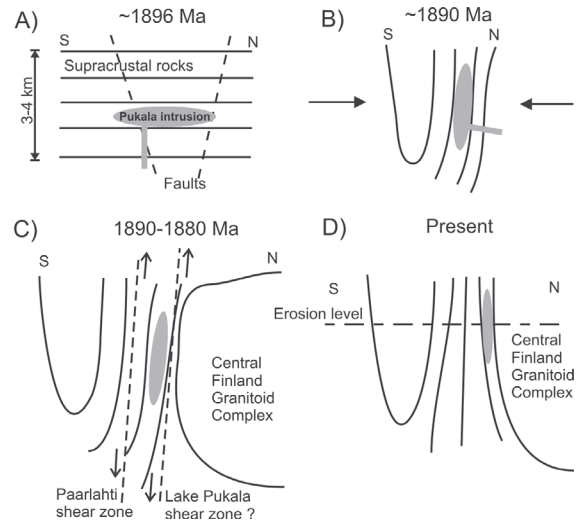

Fig. 6. Tectonic evolution of the study area during the Svecofennian orogeny. Modified from Talikka (2003).
A) Before the main regional deformation phase at ~1896 Ma. The Pukala porphyry intruded into volcanic sequence of the Tampere Belt (TB) during subduction or at the early stages of the collision between island-arcs or an island-arc and a continental margin. Shear zones may have controlled the rise of the magma to the hypabyssal levels.
B) Main regional deformation phase at ~1890 Ma. Large isoclinal folds were formed during the collisional stage. The Pukala intrusion acted as a competent mass and tilted along with the adjoining volcanic rocks of the TB.
C) 1890–1880 Ma. The supracrustal rocks of the TB were deformed and metamorphosed at greenschist facies. The synkinematic granitoids of the Central Finland Granitoid Complex intruded. The formation of large shear zones.
D) Present day situation.

(Colorado, USA) and Anticlimax Mo-W (BC, Canada) (Kirkham & Sinclair, 1988). Rhythmically banded quartz layers that resemble comb quartz texture are found in the aplite in the contact of the Pukala intrusion and the hydrothermally altered rocks at Kutemajärvi (Fig. 2d). According to Kirkham and Sinclair (1988), the comb quartz layers form in the apical parts of felsic intrusions, in the presence of aqueous phases separated from silicate melts. Intrusions hosting the comb quartz layers commonly have a similar chemical composition characterised by SiO_2 >74 %, Na_2O >3 %, K_2O >4 %, FeO_t <2 %, TiO_2 <0.2 %, CaO <0.9 %, and MgO <0.8 % (Kirkham & Sinclair, 1988). The Pukala intrusion fits to the profile with the exception of high CaO (mean 2.15 %) and low K_2O (mean 0.8 %) contents.

5. Discussion

5.1. Geologic setting and mechanism of emplacement of the Pukala intrusion

On the basis of the geochemical and tectonic data (Kähkönen, 1989; this study), the supracrustal rocks of the TB and the Pukala intrusion formed in an is-
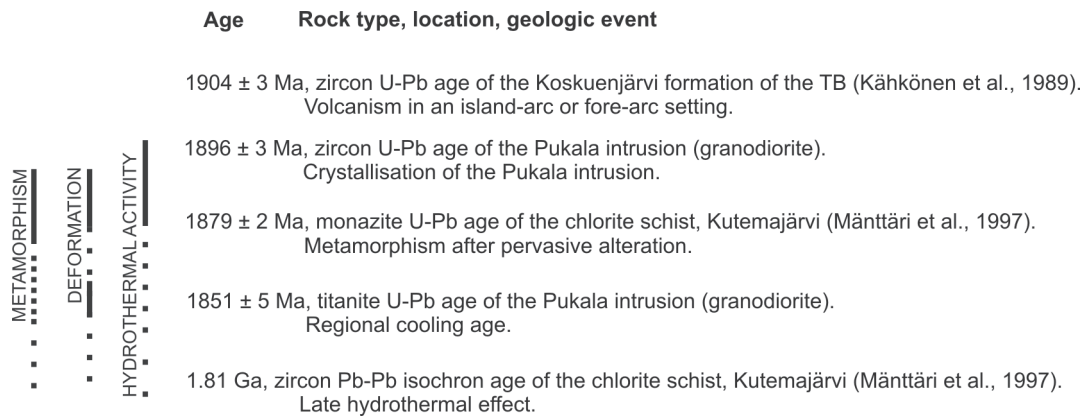
| | Age | Rock type, location, geologic event |

Age   **Rock type, location, geologic event**

1904 ± 3 Ma, zircon U-Pb age of the Koskuenjärvi formation of the TB (Kähkönen et al., 1989).
Volcanism in an island-arc or fore-arc setting.

1896 ± 3 Ma, zircon U-Pb age of the Pukala intrusion (granodiorite).
Crystallisation of the Pukala intrusion.

1879 ± 2 Ma, monazite U-Pb age of the chlorite schist, Kutemajärvi (Mänttäri et al., 1997).
Metamorphism after pervasive alteration.

1851 ± 5 Ma, titanite U-Pb age of the Pukala intrusion (granodiorite).
Regional cooling age.

1.81 Ga, zircon Pb-Pb isochron age of the chlorite schist, Kutemajärvi (Mänttäri et al., 1997).
Late hydrothermal effect.

METAMORPHISM   DEFORMATION   HYDROTHERMAL ACTIVITY

Fig. 7. Periods of metamorphism, deformation, and hydrothermal activity linked to the age data from the study area.

land-arc or fore-arc setting (Fig. 5). The absence of carbonate rocks and iron formations and the presence of turbidites indicate a steep convergent plate margin (Kähkönen, 1999).

At hypabyssal depths, magmatic stoping is the main mechanism of intrusion (Pitcher, 1978; Holder, 1979; Pitcher, 1979). The abundant xenoliths within the Pukala intrusion are compatible with this mechanism. The large difference in viscosities between low viscosity magma and high viscosity country rocks may have caused the magma to rise along large shear zones (Pitcher, 1978; Holder, 1979; Nironen, 1985), which were formed during the early stages of the Svecofennian orogeny.

The Pukala porphyry intruded into volcanic sequence at subvolcanic depths before or during the early stages of the Svecofennian orogeny (Fig. 6), ~15 Ma before the main regional metamorphic peak at ca. 1880 Ma (Mouri et al., 1999). The intrusion was probably a 1–2 km thick plate between the volcanic strata. On the basis of the stratigraphy observed today, the thickness of the volcanic rocks above the Pukala intrusion 1.90 Ga ago was 1.5–2.5 km.

5.2. Source and crystallisation of the Pukala intrusion

The Pukala intrusion shows characteristics of both S- and I-types of granitoids. The high Na content and the peraluminous nature point to a sedimentary (S-type) source, whereas the tectonic setting and the low K content are typical for I-type granitoids. It is possible that the Pukala intrusion derived from both S- and I-type sources.

The gradual contacts between different rock types suggest either fractional crystallisation of a single magma pulse or two closely related magma pulses. The granodiorite mainly forms the interior of the intrusion and the trondhjemite is commonly found near the edges. The typical compositional rim structure due to fractional crystallisation (Pitcher, 1997) is, however, not seen in the Pukala intrusion at the current erosion level.

Using the zircon saturation thermobarometry of Watson and Harrison (1983), the crystallisation temperature of the Pukala intrusion is 760–790°C (Talikka, 2003). The crystallisation was probably fast, because the temperature of a small magma chamber, such as the Pukala intrusion, decreases rapidly in the middle of cool country rocks. At subvolcanic depths, the pressure of the crystallisation was low.

5.3. Hydrothermal alteration

The periods of hydrothermal activity can be linked to the tectonometamorphic evolution of the study area (Fig. 7). We suggest that the partial silica alteration is related to the emplacement of the Pukala intrusion and

concomitant hydrothermal activity and contact metamorphism at ca. 1.90 Ga. This hypothesis is supported by the presence of several partially silicified domains in the vicinity of the southern margin of the Pukala intrusion along its whole length. Furthermore, the partial silica alteration is commonly present in the same areas (Iso-Teerijärvi, Koukkujärvi, and Kutemajärvi) as the chlorite-sericite±silica alteration.

Pervasive chlorite-sericite±silica alteration requires an extensive hydrothermal system and probably took place at epithermal depths (1.5–2.5 km) at ca. 1.90 Ga, before or during the main regional deformation phase, which occurred at ca. 1.89 Ga (Nironen 1989; Kilpeläinen, 1998). The monazite U-Pb age of 1.88 Ga from the ore related chlorite schist (Mänttäri et al., 1997) supports the timing of the alteration. The intense sericitisation, formation of quartz (± aluminium bearing) rocks and the comb quartz bands in the contact of the altered domain at Kutemajärvi and the Pukala intrusion indicate that the hydrothermal fluids were acid and probably had a magmatic origin. The small crustal component in the Pb-isotopic composition of galena, its model age (1888 Ma), and occurrence in the chlorite schist at Kutemajärvi also points to a plutonic source for the fluids (Mänttäri et al., 1997).

The sericitised shear zones may have formed when competent, partially silicified rocks were sheared and resulted in a large-scale megabreccia structure during the late stages, ~1.85 (titanite of the Pukala intrusion)–1.81 (turbid zircons at Kutemajärvi) Ga, of the regional deformation.

6. Summary and conclusions

The Pukala intrusion formed in an island-arc or fore-arc setting during the early stages of the Svecofennian orogeny. The porphyry intruded into the volcanic sequence of the Tampere Belt, resulting in a sheet-shaped pluton. The mechanism of the emplacement was magmatic stoping, which is evidenced by the abundant xenoliths.

The two main rock types of the intrusion are porphyritic granodiorite and trondhjemite; these types can be distinguished by geochemistry, petrology, and lithology. The contacts between the granodiorite and trondhjemite are gradual. During the Svecofennian orogeny, the intrusion is tilted gently towards east and steeply towards south.

The zircon U-Pb age for the Pukala intrusion is 1896 ± 3 Ma, and the titanite age of 1851 ± 5 Ma may indicate the waning stages of the Svecofennian tectonometamorphic evolution of the region. On the basis of the geochemical data, the Pukala intrusion is a volcanic arc granitoid. The magma has predominantly derived from a crustal source, although some of the trondhjemite samples show characteristics of mantle fractionates.

The Pukala intrusion was the dynamo of the hydrothermal system that resulted in the small altered domains in its country rocks to the south. This is supported by the mineral assemblages produced by alteration, geometry of the altered areas, lead isotope composition, and the presence of the comb quartz bands in the contact of the Pukala intrusion and the altered domain at Kutemajärvi.

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