Svecofennian granitic pegmatites (1.86-1.79 Ga) and quartz monzonite (1.87 Ga),
and their metamorphic environment in the Seinäjoki region, western Finland
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SVECOFENNIAN RARE-ELEMENT GRANITIC PEGMATITES OF THE OSTROBOTHNIA REGION, WESTERN FINLAND; THEIR METAMORPHIC ENVIRONMENT AND TIME OF INTRUSION

by

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Ostrobothnia is situated in western Finland along the coast of the Gulf of Bothnia. It consists of the Ostrobothnia Schist Belt, the Vaasa Migmatite Complex and part of the Central Finland Granitoid Complex, and is part of the Paleoproterozoic 1.90-1.87 Ga Svecofennian accretionary arc complex of central and western Finland. The Ostrobothnia Schist Belt consists of turbiditic metapelites exhibiting Paleoproterozoic (-Archean) provenance, and local metavolcanic rocks as interlayers. The large Central Finland Granitoid Complex, which contains syn- and post-kinematic granitoids occurs east of the schist belt and to the west of the schists are the diatexites of the Vaasa Migmatite Complex. Most of the Ostrobothnian supracrustal rocks were metamorphosed under low-pressure amphibolite facies, locally granulite facies, conditions 1.89-1.88 Ga ago. The metamorphic grade is lowest in the central and eastern parts of the Ostrobothnia Schist Belt. The grade increases towards the Vaasa Migmatite Complex and also southwards in the southern part of the schist belt.

The rare-element (RE) granitic pegmatites of the region are divided into 12 groups. All pegmatites belong to the LCT (Li,Cs,Ta) family except the Alavus NYF (Nb,Y,F) pegmatites. Most pegmatites are beryl pegmatites of the beryl-columbite subtype, but three groups belong to the spodumene subtype and one group to the albite-spodumene subtype of complex pegmatites. Two groups of the beryl-columbite subtype are topaz/andalusite- and fluorite-bearing with biotite predominant over muscovite and without tourmaline. All the RE-pegmatites of the schist belt occur in the lower to medium amphibolite facies rocks with the exception of the topaz/andalusite- and fluorite-bearing pegmatites, which are in upper amphibolite facies mica gneisses surrounding the Vaasa Migmatite Complex. The pegmatites at Alavus lie within the Central Finland Granitoid Complex.

U-Pb ages have been determined from LCT pegmatite hosted Nb-Ta minerals. Columbites from the Kaatiala, Ullava, Haapaluoma, and Korvenniemi pegmatites and tapiolite from the Seinäjoki pegmatite yielded ages between 1.80-1.79 Ga. The dated columbites are ferro- and manganocolumbites. The Alavus NYF pegmatites do not contain Nb-Ta minerals applicable for U-Pb dating. The dated monazite from these pegmatites gives an age of 1.86 Ga and, thus, these dykes may be linked to the evolution of the 1.89-1.87 Ga Central Finland Granitoid Complex. The 1.80-1.79 Ga old RE-pegmatites indicate a tectono-magmatic episode distinct from the culmination (c. 1.88 Ga) of the Svecofennian orogeny.

Key words (GeoRef Thesaurus, AGI): pegmatite, absolute age, U-Pb, columbite, monazite, metamorphism, metapelites, Svecofennian, Proterozoic, Ostrobothnia, Bothnia Belt, Seinäjoki, Finland

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INTRODUCTION

Ostrobothnia in western Finland lies roughly at the centre of the Precambrian Fennoscandian (Baltic) Shield. The main geological units of the region are (1) the marginal areas of the Central Finland Granitoid Complex in the south and east, (2) the arcuate Ostrobothnia Schist Belt in the centre, and (3) the Vaasa Migmatite Complex in the northwest (Fig. 1). All these rocks belong to the Paleoproterozoic 1.90-1.87 Ga Svecofennian accretionary arc complex of central and western Finland (Korsman et al. 1997).

The prominent Kaatiala pegmatite was probably the first pegmatite known from Ostrobothnia. It was quarried for quartz on a small scale for a long time before industrial quartz production started in 1942. The production of feldspar for the domestic ceramic industry commenced soon afterwards.

The increase of rare element (RE) prices in the 1950s resulted in exploration for RE-pegmatites in southern Finland and in Ostrobothnia, by the Geological Survey of Finland (GTK) and private enterprises. Over the next 25 years pegmatite exploration covered the whole region. Spodumene pegmatites, containing a few millions of tons of Li-ore, were traced using boulder fans in the marshy Kruunupyy-Ullava area in the northern part of the region. The Haapaluoma complex pegmatite was discovered and opened for feldspar production in 1961. Several new minor RE-pegmatite populations were detected, and the Seinäjoki tin pegmatites were found in 1979. Only two RE-pegmatite groups, namely the Haapaluoma-Kaatiala and the Seinäjoki groups, have been studied in detail (Haapala 1966, Nieminen 1978, Oivanen 1983, Nurmela 1985, Alviola 1989a).

Granitic pegmatites are classified into (1) abyssal, (2) muscovite, (3) rare-element and (4) miarolitic according to their metamorphic environment, typical minor elements, nature of their parental granites and relation to their parental granites (see Ginsburg et al. 1979, Černý 1990). Pegmatites of the rare-element class are broadly divided into three families: LCT (Li,Cs,Ta), NYF (Nb,Y,F) and a rare mixed LCT+NYF family. These are further classified into 5 types and 9 subtypes according to their rock-forming mineralogy and geochemical signature (Černý 1991, Novák and Povondra 1995) (Table 1).

About 30 major RE-pegmatite populations occur in Finland (Alviola 1989a), many of them contain several groups. Two of the groups have Archean host rocks, while others occur in a Proterozoic environment. Most of the RE-pegmatites are Paleoproterozoic in age, but the pegmatites of the anorogenic rapakivi granites are Mesoproterozoic. Prior to the present study, isotopic ages had been determined for only three of the 30 known RE-pegmatite populations.

Table 1. Classification of granitic pegmatites of the rare-element class as modified by Černý (1998).

TYPE	SUBTYPES	FAMILY
Rare-earth	Allanite-monazite	NYF
	Gadolinite	NYF
Beryl	Beryl-columbite	LCT,NYF
	Beryl-columbite-phosphate	LCT
Complex	Spodumene	LCT
	Petalite	LCT
	Amblygonite	LCT
	Lepidolite	LCT
	Elbaite	LCT
Albite-spodumene		LCT
Albite		LCT

Most of the RE-pegmatites in Finland are members of the LCT family of pegmatites, but 6 groups belong to the NYF family of pegmatites. The Kemiö pegmatite group in southwestern Finland includes some NYF pegmatites, while the remainder belong to the LCT family.

Ostrobothnia is rich in RE-pegmatites, which occur as 12 groups (Fig. 1), separated by 10-25 km wide areas sparse in pegmatites. All groups contain beryl pegmatites of the LCT family, occasionally with some columbite±phosphates. Some pegmatites in the Haapaluoma-Kaatiala, Tarikko and Seinäjoki groups are complex pegmatites with spodumene±lepidolite and Li-tourmaline. The RE-pegmatites at Seinäjoki are particularly enriched in cassiterite. The albite-spodumene pegmatites of the Kruunupyy-Ullava group contain the largest Li-concentration in Finland. The only pegmatites of the NYF family in the region occur at Alavus. The columbite-bearing topaz pegmatites along the marginal zone between the Vaasa Migmatite Complex and the Ostrobothnia Schist Belt do not fit very well into the subtype of beryl-columbite pegmatites – particularly due to their topaz and fluorite contents.

In the following, the main geological units, metamorphic zones and tectonic setting of Ostrobothnia and its RE-pegmatite groups are briefly described, and some hitherto unpublished U-Pb data on zircons and monazites are presented. U-Pb analyses of columbite, tapiolite and monazite from six RE-pegmatites representing five different RE-pegmatite groups provide further isotopic constraints. The derivation of the pegmatite-forming magmas, the time of intrusion of the granitoids and the timing of RE-pegmatite formation are then discussed in a regional context.

LITHOLOGY OF OSTROBOTHNIA

Central Finland Granitoid Complex

The large Central Finland Granitoid Complex mostly comprises granodiorites and granites (Nurmi and Haapala 1986, Nironen et al. 2000) (Fig. 1). In the context of the Svecofennian orogeny, these granitoids can roughly be divided into the following two groups (Korsman et al. 1997, Nironen et al. 2000): collision-related, foliated synkinematic tonalites and granodiorites (1.89-1.88 Ga), and porphyritic or even-grained, locally pyroxene-bearing post-kinematic granites and quartz monzonites (1.88-1.87 Ga), post-dating the main stage of crustal thickening. Adjacent to the eastern side of the Ostrobothnia Schist Belt, synkinematic granodiorites and tonalites of the Central Finland Granitoid Complex dominate.

Ostrobothnia Schist Belt

The Ostrobothnia Schist Belt (practically the same area as the Bothnia Belt, see Nironen 1997) forms an arcuate belt about 350 km long and up to 70 km wide (Fig. 1). Bedrock maps and their explanations indicate that turbiditic metapelites, often with porphyroblastic texture, are the most common rocks within the belt (Nykänen 1960a,1960b, Tyrväinen 1970, 1971, Lonka 1971, Pipping 1979, Laitala 1981, Lahti and Mäkitie 1990, Mäkitie and Lahti 1991, Mäkitie et al. 1991, Pipping and Vaarma 1992, Vaarma and Pipping 1997, Lehtonen and Virransalo, in press). There are also metavolcanic rocks, such as metalavas at Evijärvi (Vaarma and Kähkönen 1994, Vaarma and Pipping 1997) in the northern part of the belt, and porphyrite sills hosting Sb mineralizations, particularly around Seinäjoki in the south (Mäkitie and Lahti 1991).

Sheets of pegmatite granite intrusions, barren pegmatite dykes and RE-pegmatites are common rocks in the Ostrobothnia Schist Belt (e.g. Alviola 1989b), and occur most frequently in the eastern and southern parts of the schist belt. Minor orogenic intrusive rocks, mainly foliated tonalites, granodiorites and granites, occur within the belt.

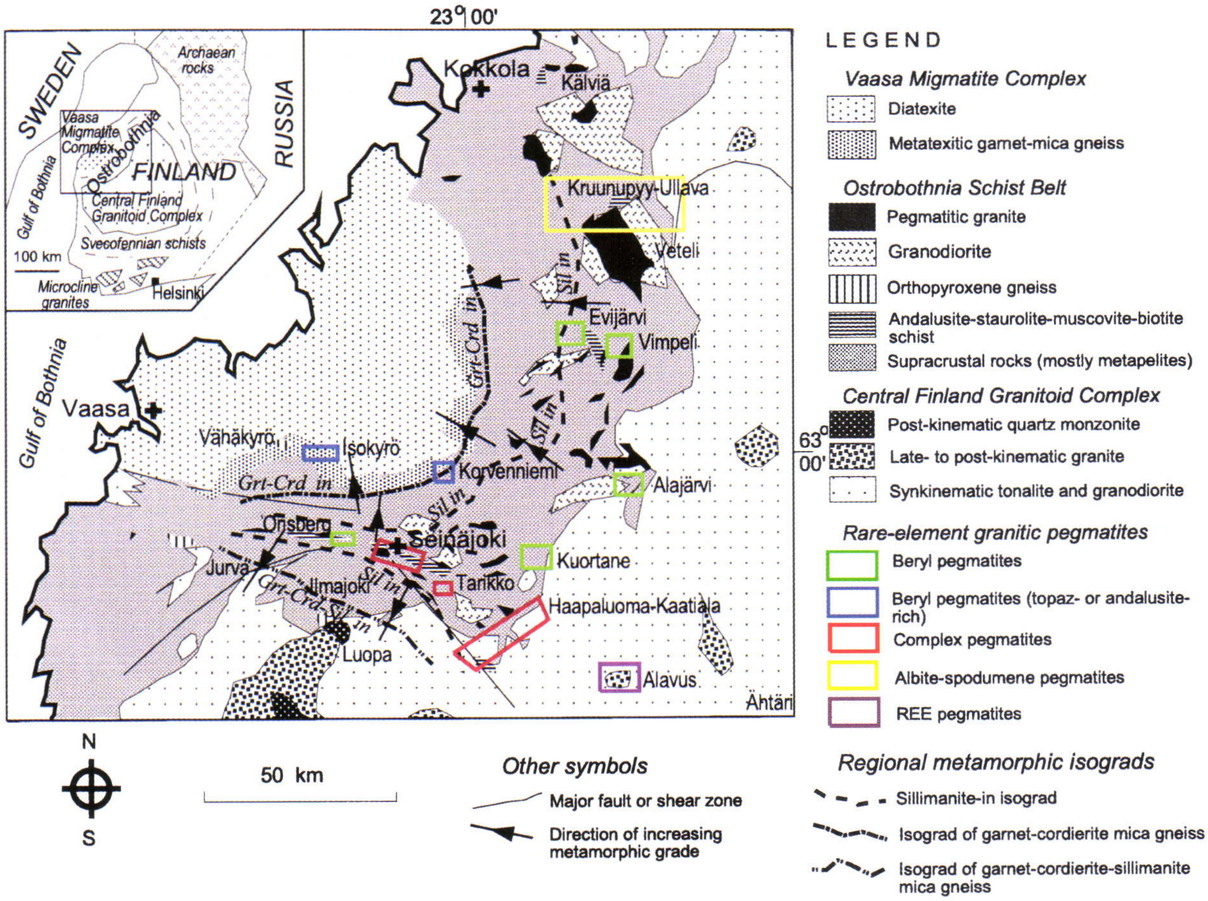

Fig. 1. Locations of the RE-pegmatite groups and the main metamorphic isograds in the Ostrobothnia Schist Belt. Abbreviations are after Kretz 1983 (map after Tyrväinen 1970, 1971, Pipping 1979, Västi 1986, Lahti and Mäkitie 1990, Mäkitie et al. 1991, Pipping and Vaarma 1992, Korsman et al. 1997, Lehtonen and Virransalo, in press).

Vaasa Migmatite Complex

A large area composed of mainly migmatitic rocks occurs north and west of the Ostrobothnia Schist Belt. These are locally granodioritic and contain leucotonalite-granodiorite veins (cf. Korsman et al. 1997). Traditionally, this area has been called the Vaasa granite (e.g. Laitakari 1942) and recently the Vaasa Granitoid Complex (Mäkitie et al. 1999). As these rocks clearly lie at the centre of a thermal dome surrounded by zones caused by regional metamorphism (Fig. 1 and the following paragraph), we have chosen to use the name Vaasa Migmatite Complex, even though some of the rocks resemble granitoids.

Biotite is usually the only mafic mineral in the rocks of the Vaasa Migmatite Complex. Garnet is a typical accessory mineral and supracrustal rock remnants are common. The southern part of the Vaasa Migmatite Complex is composed of granodioritic, peraluminous even-grained or porphyritic diatexites (Mäkitie et al. 1999). The rocks of this complex gradually change via metatexites to the mica schists of the Ostrobothnia Schist Belt.

METAMORPHISM AND TECTONICS

Metamorphism

The metamorphic grade is lowest in the central and eastern parts of the Ostrobothnia Schist Belt, where andalusite and/or staurolite-bearing muscovite-biotite schists dominate: e.g. in the Seinäjoki, Veteli and Kälviä areas (Fig. 1) (Västi 1986, Mäkitie and Lahti 1991, Vaarma and Pipping 1997). Most of the

RE-pegmatites occur within these mica schists. In metapelites, the mineral pair muscovite-quartz without sillimanite indicates low-pressure, lower amphibolite facies P-T conditions. The regional metamorphic grade increases from these mica schists towards the Vaasa Migmatite Complex and the schists change into gneisses as sillimanite becomes stable. Near Seinäjoki the regional metamorphic grade also increases towards the southwest. Thus, both on the western and southern side of the mica schist there is a sillimanite-in isograd (see Fig. 1). It is noteworthy that muscovite is usually stable in metapelites up to several kilometres on the higher temperature side of the sillimanite-in isograd.

Migmatitic mica gneisses without muscovite, but exhibiting equilibrated mineral pairs of sillimanite-K-feldspar or cordierite-K-feldspar occur on the western, northwestern and southern side of the aforementioned sillimanite-muscovite-biotite gneisses (see Mäkitie and Lahti 1991, Lundqvist et al. 1997, Vaarma and Pipping 1997). However, to the west and north these mica gneisses change over a short distance (1-3 km) into the garnet- and cordierite-bearing metatexites surrounding the Vaasa Migmatite Complex. In addition, the garnet/cordierite ratio of the gneisses increases towards these migmatites. Sillimanite is rare, probably because it was a component in the dehydration reactions that formed garnet, cordierite and K-feldspar. Hercynite occurs locally. The garnet-cordierite pair in the rocks indicates metamorphic P-T conditions of the upper amphibolite facies.

Fig. 2. Migmatitic garnet mica gneiss; the country rock of the Korvenniemi columbite-fluorite-topaz pegmatite. Korvenniemi RE-pegmatite group. x = 6994200, y = 2449420. Photo: H. Mäkitie.

The metatexitic mica gneisses in the boundary zone between the Vaasa migmatites and the Ostrobothnian schists are usually characterized by intense retrograde metamorphism. For example, cordierite is decomposed into andalusite and pinite; there has been muscovitization and chloritization in places; and garnet is partly decomposed into biotite. These rocks, usually migmatitic, are the country rocks of the Korvenniemi and Isokyrö RE-pegmatites (Fig. 2).

Southwest of Seinäjoki there are migmatitic garnet-cordierite-sillimanite mica gneisses (Mäkitie 1999). In addition to the abundance of sillimanite, these mica gneisses differ from the garnet-cordierite mica gneisses because they contain relatively well preserved bedding structures.

Compositionally intermediate, locally psammitic orthopyroxene-bearing gneisses indicating granulite facies metamorphism occur in the southern part of the Ostrobothnia Schist Belt, especially at Vähäkyrö, western Jurva and southern Ilmajoki (Fig. 1). In these areas the metapelites are migmatitic garnet-cordierite mica gneisses with or without sillimanite. The Luopa quartz monzonite, some 20 km south of Seinäjoki, is surrounded by a narrow granulite-grade contact aureole that overprints regional metamorphism (Mäkitie and Lahti 1991).

Tectonic setting and deformation

In the Svecofennian orogeny, the closure of the Bothnian basin, which, in fact, refers to the central part of the Svecofennian Domain, was associated with intense deformation and migmatization of their greywacke and argillaceous sedimentary fill (Gaál and Gorbatschev 1987). Furthermore, post-collisional crustal thickening in the Svecofennian Domain eventually resulted in the formation of crustal melts that were mainly emplaced in the sedimentary rocks of the Bothnian basin. Nironen (1997) recently modelled the evolution of the whole Svecofennian orogeny as a progressive accretion of two arc complexes to the Archean craton between 1.91 and 1.87 Ga.

Discordant U-Pb zircon data (Fig. 3, Table 2) with $^{207}Pb/^{206}Pb$ ages in excess of 2.1 Ga from a migmatitic, partially melted garnet-cordierite-sillimanite mica gneiss at Mannilankallio, Ilmajoki, probably indicate the presence of both Archean and Paleoproterozoic grains (Huhma et al. 1991, Mäkitie and Lahti 1991). U-Pb zircon analyses from the Routakallio porphyrite sill at Seinäjoki (Table 2) indicate a Svecofennian age (c. 1.9 Ga) of emplacement into mica schists for this metavolcanic rock (see also Mäkitie and Lahti 1991).

Regional metamorphism was attained in Ostrobothnia 1.89-1.88 Ga ago (e.g. Vaasjoki 1996). A rather discordant monazite U-Pb determination from the aforementioned mica gneiss at Mannilankallio, 20 km SW of Seinäjoki, has a $^{207}Pb/^{206}Pb$ age of c. 1.86 Ga and sets a minimum age for the formation of the monazite either during pelite metamorphism or cooling of the crust below c. 520 °C (Mäkitie and Lahti 1991, see also Smith and Barreiro 1990) (Fig. 3, Table 2). The age estimate is in agreement with the age of the regional metamorphic peak.

Most of the plutonic rocks in Ostrobothnia are synkinematic relative to the main stage of deformation. The U-Pb ages for synkinematic granitoids within the Ostrobothnia region are as follows: c. 1.89 Ga for a

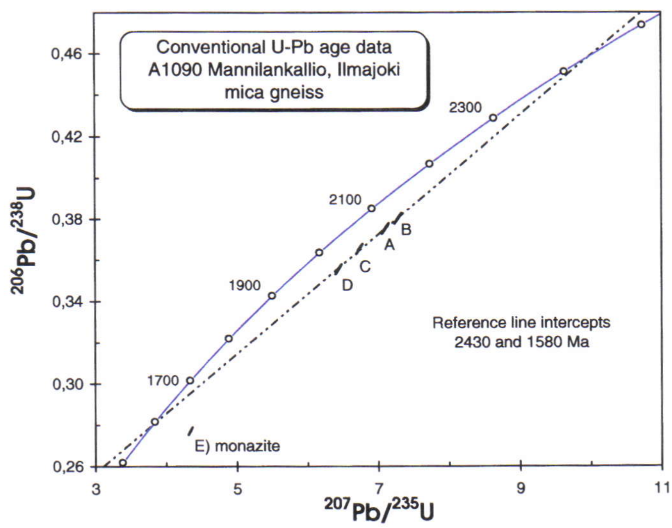

Fig. 3. Concordia diagram for analysed zircon and monazite fractions from a partially melted garnet-cordierite-sillimanite mica gneiss, Mannilankallio area.

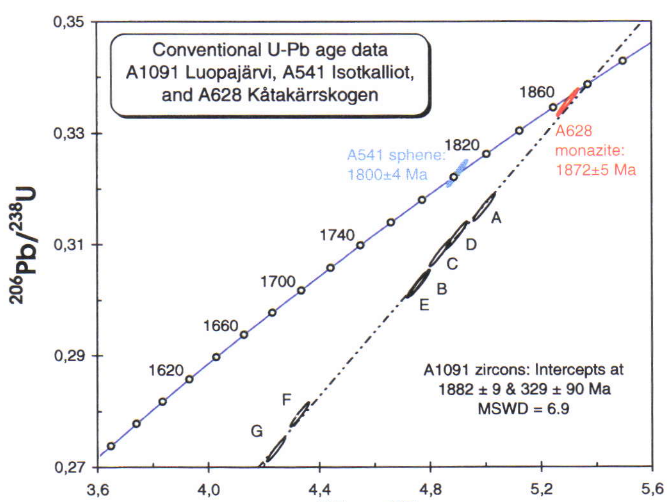

Fig. 4. Concordia diagram for analysed zircon fractions from the Luopajärvi tonalite and of sphene fractions from the Isotkalliot pegmatite, and monazite fractions of the granodioritic rock (diatexite) of Kåtakärrskogen.

gneissose granodiorite at Vimpeli (Kouvo and Tilton 1966); 1886±10 Ma for a synorogenic granite in the Ähtäri area c. 15 km southwest of the schist belt (Huhma 1986); 1882±9 Ma for the Luopajärvi tonalite at Jalasjärvi (Fig. 4, Table 2, see also Mäkitie and Lahti 1991) and 1883±6 Ma for a gneissose tonalite in the Evijärvi area, in the central part of the belt (Vaasjoki et al. 1996). However, the Evijärvi sample also contains older zircon populations (Vaasjoki et al. 1996) and ion-probe (NORDSIM) work has demonstrated the presence of Archean cores in some zircons (Vaasjoki et al. 1998).

The migmatites in the Vaasa Migmatite Complex are probably 1.89-1.88 Ga old because regional high-grade metamorphism and migmatization surrounding the complex was clearly associated with the culmination of the Svecofennian orogeny and the emplacement of the Svecofennian 1.89-1.88 Ga synkinematic granitoids (e.g. Vaasjoki 1996).

The quartz monzonite of Luopa (1872±2 Ma) in the southern part of the Ostrobothnia Schist Belt belongs to a suite of post-kinematic rocks in the Central Finland Granitoid Complex (Nironen et al. 2000, Mäkitie and Lahti, this volume). Pegmatites at Kälviä in the northern Ostrobothnia Schist Belt (see Wetherill et al. 1962) also clearly record a post-kinematic event.

A U-Pb monazite age of 1872±5 Ma (Fig. 4, Table 2) for a granodioritic rock from the Vaasa Migmatite Complex in the Kåtakärrskogen area, 10 km east of the town of Vaasa, is interpreted by the authors to indicate the cooling of crust below c. 600 °C. In addition, a U-Pb age of c. 1.84 Ga for sphene from a gneissose tonalite at Evijärvi indicates regional cooling of the crust below 500 °C (Vaasjoki et al. 1996), as probably does also the previously mentioned monazite age result for mica gneiss from Mannilankallio. The U-Pb sphene age 1800±4 Ma reported from the Isotkalliot quartz-rich pegmatite vein at Nurmo (Mäkitie and Lahti 1991) (Fig. 4, Table 2) is much younger than the aforementioned sphene from the gneissose tonalite in the Evijärvi area.

The Ostrobothnia region has undergone polyphase deformation: four deformation phases have been reported from the Evijärvi area (Vaarma and Pipping 1997) and five deformation phases at Seinäjoki (Mäkitie 1999). In both areas, the development of the S_2 schistosity has involved the synkinematic metamorphic growth of micas. Generally, the fold axes in the Ostrobothnia Schist Belt trend E-W and the region includes axial culmination and depression zones (Saksela 1935). Unfortunately, structural analysis remains to be carried out on large areas of Ostrobothnia.

In the Seinäjoki area, the pegmatite granites and associated pegmatite dykes cut the main foliation (S_2); however, some pegmatites also cut D_3 structures (Fig. 5a) (Mäkitie 1999). Many pegmatites are deformed (e.g. the cassiterite dyke of Pajuluoma in the town of Seinäjoki) and some are folded by the D_5 deformation

a) b)

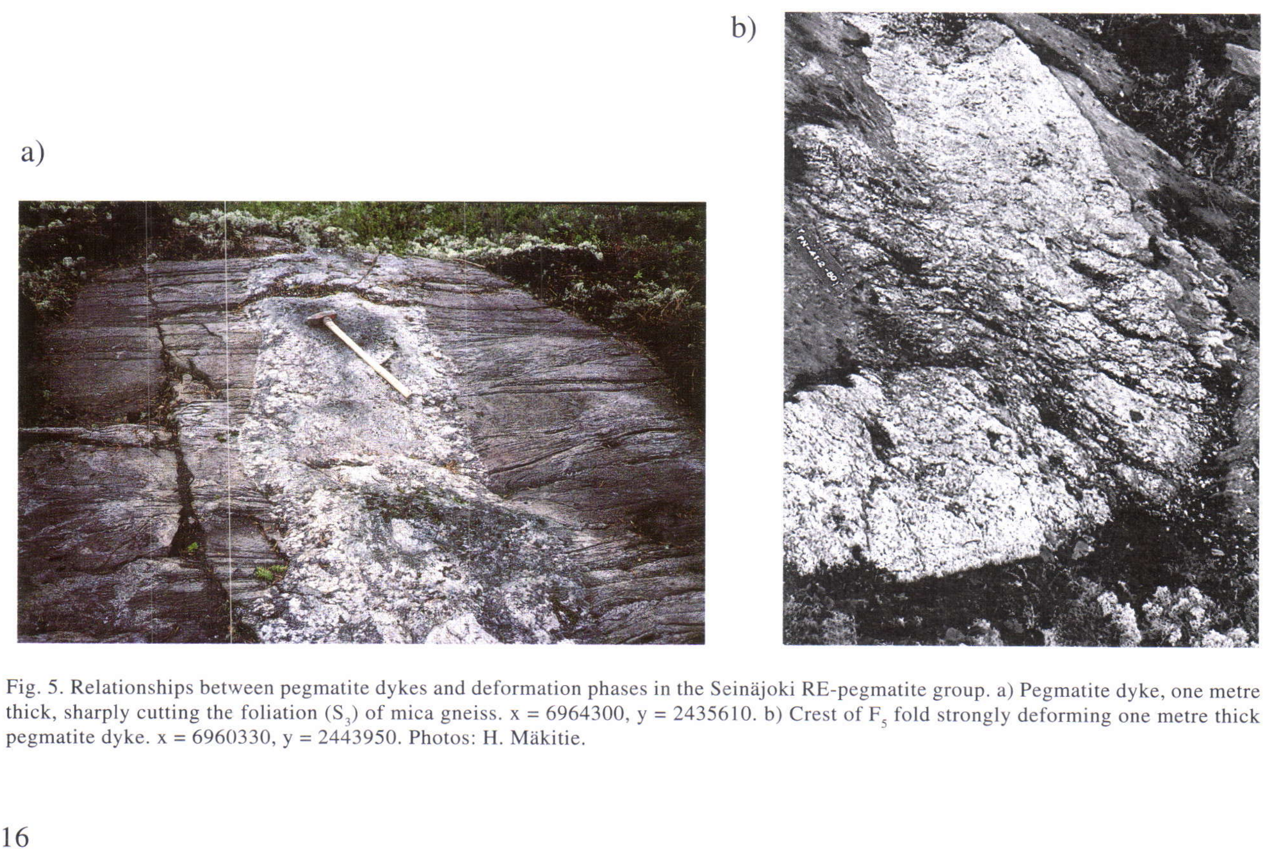

Fig. 5. Relationships between pegmatite dykes and deformation phases in the Seinäjoki RE-pegmatite group. a) Pegmatite dyke, one metre thick, sharply cutting the foliation (S_3) of mica gneiss. x = 6964300, y = 2435610. b) Crest of F_5 fold strongly deforming one metre thick pegmatite dyke. x = 6960330, y = 2443950. Photos: H. Mäkitie.

Table 2. U-Pb isotopic age data from western Finland.

Sample information	U	Pb	$^{206}Pb/^{204}Pb$	ISOTOPIC RATIOS[a,b]			APPARENT AGES / Ma (±2sigma)		
Analysed mineral / fraction		ppm	measured	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
A1019 Routakallio, Seinäjoki, plagioclase porphyrite									
A) zircon d>4.5	175	56	6055	0,3208	5,089	0,1150	1793	1834	1880
B) zircon d: 4.3-4.5	289	91	7457	0,3153	5,033	0,1158	1766	1824	1892
C) zircon d>4.5, abraded	180	58	5228	0,3218	5,120	0,1154	1798	1839	1886
A1090 Mannilankallio, Ilmajoki, mica gneiss									
A) zircon d>4.5	261	105	14070	0,3754	7,101	0,1372	2054	2124	2192
B) zircon d>4.5, abraded	266	109	13980	0,3803	7,281	0,1389	2077	2146	2213
C) zircon d: 4.3-4.5	503	196	12400	0,3654	6,732	0,1336	2007	2076	2146
D) zircon d: 4.2-4.3	877	332	9276	0,3556	6,437	0,1313	1961	2037	2115
E) monazite	8612	5893	50170	0,2772	4,340	0,1135	1577	1700	1857±6
A1091 Luopajärvi, Jalasjärvi, tonalite									
A) zircon d: 4.3-4.5, +100mesh, abraded	669	224	8595	0,3167	4,996	0,1144	1773	1818	1870
B) zircon d:4.3-4.5, +100mesh	689	221	6821	0,3031	4,763	0,1140	1706	1778	1864
C) zircon d:4.2-4.3, +100mesh	831	271	6766	0,3085	4,837	0,1137	1733	1791	1859
D) zircon d:4.2-4.3, +100mesh, red	941	312	5008	0,3117	4,896	0,1139	1748	1801	1863
E) zircon d:4.2-4.3, +100mesh, white	808	258	8767	0,3028	4,754	0,1139	1705	1776	1862
F) zircon d:4.0-4.2, +100mesh, red	1190	352	5610	0,2795	4,329	0,1124	1588	1698	1838
G) zircon d:4.0-4.2, +100mesh, white	1031	298	6996	0,2732	4,243	0,1127	1556	1682	1843
A541 Isotkalliot, Seinäjoki, pegmatite[c]									
sphene	187	64	822	0,3227	4,896	0,1101	1802	1801	1800±4
A628 Kåtakärrskogen, Vaasa, granite[c]									
monazite	2218	644	53866	0,3353	5,295	0,1145	1864	1868	1872±5

a) Isotopic ratios corrected for fractionation, blank (500 pg) and age related common lead (Stacey & Kramers 1975).
b) Errors for Pb/U and $^{207}Pb/^{206}P$ ratios are less or equal than 0.8% and 0.25%, respectively.
c) Analyses by Dr. Olavi Kouvo, GTK.

(Fig. 5b). The ages of these relatively young deformations are not known.

At Seinäjoki, pegmatites in the mica schists have a greater tendency to be parallel to the foliation than those in more massive rocks such as plagioclase porphyrites (Nurmela 1985). According to Mäkitie (1999) the structure of the country rocks of the Seinäjoki RE-pegmatites is characterized by a large antiform in which S_2, S_3 and S_5 have almost parallel trends. It is probable that suitable extensional sites for pegmatite emplacement formed during the development of this antiform.

Haapala (1966, 1983) reported that the Haapaluoma pegmatite sharply intersects the lineation of its granodioritic country rock and that deformed pegmatites occur in the Haapaluoma-Kaatiala area. According to Vaarma and Pipping (1997), pegmatites at Evijärvi intersect local S_2 schistosity and their emplacement was probably synkinematic with D_3 and/or D_4.

Several faults and shear zones traverse Ostrobothnia (Fig. 1; see also Talvitie et al. 1975, Tyrväinen 1984, Korsman et al. 1997). Schollen migmatites occur in these shear zones. Locally, the foliation trends of rocks differ on different sides of the major shears which probably indicates that the zones are young (Tyrväinen 1984).

PEGMATITE GRANITES AND RE-PEGMATITE GROUPS

Most of the RE-pegmatites, particularly those containing spodumene, lie in the northern and southeastern parts of the Ostrobothnia Schist Belt (Fig. 1). A few beryl/beryl-columbite(± phosphate) pegmatite groups occur in the centre of the schist belt. Topaz/andalusite-bearing pegmatites are concentrated along the margin of the Vaasa Migmatite Complex, and the Alavus NYF-pegmatite group lies within the Central Finland Granitoid Complex. During the last decades, pegmatite exploration has been intensive in the southern and the northern parts of Ostrobothnia (Fig. 1). It is anticipated that more beryl pegmatites will be discovered especially from Evijärvi and Vimpeli around the Vimpeli pegmatite granites, in central Ostrobothnia.

Practically all of the RE-pegmatites within the Ostrobothnia Schist Belt are tourmaline-bearing with muscovite predominanting over biotite. The only exceptions are the topaz-bearing Isokyrö and Korvenniemi pegmatites where biotite clearly predominates over muscovite, and tourmaline is absent. The Alavus group pegmatites that occur outside the schist belt are also biotite pegmatites, but without tourmaline.

The Haapaluoma-Kaatiala group lies in the southeastern bend of the Ostrobothnia Schist Belt. The host rock of the pegmatites is usually a foliated tonalite/granodiorite. About 20 RE-pegmatites occur in the

Table 3. Classification (after Černý 1998, see also Table 1) of the Ostrobothnian RE-pegmatites. Characteristic rare minerals and country rocks of the RE-pegmatite groups are listed. Mineral abbreviations are after Kretz (1983) with the following additions: Amg = amblygonite, Clb = columbite, Tap = tapiolite, Trp = triphylite and Frg = fergusonite.

PEGMATITE TYPE	PEGMATITE SUBTYPE	PEGMATITE GROUP	CHARACTERISTIC RARE MINERALS IN THE PEGMATITES	COUNTRY ROCKS OF THE PEGMATITES
Rare-earth	Allanite-monazite	Alavus	Frg, Mnz, Aln	Granite & foliated tonalite
Beryl	Beryl-columbite	Vimpeli	Brl, Clb	St-Ms-Bt schist
		Orisberg	Brl, Clb	And-Ms-Bt schist
		Isokyrö	Toz, And, Clb	Grt(-Crd)-Bt gneiss
		Korvenniemi	Toz, Fl, Clb	Grt(-Crd-Hc)-Bt gneiss
	Beryl-columbite-phosphate	Evijärvi	Brl, Clb	St-Ms-Bt schist
		Kuortane	Brl, Clb, Trp	Foliated granodiorite & Ms-Bt gneiss
		Alajärvi	Brl, Clb, Trp	Foliated tonalite & Ms-Bt schist
Complex	Spodumene (with rare amblygonite pegmatites)	Haapaluoma-Kaatiala	Spd, Lpd, Elb, Brl	Foliated granodiorite & Sil-Ms-Bt gneiss
		Seinäjoki	Cst, Brl, Clb, Tap, Spd	And-Ms-Bt schist & metavolcanic rock
		Tarikko	Cst, Brl, Spd, Clb	Sil-Ms-Bt gneiss & And-Ms-Bt schist
Albite-spodumene		Kruunupyy-Ullava	Spd, Clb, Brl	And-Ms-Bt schist & metavolcanic rock

area and three of them have been studied in detail. These are the Hunnakko, Haapaluoma (Haapala 1966) and Kaatiala (Nieminen 1978) complex pegmatites. Of these, the large (30 m x > 200 m), almost horizontal (dip 15° NE) Kaatiala dyke is a spodumene pegmatite; the smaller (5 m x 70 m) Hunnakko dyke is an amblygonite pegmatite and the largest, the Haapaluoma dyke (10-30 m x 500 m, dip 50-60° N), is a spodumene-lepidolite subtype pegmatite. All other pegmatites are beryl pegmatites with or without columbite/tapiolite, except one dyke with red tourmaline and some lepidolite. The Haapaluoma dyke is a highly fractionated pegmatite with pollucite, but it is slightly similar to NYF pegmatites in character as indicated by accessory xenotime, monazite-cheralite and brockite. Altogether 48 minerals have been identified from the Haapaluoma-Kaatiala pegmatites. The Kaatiala pegmatite was extensively quarried during 1942-1968. It produced 160 000 tons of K-feldspar, 30 000 tons of quartz and a few tons of beryl and columbite. The Haapaluoma quarry was in operation during 1961-1998 and about 350 000 tons of K-feldspar were produced.

The pegmatite granites, i.e. pegmatite-generating granites, occur north of the Haapaluoma-Kuortane pegmatite population. Pegmatite granites contain coarse-grained pegmatitic patches or veins occasionally with a few beryl crystals.

The Seinäjoki, Tarikko and Orisberg groups occur at 10-15 km intervals in metasedimentary and metavolcanic rocks within the southern part of the schist belt, c. 20 km NW of the Haapaluoma-Kaatiala group (Fig.1). About 60 RE-pegmatites of the Seinäjoki group (Oivanen 1983, Nurmela 1985, Alviola 1986) lie between two sets of elongated pegmatite granite bodies. Barren and beryl pegmatites occur within and close to the pegmatite granites, whereas beryl-columbite or beryl-tapiolite pegmatites

a) b)

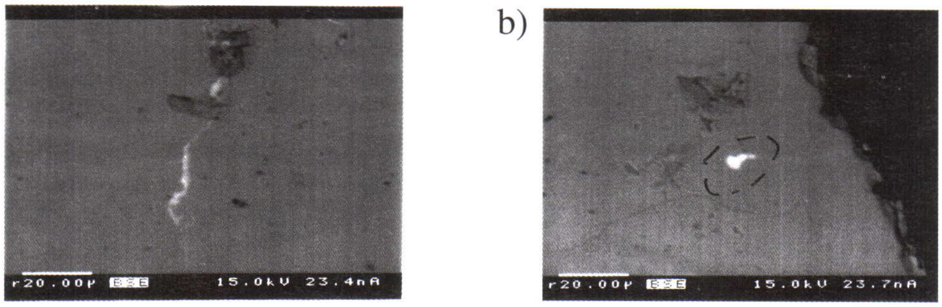

Fig. 6. Backscatter electron images of the dated columbites. a) Uranium-rich crack (light-coloured line in the centre of the Figure) in ferrocolumbite from the Kaatiala pegmatite. b) Uranium-, calcium- and titanium-bearing inclusion (marked by broken lie) in ferrocolumbite from the Korvenniemi pegmatite. Photos: B. Johanson.

with or without phosphates lie further away. Cassiterite-bearing beryl-columbite pegmatites occur in the centre of the pegmatite swarm, as do also the more south-easterly spodumene-bearing complex pegmatites. Altogether 47 minerals have been identified from the pegmatites at Seinäjoki. The Perälä cassiterite-bearing dykes are estimated to contain 100 000 tons of pegmatite with 0.3 % Sn to a depth of 100 m (Saltikoff 1982).

Long (0.1 km-3 km), narrow (20 m-200 m) pegmatite granite bodies at Seinäjoki contain numerous pegmatite veins running parallel, diagonally and at right angles to the contacts. Most of them are barren, but many are beryl-bearing and at least one of them is columbite-bearing. Usually the pegmatite granites are very coarse-grained with reddish or bluish phenocrysts of graphic feldspar up to 2 m in size. The matrix consists of K-feldspar, plagioclase, quartz, muscovite, crow-foot biotite, black tourmaline, garnet, apatite and arsenopyrite/löllingite. In places the pegmatite granite is fine- to medium-grained and banded with alternating aplitic (feldspar- and quartz-rich), and tourmaline- and garnet-rich bands.

There is a small group of RE-pegmatites at Tarikko (Alviola 1987). There are a few beryl-bearing pegmatites and one complex pegmatite of the spodumene subtype with accessory beryl, columbite, cassiterite, triphylite and alluaudite. The small Orisberg group consists of about half a dozen of beryl-pegmatites and two beryl-columbite pegmatites.

The Kuortane group RE-pegmatites are rather primitive beryl-columbite pegmatites with triphylite and some secondary phosphates e.g. strunzite.

The RE-pegmatites of the Kruunupyy-Ullava group are believed to belong to the albite-spodumene group of RE-pegmatites. These pegmatites and their exploitation were investigated for 30 years by a private company, but very little information has been published (Boström 1988). The dykes are 200-400 m long, some of them are very narrow, but others up to 10-20 m wide. In this marshy area the thickness of overburden is 2-10 m, and none of the dykes were originally exposed. However, the area is rich in erratic boulders of pegmatite, some of them barn-sized. The number of traced dykes is at least half a dozen. Li-ore

Table 4. Microprobe analyses of the dated columbite-tantalites from the RE-pegmatites.

PEGMATITE GROUP / host rock	columb.-tant. generation	FeOtot wt%	MnO wt%	MgO wt%	Nb_2O_5 wt%	Ta_2O_5 wt%	SnO_2 wt%	TiO_2 wt%	Sc_2O_5 wt%	U_2O_3 wt%	Total
ULLAVA R5 / gneiss	several										
average of 14 points in 3 grains		4,84	**14,46**	0,00	**64,17**	15,19	0,02	0,55	0,01	0,12	99,36
range		3.05-6.19	13.12-16.30	0.00-0.03	62.52-66.23	13.52-16.26	0.00-0.06	0.39-0.75	0.00-0.06	0.00-0.43	
KORVENNIEMI / mica gneiss	first										
average of 12 points in 4 grains		**11,83**	8,33	0,02	**71,11**	2,61	0,03	2,31	0,03	0,18	96,45
range		9.78-12.89	7.29-10.45	0.00-0.06	68.99-73.11	2.29-3.18	0.00-0.08	1.34-2.82	0.00-0.13	0.00-0.54	
SEINÄJOKI (Routakallio) * / pl. porphyrite	first										
average of 40 points in 6 grains		**13,18**	3,51	0,18	**42,72**	37,11	0,70	2,18	0,06	0,19	99,83
range		12.75-13.62	3.31-3.80	0.12-0.23	39.28-47.08	33.51-44.18	0.40-0.92	1.67-2.67	0.01-0.11	0.00-0.45	
SEINÄJOKI (Perälä W) * / mica schist	first										
average of 13 points in 2 grains		**9,22**	7,92	0,01	**43,51**	39,43	0.21	0,26	0,04	0,07	100,46
range		8.84-9.83	7.36-8.44	0.00-0.07	40.09-45.41	38.01-42.47	0.09-0.38	0.20-0.34	0.00-0.09	0.00-0.27	
KAATIALA / granodiorite	early										
average of 9 points in 3 grains		**13,56**	5,83	0,07	**69,47**	7,40	0,02	2,07	0,25	0,22	98,89
range		13.24-14.02	5.59-6.11	0.05-0.12	68.17-69.87	7.19-7.64	0.00-0.12	1.87-2.36	0.23-0.30	0.05-0.47	
HAAPALUOMA / granodiorite	early										
average of 15 points in 5 grains		5,30	**13,74**	0,00	**68,97**	8,34	0,28	1,53	0,84	0,28	99,28
range		2.70-5.98	12.75-16.55	0.00-0.01	67.97-71.05	8.20-8.54	0.00-0.46	1.27-1.60	0.77-0.90	0.11-0.47	

* These columbites were not dated (the dated Nb,Ta-mineral from the Seinäjoki pegmatites was TAPIOLITE).

reserves are a few million tons of spodumene-bearing pegmatite with about 1 % Li_2O. In addition to greenish and reddish spodumene, the dykes are known to contain feldspars, quartz, muscovite, accessory garnet, apatite, black tourmaline, triphylite, mangano-columbite, and trace beryl, amblygonite and bismuth.

The Kruunupyy-Ullava pegmatite dykes occur between three large granite-pegmatite granite intrusions. The southernmost of them, the Kaustinen pegmatite granite, is known to contain many pegmatitic pods. Some of them are beryl-bearing, but a few contain spodumene and a little triphylite.

The RE-pegmatites of the Alajärvi group lie south of the Alajärvi pegmatite granites. The pegmatite granites contain many pegmatitic pods, but all are barren. A few RE-pegmatites occur in three areas: 1) at Soini; a beryl pegmatite dyke rich in black tourmaline, 2) at Jyrkäys; a 10 m wide beryl-columbite pegmatite, and 3) at Kirkkokallio; a beryl-pegmatite with Fe,Mn-phosphates.

Almost twenty pegmatite granite bodies occur c. 30 km north and northwest of Alajärvi. At least some of the bodies are flat-lying, sheet-like intrusions. Barren pegmatites adjacent to them are rich in black tourmaline containing 10-25 % of schorl. A few beryl-columbite pegmatites, the Evijärvi group, with or without Li,Fe,Mn-phosphates were recently discovered unexpectedly northwest of the pegmatite granites, and southeast of the pegmatite granites, the Vimpeli group.

Near Isokyrö and Korvenniemi, in the boundary zone between the Vaasa Migmatite Complex and the Ostrobothnia Schist Belt, there are about half a dozen RE-pegmatites. These pegmatites are flat-lying, topaz- or andalusite- and fluorite-bearing, and, in particular, there is clearly more biotite than muscovite. The Isokyrö group pegmatites contain accessory beryl and columbite. There is light brown and diamond-shaped accessory muscovite and greenish yellow topaz crystals that are usually enveloped with brownish mica. West of Isokyrö, there are small andalusite-bearing pegmatites. These contain reddish gray, elongated crystals of andalusite up to 10 cm long, and some slightly altered cordierite crystals. Accessory minerals are muscovite, columbite and microlite. Large (100 x 40 m) pegmatites of the Korvenniemi group are more zoned than the Isokyrö dykes. Pinkish and fine- to medium-grained muscovite is present only in the coarse-grained K-feldspar cores, which are surrounded by quartz-topaz-microcline-plagioclase pegmatite with green and brown fluorite. Topaz crystals are subhedral, bluish-white in colour and 5-10 cm in diameter. In the presence of albitic 'sugary' plagioclase, the topaz crystals are surrounded by a greenish rim of fibrous mica. K-feldspar is in places amazonitic and graphic feldspar is absent. Accessory minerals are ferrocolumbite, apatite, garnet and pyrite.

The Alavus RE-pegmatite group occurs on either side of the border of the Alavus and Töysä parishes. About a dozen 1-10 m wide almost horizontal pegmatites occur in the vicinity of the Alavus microcline granite and one dyke lies within the granite. Most dykes are biotite pegmatites with accessory allanite crystals. Two of them have been quarried for feldspar in the 1980s. A few grains of fergusonite and monazite were found in the dumps of an abandoned quarry, located at the endocontact of the Alavus granite, and a few grains of allanite from another abandoned quarry.

The mineralogical characteristics and country rocks of the RE-pegmatite groups of Ostrobothnia are summarized in Table 3.

U-Pb DATING OF PEGMATITES

Radiometric dating of pegmatites in Precambrian areas has been problematic, as most traditional dating methods have often yielded results that, generally, have been of little value because of large analytical uncertainties. The main reason has been the nature and geological history of the available sample material. Thus, for example, zircon U-Pb data from pegmatites are very often discordant, which probably arises because the zircons were hydrated during crystallization and, as their lattices were originally distorted, were consequently more susceptible to lead loss by diffusion than ordinary zircons.

In a similar manner, precise U-Pb dating of sphene has often been hindered by the very high initial lead contents of the sample material, which has caused precise age estimates to depend on the isotopic composition chosen for the common lead correction. Determinations made with other isotopic systems, such as Rb-Sr and K-Ar, have proven unsatisfactory partly because of the uncertain closure temperatures of the minerals employed, and partly because of the effects of prolonged weathering on their isotopic systems.

In the 1990s, it became apparent that the columbite-tantalite series as well as Nb,Ta-minerals occurring in complex pegmatites may contain appreciable amounts of uranium and are thus amenable for U-Pb dating (Romer and Wright 1992). Furthermore, experience (e.g. Romer and Smeds 1994, Romer et al. 1996) has shown that the results from these minerals are very often practically concordant, and thus the results obtained are rather precise.

Sample material

Various Nb,Ta-minerals were selected from different RE-pegmatite occurrences of Ostrobothnia for U-Pb dating. Monazite was used for the Alavus pegmatite, as fergusonite gave discordant ages. The Seinäjoki group is the only one where tapiolite was discovered. In the other groups columbite was used in age determination. The dated columbites have been analysed using a Cameca SX 50 electron microprobe at the Geological Survey of Finland and their chemical compositions are reported in Table 4.

The dated samples have usually been taken from large pegmatites. Manganocolumbite from the Kruunupyy-Ullava group is from the Länttä dyke at Ullava, which is the largest of the spodumene pegmatites. The sample is from a heavy mineral concentrate from drill hole 5/63. Backscatter electron (BSE) images indicate that the Ullava manganocolumbite is homogeneous in composition. The marginal parts of some grains contain inclusions of manganocolumbite with somewhat higher Ta-content.

The sample from Korvenniemi is a fragment of a single ferrocolumbite crystal from the largest pegmatite. The ferrocolumbite is inhomogeneous in composition, and contains small irregular patches with higher Mn-content and Ta-content. One U-Ca-Ti-bearing inclusion was detected.

The Haapaluoma columbite is a homogeneous manganocolumbite. The U-content is rather high (average 0.27 wt% U_2O_3), but no U-mineral inclusions were detected. Some cassiterite inclusions were found on grain margins. The Haapaluoma sample is in fact the Sc-bearing manganocolumbite$_I$ described by Haapala (1966). Columbite$_I$ crystallized with black tourmaline, cassiterite, albite and quartz in Na-replacement bodies. Needle-form Li-stage columbite gave discordant ages and was rejected.

The Kaatiala columbite represents also an early generation, which occurs as large platy crystals and is homogeneous ferrocolumbite in composition. The U-content (0.22 wt% U_2O_3) is roughly the same as that of the Haapaluoma mangano-columbite, but rare micron-sized U-mineral spots and fracture fillings were noted in BSE images (Fig. 6a).

The Alavus samples are from an abandoned feldspar quarry in the largest RE-pegmatite of the group. A U-rich fergusonite was rejected because it gave discordant ages and a monazite from the same pegmatite was used instead.

Analytical methods

For U-Pb dating, columbite and tapiolite grains were crushed and some fragments with fresh surfaces selected. Unleached and HF (5%, 10% and 20%) leached fractions were washed with a HNO_3-HCl-H_2O mixture in an ultrasonic bath. Sample dissolution was carried out in steel jacketed 0.3 ml Savillex® capsules or 2 ml Savillex® beakers. Aliquoting of the sample was done directly from the HF-solution to avoid the formation of some unsoluble complexes with HCl (methods described in Romer and Wright 1992). Monazite and fergusonite dissolution followed the procedure described by Krogh (1973).

A ^{235}U- ^{208}Pb-tracer was added to the aliquoted liquids. Uranium and lead were extracted using anion-exchange chromatography and uranium extracted from columbites and tapiolites were further purified with anion-exchange in HNO_3-form (Romer and Wright 1992). For isotopic composition measurement, lead was loaded on a single Re-filament (silica gel - phosphoric acid-mixture), and for concentration measurements lead and uranium (phosphoric acid) were loaded as a triple filament system (Pb on a centre Re-filament and U on a Ta-side filament). Based on multiple runs of SRM981 and U500 standards, the measured Pb and U ratios were corrected for mass fractionation of 0.12%/amu and 0.14%/amu, respectively.

U-Pb isotopic results

U-Pb data from the Kaatiala, Seinäjoki, Ullava and Haapaluoma columbites and tapiolites share some characteristics (Table 5): the U-Pb data from slightly (5% HF) leached and unleached fractions scatter on the

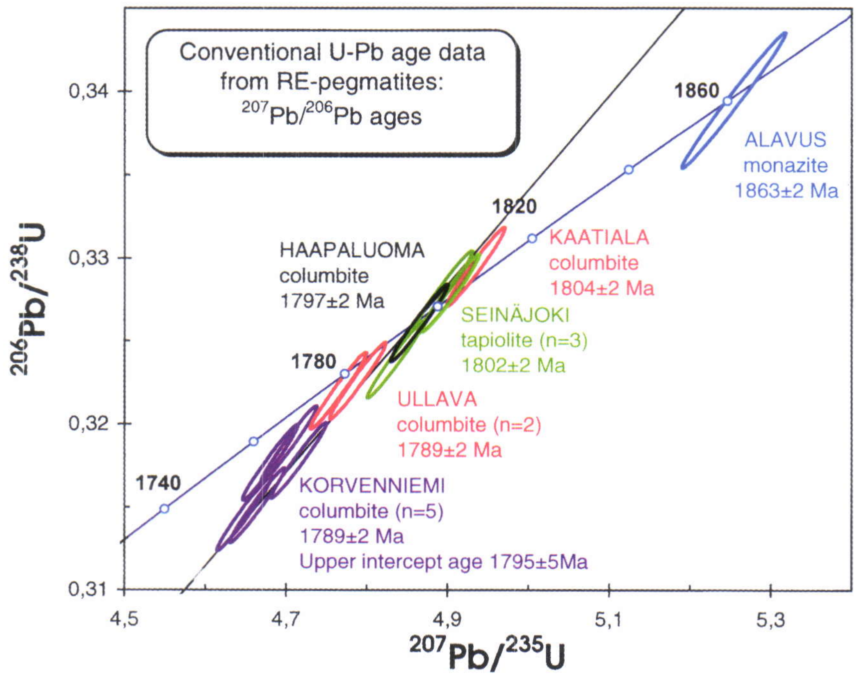

Fig. 7. Concordia diagram for analysed columbite, tapiolite and monazite fractions taken from the Ostrobothnia RE-pegmatites.

Table 5. U-Pb isotopic age data from RE-pegmatites, Ostrobothnia, western Finland. The data with bold letters are presented in Figure 7.

Sample information Analysed mineral / fraction	Sample weight /mg	U ppm	Pb ppm	$^{206}Pb/^{204}Pb$ measured	$^{206}Pb/^{208}Pb$ radiogenic	ISOTOPIC RATIOS[a,b] $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	APPARENT AGES / Ma (±2sigma) $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
KAATIALA - Columbite											
A) Powdered grains	2.0	1731	478	2897	282	0,2828	4,251	0,1090	1605	1684	1783±2
B) Abraded grains	4.7	1795	524	1215	192	0,2901	4,329	0,1082	1642	1699	1769±2
C) 10% HF-leached grains	**2.4**	**1357**	**422**	**26113**	**443**	**0,3245**	**4,934**	**0,1103**	**1812**	**1808**	**1804±2**
SEINÄJOKI - Tapiolite											
36A) Untreated fragments	0.9	108	33	6586	1685	0,3189	4,835	0,1100	1785	1791	1799±2
36B) 5% HF-leached fragments	**2.1**	**113**	**35**	**9234**	**2068**	**0,3228**	**4,899**	**0,1101**	**1804**	**1802**	**1800±2**
36C) 10% HF-leached fragments	**1.8**	**110**	**34**	**2832**	**2954**	**0,3231**	**4,894**	**0,1099**	**1805**	**1801**	**1797±2**
36D) 20% HF-leached fragments	**1.6**	**127**	**39**	**16356**	**»10000**	**0,3229**	**4,903**	**0,1101**	**1804**	**1803**	**1802±2**
ALAVUS - Fergusonite											
106K) Translucent fragments	0.3	1.98%	5397	850	2.4	0,1973	2,877	0,1058	1161	1376	1728±2
106S) Turbid fragments	0.8	1.93%	6282	5038	2.3	0,2409	3,735	0,1125	1391	1579	1840±2
ALAVUS - Monazite											
112) Untreated fragments	0.2	449	1825	949	0.1	0,3271	5,141	0,1140	1825	1843	1864±2
112A) Abraded fragments	**0.9**	**507**	**2327**	**1157**	**0.1**	**0,3345**	**5,253**	**0,1139**	**1860**	**1861**	**1863±2**
KORVENNIEMI - Columbite											
Columbite plate; disordered lattice structure											
1) small fragments	1.7	1764	525	5354	102	0,3060	4,582	0,1086	1721	1746	1776±2
2) 20%HF-leached fragments	**0.6**	**1874**	**564**	**83414**	**99**	**0,3128**	**4,715**	**0,1094**	**1754**	**1770**	**1789±2**
3) abr. Fragments	2.3	1740	522	3474	113	0,3072	4,588	0,1083	1727	1747	1771±2
4) abr. 5%HF-leached fragments	**2.4**	**1658**	**495**	**14599**	**108**	**0,3096**	**4,648**	**0,1089**	**1739**	**1758**	**1781±2**
5) abr. 20%HF-leached fragments	**1.6**	**1705**	**514**	**12601**	**132**	**0,3127**	**4,680**	**0,1085**	**1754**	**1764**	**1775±2**
Columbite grain; ordered lattice structure											
6) abr. small fragments	2.4	1371	392	2470	84	0,2900	4,311	0,1078	1741	1695	1763±2
7) abr. fragments	**4.0**	**1492**	**447**	**10125**	**109**	**0,3101**	**4,664**	**0,1091**	**1741**	**1761**	**1784±2**
8) abr. 5%HF-leached fragments	**2.1**	**1289**	**392**	**6664**	**103**	**0,3138**	**4,703**	**0,1087**	**1759**	**1768**	**1778±2**
9) abr. small fragments	1.1	1332	377	1730	84	0,2847	4,216	0,1074	1615	1677	1756±3
ULLAVA (R5) - Columbite											
1d) abr. small fragments	0.3	2227	749	332	32	0,2909	3,974	0,0991	1646	1629	1607±5
2d) abr. larger fragments	2.4	1807	577	403	24	0,2816	4,049	0,1043	1599	1644	1702±5
3d) abr. 5%HF-leached fragments	0.5	1048	344	2388	77	0,3316	4,970	0,1087	1846	1814	1778±2
4d) abr. 10%HF-leached fragments	**0.6**	**1162**	**356**	**7089**	**128**	**0,3170**	**4,764**	**0,1090**	**1775**	**1779**	**1783±2**
5d) abr. 20%HF-leached fragments	**0.4**	**786**	**240**	**16300**	**135**	**0,3176**	**4,788**	**0,1094**	**1778**	**1783**	**1789±2**
HAAPALUOMA - Columbite I and II											
1/II) abr. 20%HF-leached fragments	3.6	869	283	2819	69	0,3296	5,043	0,1110	1836	1827	1816±2
2/II) abr. HNO3-leached fragments	0.9	2095	430	2119	65	0,2070	3,015	0,1057	1213	1412	1726±2
3/I) abr. 10%HF-leached fragments	**0.5**	**1622**	**502**	**12266**	**158**	**0,3211**	**4,864**	**0,1099**	**1795**	**1796**	**1797±2**

a) Isotopic ratios corrected for fractionation, blank (<50 pg) and age related common lead (Stacey & Kramers 1975).
b) Errors for Pb/U ratios are 0.6% and for $^{207}Pb/^{206}P$ ratios less or equal than 0.1%. Correlations for the $^{206}Pb/^{238}U$ vs. $^{207}Pb/^{235}U$ errors are 0.98.

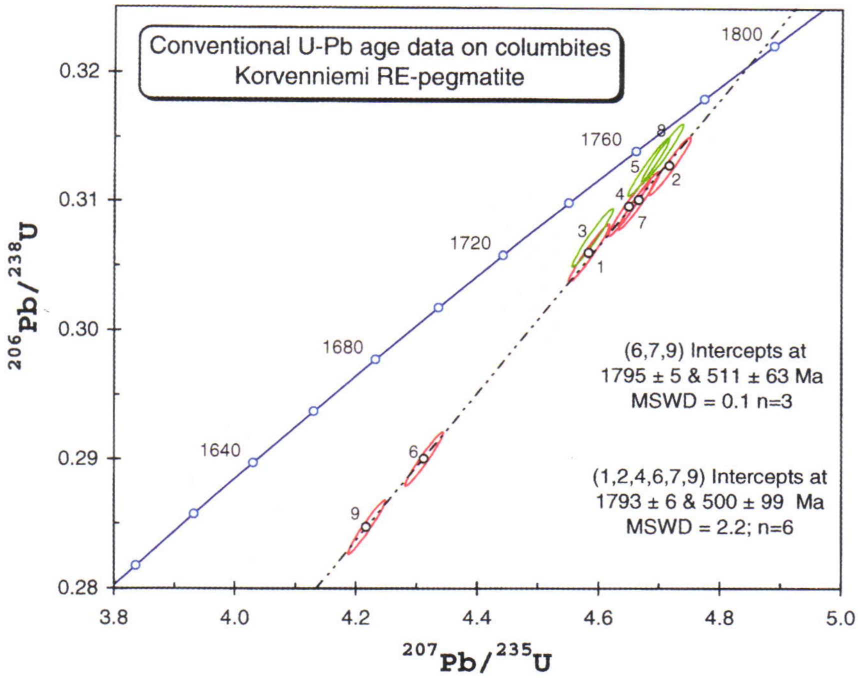

Fig. 8. Concordia diagram for analysed columbite fractions from the Korvenniemi RE-pegmatite.

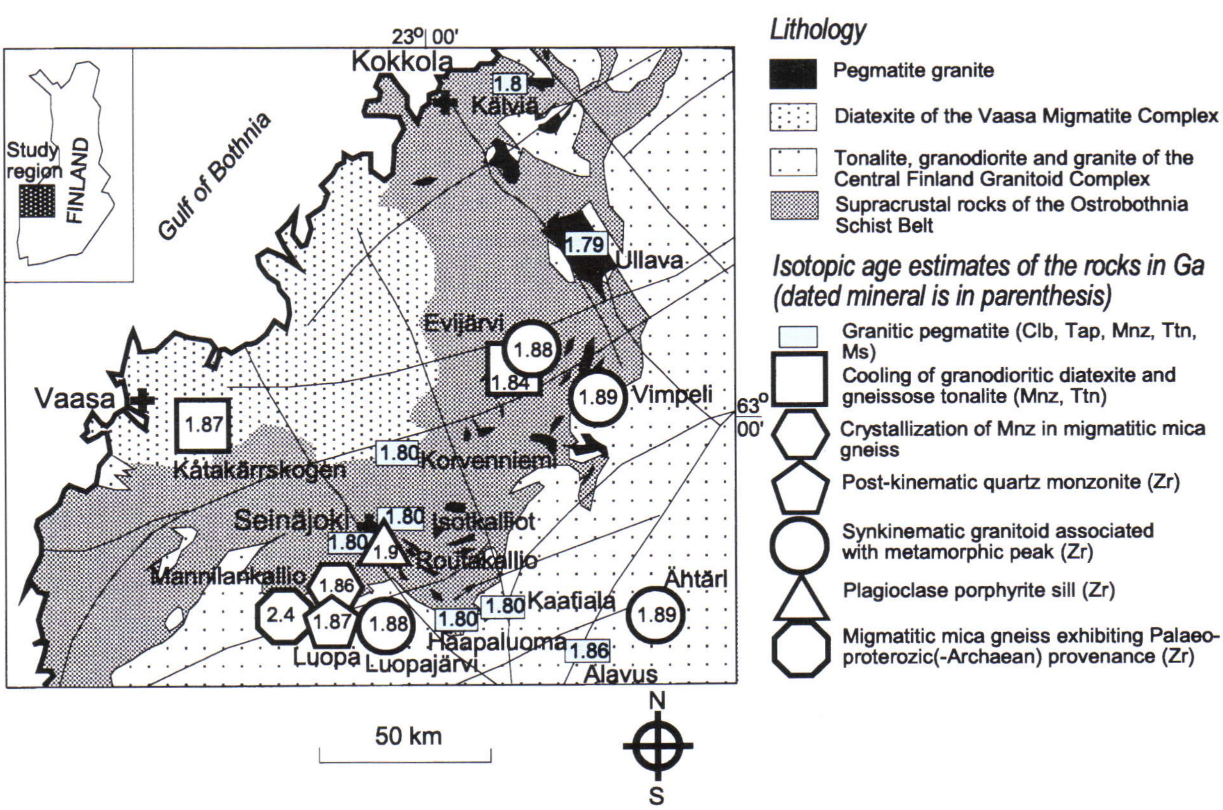

Fig. 9. Locations with age estimates of the isotopically dated rocks from Ostrobothnia. All age measurements, except that from the Kälviä area, are U-Pb measurements. For references, see Appendix 1 and for abbreviations, see Table 3. Lines indicate shear and fracture zones (map after Korsman et al. 1997).

concordia diagram and data points are normally or reversely discordant, but the 10% or 20% HF-leached fractions give concordant or nearly concordant ages. In addition, these leached fractions clearly have the most uranogenic $^{206}Pb/^{208}Pb$ and $^{206}Pb/^{204}Pb$ ratios. This can be explained by the existence of at least two separate U-Pb-systems in the mineral. When leached, the phase with more thorogenic lead (i.e. more ommon lead) is extracted and the $^{206}Pb/^{208}Pb$ and $^{206}Pb/^{204}Pb$ ratios increase significantly. These results agree with those reported by Romer and Wright (1992) and Romer et al. (1996), who have studied the U-Pb systematics of the columbite-tantalites and their potential use as a dating tool.

The concordant U-Pb age data for the Kaatiala, Seinäjoki, Ullava and Haapaluoma columbites and tapiolites are shown in Figure 7. The two unleached columbite fractions from the Kruunupyy-Ullava pegmatite give strongly discordant ages. However, the 10% HF-leached fraction (C) gives a concordant age of 1804±2Ma. All four analysed tapiolite fractions in the Seinäjoki pegmatite give concordant or nearly concordant ages. The 20% HF leached fraction (36D) gives the most concordant age of 1802±2Ma. Five fractions of columbite were analyzed from the albite-spodumene dyke from the Kaustinen area. In these, unleached fractions give discordant ages and the 5% HF-leached fraction gives a reversely discordant age. The 10% and 20% HF-leached fractions give nearly concordant ages. The highest $^{207}Pb/^{206}Pb$ age of the two concordant data points (4d and 5d) is 1789±2Ma, which may be considered as a good age estimate for the Ullava columbite. Two columbite grains were available from the Haapaluoma pegmatite. One gives discordant and reversely discordant ages while the other (3/I) is concordant at 1797±2Ma.

The uranium-rich fergusonite in the Alavus pegmatite is clearly metamict and gives strongly discordant ages (Table 5). However, the concordant monazite analysis (112A) gives an age of 1863±2 Ma for the Alavus pegmatite (Fig. 7, Table 5).

From the Korvenniemi pegmatite, nine leached and unleached fractions from two columbite grains were analyzed (Table 5). The data scatter on the concordia diagram (Fig. 8) and clearly do not share the common characteristics of the Kaatiala, Seinäjoki, Ullava and Haapaluoma columbites and tapiolites (cf. Table 5). However, all three unleached fractions from a columbite grain with an ordered lattice structure plot on a discordia line with an upper intercept age of 1795±3Ma (MSWD=0.1) (Fig. 8). Further, a six point discordia line gives a similar age of 1793±6 Ma with a slightly higher MSWD-value of 2.2. Three of the data points (3, 5 and 8) plot clearly on the younger side of these discordia lines, most probably indicating the existence of younger uranium-rich phases in microfractures, visible also in BSE images (Fig. 6b).

DISCUSSION

The data presented in this paper demonstrate that crustal evolution in Ostrobothnia followed the general pattern established elsewhere within the Svecofennian domain in Finland (cf. Vaasjoki 1996). Thus the zircons in the Mannilankallio metapelite exhibit the same pattern of bulk analyses as has been found in metapelites in which ion probe data has proven a bimodal Archean-Paleoproterozoic provenance. The age of the synkinematic Luopajärvi tonalite, 1882±9 Ma, is typical for the Svecofennian culmination in central Finland. However, both the monazite (although discordant) from Mannilankallio and the age of the undeformed Luopa quartz monzonite, 1872±2 Ma, indicate that orogenic deformation ceased soon after its culmination. The presence of a contact metamorphic aureole around the Luopa quartz monzonite constitutes particularly strong evidence that regional metamorphism had ceased when this pluton was emplaced. Inhomogeneous pegmatite granites and pegmatites are the youngest rocks in the region. Locations of the isotopically dated rocks of Ostrobothnia are shown in Figure 9.

The age of the Vaasa migmatitic gneisses (formerly the Vaasa granite) has been a major analytical problem for several decades, as all samples taken so far have contained heterogeneous zircon populations. However, the above constraints on the duration of regional metamorphism, the generally granodioritic composition of the neosome and, in particular, the nearly concordant monazite cooling age of 1872±5 Ma from the Kåtakärrskogen sample argue that migmatization in the Vaasa area was syndeformational with the tectono-metamorphic culmination (1.89-1.88 Ga) of the Svecofennian orogeny.

Almost all of the Ostrobothnian RE-pegmatites can be readily divided into the types and subtypes of Černý (1991, 1998). Exceptions are the pegmatites at Kruunupyy-Ullava, Isokyrö and Korvenniemi. Classification of the Kruunupyy-Ullava RE-pegmatites into albite-spodumene type is based on a somewhat scanty knowledge of these rocks and a future reassessment is possible. The RE-pegmatites at Isokyrö and Korvenniemi are primitive pegmatites of the beryl-columbite subtype, but are distinct – because biotite is the dominant mica – as they contain neither tourmaline nor Fe,Mn-phosphates, but topaz or andalusite, cordierite, and fluorite. In fact, these pegmatites are the only ones without tourmaline in the Ostrobothnia Schist Belt.

Every RE-pegmatite group occurs in the vicinity of pegmatite granite intrusions. It appears that these intrusions are often phacoliths, or flat-lying sheets, almost parallel to the schistosity of the adjacent rocks. Their size is very variable, from some hundreds of metres to a few kilometres, and only the major ones are shown on the lithological map (Fig. 1). The pegmatite granites contain lengthy pegmatitic bodies or veins which are mostly barren, but sometimes beryl±columbite±spodumene-bearing similar to the pegmatites in the vicinity.

The new age data from the pegmatites are particularly interesting against the regional background. According to radiometric dating, the pegmatites fall into two age groups: the NYF family pegmatites, such as the Alavus REE-pegmatites, crystallized at 1.86 Ga and other pegmatites, i.e. the pegmatites of the LCT family, much later at 1.80-1.79 Ga. A temperature-time diagram of the isotopically dated rocks from Ostrobothnia is given in Figure 10. The dated rocks with age results from the study area are summarized in Appendix 1.

Usually the youngest (c. 1.80 Ga) Svecofennian RE-pegmatites, for example the 1.79-1.80 Ga old Gruvdalen REE-pegmatites in Sweden and the Brändö REE-pegmatites in southwestern Finland, occur in the vicinity of granites of approximately the same age (Suominen 1991, Romer and Smeds 1994, Lindroos et al. 1996). In the Seinäjoki RE-pegmatite group, zircons in the rock suite called pegmatite granite appear to be metamictic. So far, no record of intrusive activity coeval with the c. 1.80 pegmatite age group is encountered in the Ostrobothnia region.

The Alavus NYF pegmatites are located both inside and outside of a microcline granite intrusion, 5 km in diameter, in the Central Finland Granitoid Complex. This intrusion contains accessory fluorite and belongs to a suite of post-kinematic rocks (Tyrväinen 1984, Nironen et al. 2000). The age difference between the granite pluton and the NYF pegmatites is about 10 Ma. The position of the pegmatites and the relatively small time gap indicate that the Alavus NYF pegmatites are derived from this granite intrusion.

The Kemiö pegmatites of the LCT family, in southwestern Finland, are practically coeval with the Ostrobothnian LCT pegmatites (see Masuda et al. 1988, Lindroos et al. 1996). Thus, it appears that there is no relationship between the Finnish pegmatites of this age (c. 1.80 Ga, U-Pb age) and the important east-west trending terrane boundary in southern Finland as described by, for example, Vaasjoki and

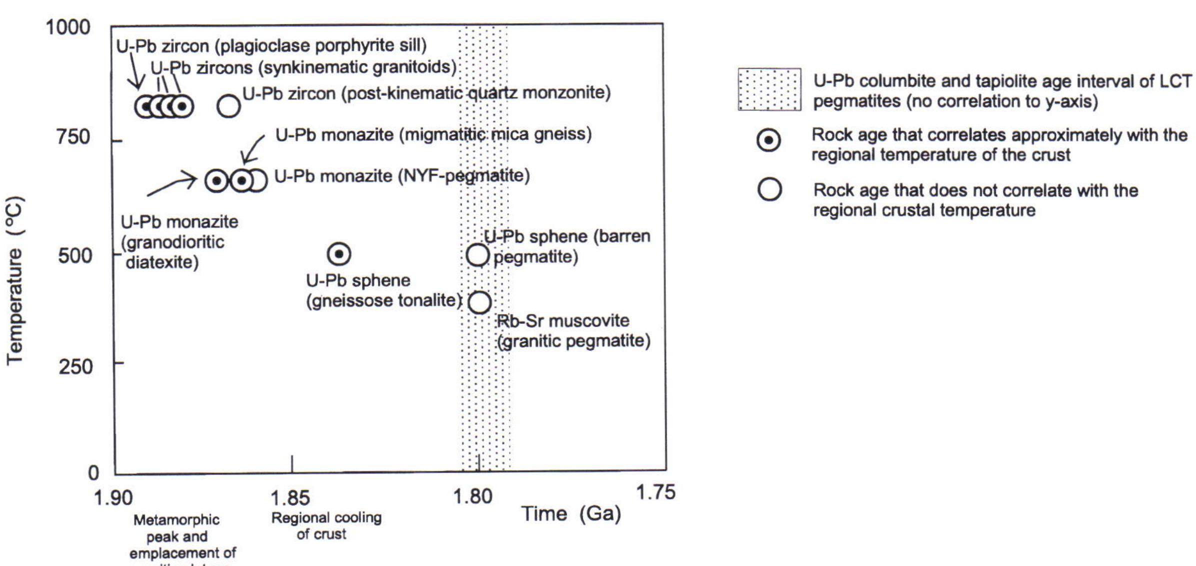

Fig. 10. Temperature-time diagram for isotopic rock ages, Ostrobothnia, western Finland.

Sakko (1988) and Kähkönen et al. (1994).

The closure temperatures of Nb-Ta minerals are not as well known as those for zircon, monazite, and sphene. In addition, comparison of zircon and monazite ages with columbite-tapiolite ages has been difficult, because related zircons and monazites in LCT pegmatites are either lacking or too metamict for accurate dating. However, if it is considered that pegmatite dykes are usually relatively narrow (<100 m) and intruded into cooled country rocks, we can assume that pegmatitic magma cools rapidly. Evidence for coeval crystallization ages for zircon, monazite and sphene have been reported from small granites and related dykes (e.g. Suominen 1991) and even monazites in the vast Wiborg batholith register identical ages with zircons of the same samples (Vaasjoki et al. 1991). More importantly, Romer and Wright (1992) report that the Vassijaure area, where U-Pb ages from columbite and zircon in pegmatite from the genetically related Vassijaure granite coincide at c. 1780 Ma, was subjected to lower amphibolite facies metamorphism during the Caledonian orogeny c. 400 Ma ago. We thus consider it safe to assume that columbite U-Pb ages from pegmatites date the emplacement of these rocks and have not been reset by subsequent geological processes.

In Central Finland, large scale ductile deformation ceased at the latest 1850 Ma ago (Vaasjoki 1996). However, many schist-hosted RE-pegmatites are deformed and folded in both the Seinäjoki and Haapaluoma-Kaatiala areas. Most of these pegmatites occur in prominent shear zones shown on large scale geological maps (e.g. Korsman et al. 1997). Clearly, the shear zones have been active later than 1.80 Ga ago.

Most of the LCT pegmatites occur in relatively low-grade metamorphic rocks such as andalusite mica schists, but a few, compositionally unique LCT pegmatites lie in high-grade metamorphic mica gneisses. Černý (1998) has shown that none of the metamorphogenic hypotheses, such as derivation from anatectic melts, can be used to explain the attributes of RE-pegmatites and, thus, magmatogenic derivation of RE-pegmatites should be the only model supported. However, in the study area, there is a strong correlation between the LCT type pegmatites and relatively low-grade metamorphic country rocks (see also Mäkitie et al., this volume) (Fig. 1). This indicates that the metamorphic zoning has had some control on the accumulation of the pegmatite melts, although the time gap between the metamorphic peak to the crystallization of the pegmatites is about 80 Ma.

All the 12 pegmatite groups studied have individual features separating them from each other. This indicates that each group of pegmatites is a product of the fractionation of local melts. It appears likely that the c. 1.80 Ga pegmatites occurring in the Ostrobothnia represent a distinct tectono-magmatic episode separate from the Svecofennian orogenic culmination (1.89-1.88 Ga) and from the migmatite forming microcline granite event (c. 1.83 Ga) in southern Finland.

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Appendix 1. Summary of the published isotopic age data from Ostrobothnia, western Finland. Abbreviations are explained in Table 3.

ROCK TYPE (dated mineral is in parenthesis)	AGE RESULT	LOCATION/ GEOLOGICAL INTERPRETATION	CLOSURE °C	REFERENCE
Albite-spodumene pegmatite (Clb)	1789±2 Ma	Ullava (R5)/ crystallization		This paper
Columbite-topaz pegmatite (Clb)	1795±5 Ma	Korvenniemi/ crystallization		This paper
Spodumene-lepidolite pegmatite (Clb)	1797±2 Ma	Haapaluoma/ crystallization		This paper
Pegmatite granite (Ms)	c. 1.8 Ga	Kälviä/ crystallization	c. 350	Wetherill et al. 1962
Barren pegmatite (Ttn)	1800±4 Ma	Isotkalliot/ crystallization	c. 500	This paper
Cassiterite-tapiolite pegmatite (Tap)	1802±2 Ma	Seinäjoki/ crystallization		This paper
Spodumene-columbite pegmatite (Clb)	1804±2 Ma	Kaatiala/ crystallization		This paper
Gneissose tonalite (Ttn)	1838±5 Ma	Evijärvi/ cooling of crust	c. 500	Vaasjoki et al. 1996
Garnet-cordierite-sillimanite mica gneiss (Mnz)	≥1.86 Ga	Mannilankallio/ cooling of crust	c. 600	This paper
Fergusonite-monazite pegmatite (Mnz)	1863±2 Ma	Alavus/ crystallization	c. 600	This paper
Granodioritic rock from the Vaasa Migmatite Complex (Mnz)	1872±5 Ma	Kåtakärrskogen/ cooling of crust	c. 600	This paper
Quartz monzonite (Zr)	1872±2 Ma	Luopa/ crystallization	c. 800	Mäkitie & Lahti, this volume
Tonalite (Zr)	1882±9 Ma	Luopajärvi/ crystallization & metamorphic peak	c. 800	This paper
Gneissose tonalite (Zr)	1883±6 Ma	Evijärvi/ crystallization & metamorphic peak	c. 800	Vaasjoki et al. 1996
Granite (Zr)	1886±10 Ma	Ähtäri/ crystallization	c. 800	Huhma 1986
Gneissose granodiorite (Zr)	c. 1.89 Ga	Vimpeli/ crystallization	c. 800	Kouvo & Tilton 1966
Plagioclase porphyrite sill (Zr)	c. 1.9 Ga	Routakalliot/ emplacement	c. 800	This paper
Garnet-cordierite-sillimanite mica gneiss (Zr)	c. 2.4 Ga	Mannilankallio/ mixture of Archaean and Proterozoic grains	c. 800	This paper