Titanite–rutile thermochronometry across the boundary between the Archaean Craton in Karelia and the Belomorian Mobile Belt, eastern Baltic Shield

Article *in* Precambrian Research · January 2001

DOI: 10.1016/S0301-9268(00)00117-0

E. V. Bibikova
Russian Academy of Sciences

Svetlana V. Bogdanova
Lund University

Roland Gorbatschev
Lund University

Alexander Slabunov
Institute of Geology, Karelian Reaearch Centre, Russian Academy of Scie…

ELSEVIER

Precambrian Research 105 (2001) 315–330

Precambrian Research

www.elsevier.com/locate/precamres

Titanite-rutile thermochronometry across the boundary between the Archaean Craton in Karelia and the Belomorian Mobile Belt, eastern Baltic Shield

E. Bibikova [a], T. Skiöld [b], S. Bogdanova [c,*], R. Gorbatschev [c], A. Slabunov [d]

[a] *Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, 19 Kosygin Street, RU-117975 Moscow, Russia*
[b] *Swedish Museum of Natural History, P.O. Box 50 007, S-104 05 Stockholm, Sweden*
[c] *Department of Geology, Lund University, Sölvegatan 13, S-223 62 Lund, Sweden*
[d] *Institute of Geology, Karelian Science Centre, Pushkinskaya 11, Petrozavodsk, Russia*

Received 20 August 1999; accepted 6 October 1999

Abstract

U–Pb isotopic dating has been carried out on titanites and rutiles from the Karelian Protocraton, the Belomorian Mobile Belt and the intervening junction zone. These are some of the principal Archaean crustal units in the Baltic Shield which have undergone regeneration to various degrees during the Palaeoproterozoic. Palaeoproterozoic resetting of U–Pb titanite ages was complete in the Belomorian Belt and almost complete in the junction zone, while it hardly affected the Karelian Protocraton. In the latter, major crustal cooling occurred at 2.71–2.69 Ga after a major igneous event at 2.74–2.72 Ga, but a tectonothermal event at 2.65–2.64 Ga was less comprehensive. In the Belomorian Belt, a northeastern marginal zone immediately underlying the collisional-thrusting suture of the Lapland-Kola orogen has somewhat higher titanite ages of ca. 1.94–1.87 Ga than the central zone where these ages range between 1.87 and 1.82 Ga. Comparison between the titanite and rutile U–Pb ages suggests a postorogenic cooling rate between 2 and 4°/Ma in these parts of the Belt. The Neoarchaean junction zone between the Karelian and Belomorian provinces was a zone of particularly intense tectonic, magmatic and hydrothermal activity during or after the Palaeoproterozoic Lapland-Kola orogeny. Dominant, newly grown titanites in that zone have ages as young as 1.78–1.75 Ga, and the age differences between the titanite and rutile U–Pb ages are substantially smaller than elsewhere. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: U–Pb dating; Titanite; Rutile; Palaeoproterozoic; Eastern Baltic Shield

1. Introduction

Since the fundamental work of Dodson (1973, 1979) on the closure temperatures of isotopic systems in minerals, these parameters have been

---

* Corresponding author. Tel.: +46-46-2224597; fax: +46-46-121477.

E-mail address: svetlana.bogdanova@geol.lu.se (S. Bogdanova).

PII: S0301-9268(00)00117-0

used widely to decipher the tectonothermal history of the crust. Many of the problems of Alpine geodynamics have thus been solved employing the K–Ar and Rb–Sr isotope systems in various minerals. These have closure temperatures somewhat below 500°C.

Among other accessory minerals common in igneous and metamorphic rocks, titanite has closure temperatures of its U–Pb isotope system substantially above 500°C. It has been successfully used in the study of tectonothermal processes (e.g. Corfu, 1996; Tucker et al., 1987). The titanite closure temperatures have been estimated both by petrological (Mezger et al., 1991; Scott and St-Onge, 1995; Pidgeon et al., 1996; Zhang and Schaerer, 1996) and experimental means (Cherniak, 1993). At present there is general agreement that they are ca. 650–700°C for titanite crystals with radii of approximately 300 μm at cooling rates around 2°C/Ma.

Much lower are the closure temperatures of the U–Pb isotope systems in rutile, which is yet another accessory mineral currently employed in age determination; temperatures have been estimated at ca. 450°C (Mezger et al., 1989).

In Precambrian geology, knowledge of the closure temperatures of the titanite and rutile geochronometers has been applied to reconstruct the pressure–temperature (‘P–T–t paths’) evolution of high-grade polymetamorphic terrains (e.g. Mezger et al., 1989, 1991; Verts and Chamberlain, 1996). Because newly grown grains of titanite are common in shear zones, that mineral has also been used to date timing of deformation (e.g. Gromet, 1991; Resor et al., 1996),

Our approach in the present investigation of the U–Pb ages of titanites and rutiles is principally to compare the Palaeoproterozoic tectonothermal evolutions of the Karelian Protocraton and the adjacent high-grade Belomorian Mobile Belt. These are two of the major provinces of Archaean crust in the Baltic Shield.

An equally important feature is the intervening junction zone whose nature and significance have long been controversial. Some authors (e.g. Volodichev, 1990) have suggested that the Karelian-Belomorian junction is a fault zone along which a continuation of the lower crust of the present Karelian domain had been uplifted and later exposed in the shape of the Belomorian Belt. Gaál and Gorbatschev (1987), however, proposed a fundamentally different interpretation, concluding from lithological and structural evidence that the Belomorian Belt is an autonomous, late Archaean assemblage of orogenic terranes that had been formed outboards of and partly thrusted over the margin of the Karelian Protocraton. Subsequently, the Neoarchaean junction was reactivated in the Palaeoproterozoic.

The particulars of the Palaeoproterozoic development are still debatable. During that period, the Karelian-Belomorian border zone had first been a site of rifting in the Archaean crust (e.g. Kratz, 1978; Gaál and Gorbatschev, 1987; Rybakov, 1987), and later a Palaeoproterozoic front of renewed thrusting toward the southwest (Miller and Mil’kevich, 1995; Miller, 1997).

2. Geological background

The Archaean domain of the Baltic Shield comprises the Kola, Karelian and, Belomorian provinces. Several rift systems developed during the extension and break-up of Archaean crust between 2.5 and 2.0 Ga and intervene between these crustal units. During the later Palaeoproterozoic, ca. 1.95–1.8 Ga, the fragments of previously dispersed Archaean crust were partly reassembled which resulted in the formation of the Lapland-Kola collisional orogen (e.g. Bridgwater et al., 1992). The trace of the collisional suture has been assumed to follow the Lapland Granulite Belt through Norway, Finland and Russia, and farther southeast the Kolvitsa and Umba granulite terranes situated immediately to the north of the northwestern bay of the White Sea (Fig. 1, cf. Balagansky et al., 1998). In Russian literature, that suture is referred to as the ‘Main Lapland, or Belomorian Suture (also Thrust)’.

In the northeastern part of the Lapland-Kola orogen, in the Kola Peninsula, the various component terranes only partly preserve their primary, Neoarchaean relationships (e.g. Bridgwater et al., 1992; Glebovitsky, 1993; Timmerman and

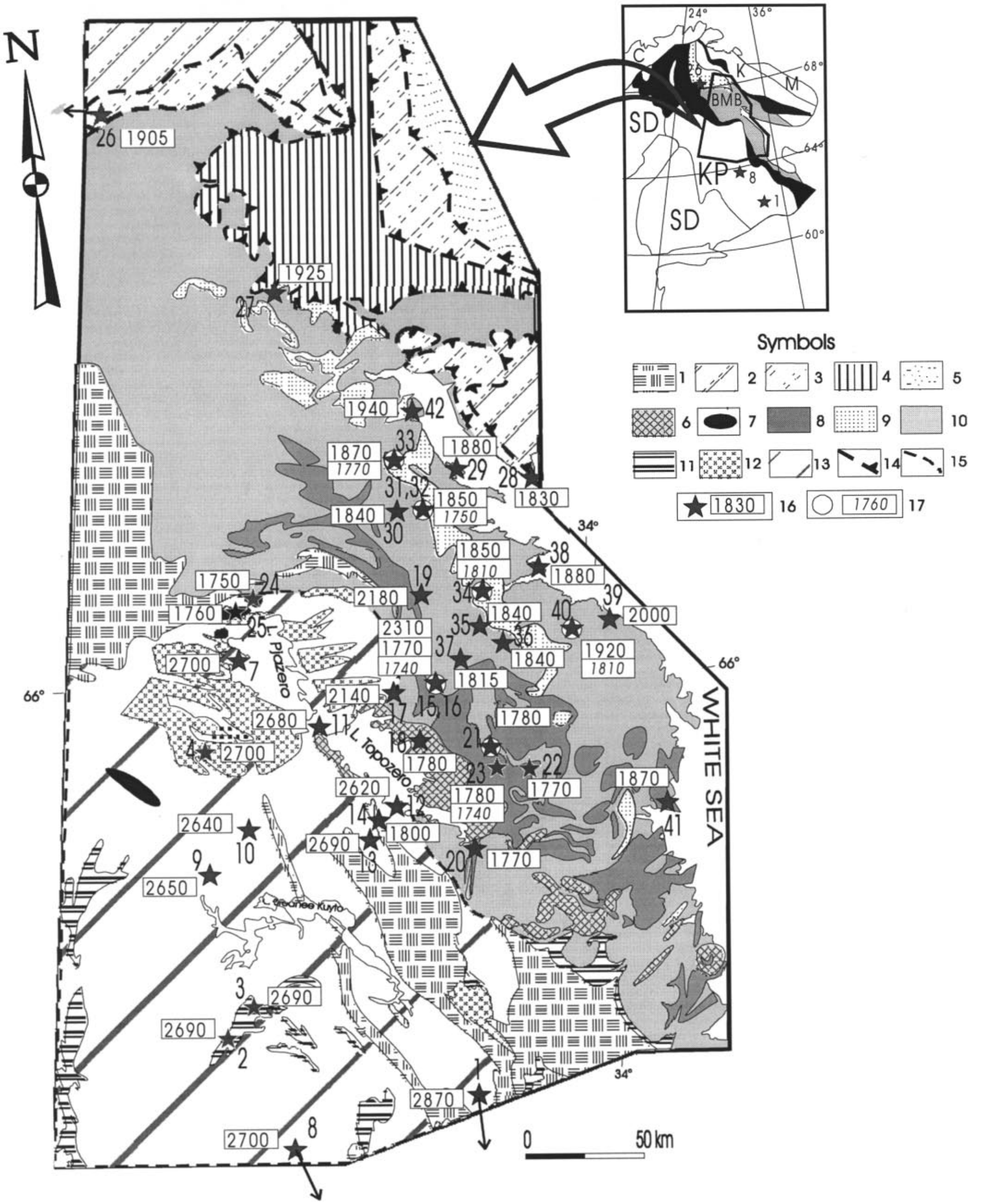

Fig. 1. Sketch map of the eastern Baltic Shield showing the sampling sites of the dated titanites and rutiles, and their U–Pb ages: (1) Palaeoproterozoic sedimentary and volcanic formations of the Karelian Protocraton (2.5–1.9 Ga); (2–5): the Lapland-Kola Palaeoproterozoic nappe system (Miller and Mil'kevich, 1995): (2) Lapland, (3) Korvatundra, (4) Rikolatvi, (5) Central Kola; (6) intrusive charnockites of the Topozero type (ca. 2.45–2.40 Ga); (7) layered peridotite-gabbronorite intrusions of (ca. 2.45–2.40) Ga age; (8–10): Neoarchaean complexes of the Belomorian Mobile Belt: (8) the system of North-Karelian greenstone belts, 9 the Chupa paragneiss belt, (10) undivided rock complexes; (11–13): Archaean complexes of the Karelian Protocraton: (11) Neoarchaean greenstone belts, (12) the Tavayarvi TTG -complex of ca. 2.72 Ga age, (13) undivided rock complexes; (14) the Palaeoproterozoic thrusts delimiting the Lapland-Kola nappes; (15) the boundary between the Belomorian Mobile belt and the Karelian Protocraton according to structural and metamorphic criteria; (16) sampling sites for titanites (ages in Ma); (17) sampling sites for rutiles (ages in Ma). The numbering of the localities corresponds to that in Table 1 and Table 2. The inset shows the position of the studied area in the eastern Baltic Shield. The letter symbols are: (C) Caledonides; M, Murmansk subprovince; BMB, Belomorian Mobile Belt; KP, Karelian Protocraton; SD, Svecofennian Domain. The Lapland Granulite Belt is stipled, early Palaeoproterozoic rifts are marked in black.

Daly, 1995; Mitrofanov, 1995; Mints et al., 1996). In the southwest in contrast, the Archaean Karelian province is a coherent, typical granite-gneiss-greenstone terrain that comprises crustal components as old as 3.4–3.5 Ga (e.g. Puchtel et al., 1991). There are three generations of greenstone belts formed between 3.2 and 2.7 Ga ago. Some of these are intracratonic while others outline the margins of the Karelian province. Many of the former are highly discordant in the relationship to the borders of the Karelian Protocraton and probably have rift- (e.g. Gaál and Gorbatschev, 1987; Lobach-Zhuchenko et al., 1993b) as well as back-arc (Taipale, 1983) origins, while some of the marginal belts trend parallel to the protocraton boundaries and may rather be vestiges of Neoarchaean accretionary tectonics (e.g. Sokolov and Heiskanen, 1985; also Puchtel et al., 1998).

The large Tavayarvi TTG (tonalite-trondhjemite-granodiorite) and granite pluton (Fig. 1) as well as the similar Notozero pluton appear to be parts of a relatively late igneous belt that had developed within the Karelian continental margin ca. 2.74–2.72 Ga ago (cf. Lobach-Zhuchenko et al., 1995; Bibikova et al., 1997).

In the earliest Palaeoproterozoic, at ca. 2.5–2.0 Ga the Archaean crust of the Karelian Protocraton was rifted and penetrated by dyke swarms as described e.g. by Gorbatschev et al., 1987; Vuollo et al. (1994). Sizable intracontinental volcanogenic and sedimentary, so-called 'Karelian' rift-and-basin structures were also developed. At ca. 2.0–1.9 Ga, the Svecofennian orogeny was initiated, and the Palaeoproterozoic crust to the west of the Karelian Protocraton was created (cf. Gaál and Gorbatschev, 1987).

During the last decade, numerous isotope-geochronological and petrological studies (e.g. Bogdanova and Bibikova, 1993; Bibikova et al., 1993; Timmerman and Daly, 1995; Bibikova et al., 1996, 1999) have confirmed the original interpretation of Gaál and Gorbatschev (1987), cf. above) that the Belomorian Mobile Belt is an independent Neoarchaean orogen reactivated in the Palaeoproterozoic. It was first developed during the subduction of oceanic crust towards and beneath the Karelian Protocraton between ca. 2.9 and 2.7 Ga ago.

Due to the two Neoarchaean and Palaeoproterozoic collisional orogenies considered above, the Belomorian Belt represents lower-crustal sections of both the Neoarchaean and the Palaeoproterozoic crusts. Its major Neoarchaean structure is regarded as a collisional allochton (Miller and Mil'kevich, 1995) developed ca. 2.74–2.70 Ga ago (Bibikova et al., 1999). During the following earliest Palaeoproterozoic interorogenic rifting period, already mentioned above in connection with the Karelian Protocraton, the Belomorian Belt was also partly reworked. It became affected rather thoroughly by bimodal, dominantly ultramafic-mafic but subordinately also granitic magmatism, here even accompanied by high-grade metamorphism and penetrative deformation (Bridgwater et al., 1994; Bogdanova, 1996; Balagansky et al., 1998).

During and after the Palaeoproterozoic Lapland-Kola collisional orogeny, which was approximately coeval with the Svecofennian orogeny farther west, the Belomorian Mobile Belt was involved once more in strong deformation and anatectic melting of the crust. The latter is demonstrated particularly well by the widespread occurrence of ca. 1.80–1.75 Ga pegmatites (e.g. Tugarinov and Bibikova, 1980). Recurrent Palaeoproterozoic high-grade metamorphism and folding were common all along the Belt. Granite-gneiss domes sometimes overfolded recumbently toward the southwest, occupy a wide zone in the southwestern foreland of the Lapland-Kola collisional suture, also occurring within the Belomorian Belt (cf. Miller and Mil'kevich, 1995; Miller, 1997).

The 30–50 km wide *junction zone* between the Karelian Craton and the Belomorian Belt is marked by a chain of greenstone belts including the Hizovaara, Keret' and Tikshozero (e.g. Kozhevnikov, 1992). These appear to outline a Neoarchaean collisional front (cf. Miller and Mil'kevich, 1995), but they have been previously referred to the Karelian province. Stepanov and Slabunov (1989) however, related that chain to the Belomorian Belt, finding no substantial differences between the named belts and rock complexes common in the latter. That inference was subsequently substantiated by geochemical and isotope-geological study (Bibikova et al., 1999).

The Karelian-Belomorian junction zone, which was originally named either the 'Belomorian-Karelian Deep Fault' (Shurkin, 1974) or the 'East Karelian Mobile-Penetrative Zone' (Kratz, 1978) comprises Archaean as well as Palaeoproterozoic lithological and structural rock complexes. It outlines the northern and northeastern boundaries of the Karelian Protocraton. All these rock complexes have undergone strong folding, shearing and mylonitisation, including the seemingly anorogenic, rift- and fault-related intrusions of 2.45–2.40 Ga charnockites and riftogenic, earliest Palaeoproterozoic volcanic and sedimentary trough fillings (Shurkin, 1974; Kratz, 1978). Numerous late Palaeoproterozoic mafic, ultramafic and alkaline intrusions also mark the junction zone.

3. Titanite and rutile thermochronometry

To assess the differences between the Palaeoproterozoic tectonothermal evolutions in the Karelian Protocraton and the Belomorian Belt, we studied the U–Pb isotope systems in more than 50 titanite and 15 rutile samples. The sampling principally followed two profiles. The first of these crosses the Belomorian and Karelian provinces from the west to the east, while the second follows the Belomorian Belt from the north to the south. The locations of the sampling sites and the average U–Pb ages of the titanites and rutiles are indicated in Fig. 1. In addition, representative data are presented in Table 1 and Table 2, and the same data illustrated graphically in Fig. 2 and Fig. 3.

4. Analytical procedure

The U–Pb analyses were carried out at the Laboratory of Isotope Geology of the Swedish Museum of Natural History, Stockholm. A conventional technique (Krogh, 1973) employing mixed spike (^{205}Pb plus$^{235 \text{ and } 233}$U) was employed. Additional purifications of lead in 1-N HBr and uranium in 7-N HNO_3 were done during the column procedure. The isotope measurements were performed on a Finnigan MAT 261 mass-spectrometer. The errors of the U–Pb isotope ratios were in the range of 0.5–2.0%. They depend highly on the amounts of common lead in the minerals, which occasionally were particularly high in the titanites. Radiogenic lead is normally well retained in the crystal lattice of titanite and the U–Pb isotopic data obtained on that mineral are therefore usually much more concordant than those from the zircons. However, the capacity of Pb to substitute Ca in the structure of titanite ($Ca^{+2} = 1.12$Å, $Pb^{+2} = 1.29$Å) can lead to high concentrations of common lead, which makes the obtained ages less precise. The isotopic composition of lead in rutiles is usually highly radiogenic and the U–Pb ages concordant. Common-lead correction was made according to Stacey and Kramers (1975).

5. Results

5.1. The Karelian Protocraton

As can be seen from the data presented in Table 1 (Samples 1 through 11), all the analysed titanites from the Karelian Protocraton, both those from the metavolcanic and those from the TTG-type plutonic rocks, have Neoarchaean ages between 2.87 and 2.65 Ga. In that crustal domain, the titanite ages are generally somewhat lower than those determined from the zircons in the same rocks. The differences between the upper-intercept zircon- and the concordant titanite ages are evident from Table 1 and are also presented graphically in Fig. 2a and b. They are substantially higher in the volcanic than in the plutonic rocks, amounting to ca. 100 Ma in the dacites of the Kostomuksha Belt (Fig. 1 and Sample 2 in Table 1) and ca. 70 Ma in the dacites of the Semch belt (Sample 1 in Table 1, and Fig. 2a). This, however, mostly only reflects the circumstance that the investigated plutonics are substantially younger than the studied volcanics.

Table 1
U–Pb isotope data for titanites from the Eastern Baltic Shield[a]

N	Locality	Rock type, titanite color	Concentration in ppm		Mean 206Pb/204Pb	Atomic ratios and ages ±2σ, Ma			Zircon age	Reference
			U	Pb		206Pb/238U	207Pb/235U	207Pb/206Pb	Ma	
The Karelian Protocraton										
1	Semch	Metadacite	56.0	45.0	250	0.5664, 2890	16.066, 2880	2872 ± 3.0	2935	Bibikova, 1989
2	Kostomuksha	Metaandesite, dark	32.0	17.8	387	0.5184, 2693	13.145, 2690	2688 ± 6.3	2800	Puchtel et al., 1998
3	Shurlovaara	Metaryolite, dark	28.6	16.3	230	0.5173, 2688	13.138, 2690	2691 ± 5.3	2800	Puchtel et al., 1998
4	Tavayarvi	Quartz diorite, dark	53.0	30.0	398	0.5185, 2692	13.213, 2695	2697 ± 2.0	2725	Bibikova et al., 1997
5	the same sample	Quartz diorite, dark	48.6	27.8	400	0.5231, 2712	13.310, 2702	2694 ± 2.2	2725	Bibikova et al., 1997
6	the same sample	Quartz diorite, light	6.3	3.2	100	0.5031, 2627	12.396, 2635	2640 ± 60	2725	Bibikova et al., 1997
7	Tavayarvi	Quartz diorite, dark	68.4	37.7	390	0.5190, 2695	13.135, 2689	2685 ± 3.0	2725	Bibikova et al., 1997
8	Ondozero	Diorite, dark	41.8	39.3	466	0.5227, 2711	13.424, 2710	2709 ± 2.0	2740	Bibikova, 1989
9	Voynitza	Amphibolite, light	14.4	8.8	95	0.5088, 2652	12.606, 2651	2650 ± 7.5	(2700)	
10	Okhtonyarvi	Metadiorite, dark	63.5	32.8	252	0.4240, 2280	10.411, 2472	2635 ± 3.0	(2700)	
11	Sofporog	Metadiorite, dark	203.8	171.0	860	0.5175, 2689	13.084, 2686	2683 ± 2.0	(2700)	
12	Kizerka	Metatonalite, dark	200.6	143.1	2090	0.4670, 2470	11.385, 2555	2623 ± 3.0	(2700)	
13	Kizerka	Metadiorite, dark	38.4	21.1	590	0.5170, 2687	13.105, 2687	2688 ± 2.5	(2700)	
14	Kizerka	Andesitic basalt, light	19.6	6.3	169	0.3245, 1812	4.964, 1813	1815 ± 9.0	(2400)	
The junction zone										
15	Hizovaara	Metatonalite, dark	28.0	15.9	292	0.3065, 1724	6.209, 2005	2310 ± 3.0	(2800)	
16	the same sample	Metatonalite, light	8.1	2.5	123	0.3113, 1747	4.636, 1756	1766 ± 11.0	(2800)	
17	N Topozero	Charnockite, dark	68.3	40.0	35.4	0.3828, 2009	7.039, 2.116	2143 ± 15	(2700)	
18	Topozero	Charnockite, light	27.0	8.4	369	0.3158, 1769	4.740, 1774	1780 ± 3.0	(2400)	Tugarinov and Bibikova, 1980
19	Ryabovaara	Gneiss, light	13.6	5.3	103	0.3150, 1765	5.923, 1965	2180 ± 40.0	(2700)	

Table 1 (*Continued*)

N	Locality	Rock type, titanite color	Concentration in ppm		Mean 206Pb/204Pb	Atomic ratios and ages ±2σ, Ma			Zircon age	Reference
			U	Pb		206Pb/238U	207Pb/235U	207Pb/206Pb	Ma	
20	Lake Pon'goma	Amphibolite, Light	6.6	2.3	76.1	0.3114, 1748	7.652, 1759	1772 ± 28	(2700)	
21	Keret'	Metatonalite, Dark	31.6	10.1	360	0.3191, 1785	4.792, 1783	1781 ± 14.0	2800	Bibikova et al., 1999
22	Keret'	Metaandesite, Light	7.5	2.6	54.3	0.3190, 1785	4.772, 1778	1774 ± 30.0	2870	Bibikova et al., 1999
23	Keret'	Gabbro-norite, Light	25.9	8.1	245	0.3160, 1770	4.751, 1776	1783 ± 21.0	(2430)	
24	Lukkulaisvaara	Gabbro	Data from Amelin et al., 1995					1750		
25	Tsipiringa	Gabbro	Data from Amelin et al., 1995					1760		
The Belomorian Mobile Belt										
26	Tana belt	Amphibolite, Dark	36.4	17.9	640	0.3462, 1916	5.565, 1911	1905 ± 2.5	1925	Bibikova et al., 1993
27	Rikolatvi	Amphibolite, light	1.15	.52	123	0.3489, 1929	5.672, 1927	1925 ± 45.0	(2800)	
28	Kochin	Sheared gabbro, light	1.31	.42	76.5	0.3278, 1828	5.063, 1830	1833 ± 75	2400	Balagansky et al., 1998
29	Tolstik	Garnet amphibolite, dark	63.6	37.1	1234	0.3378, 1876	5.343, 1876	1876 ± 4.0	2440	Bogdanova and Bibikova, 1993
30–32	Tupaya Bay	Metadiorite, K-granites	Data from Skiöld et al., 1997					1840, 1850		
33	Lyagkomina	Tonalite	Data from Skiöld et al., 1997					1870		
34	Chupa	Tonalitic gneiss, dark	58.5	20.8	530	0.3321, 1849	5.189, 1851	1853 ± 3.0	(2700)	
35	Chupa	Al-gneiss, dark	236.6	77.4	520	0.3298, 1837	5.108, 1837	1837 ± 4.5	(2700)	
36	Loukhi	Tonalitic gneiss, dark	160.6	51.8	1063	0.3305, 1841	5.136, 1842	1844 ± 2.2	(2700)	
37	Loukhi	Granitic gneiss, light	19.8	6.3	270	0.3249, 1814	4.971, 1814	1815 ± 9.0	(2700)	
38	Kartash	Diorite, light	6.00	2.1	97	0.3380, 1879	5.355, 1878	1877 ± 14	2800	Bibikova et al., 1999
39	Kuyvikanda	Tonalite, dark	51.2	18.3	725	0.3523, 1946	6.250, 2011	2000 ± 2.0	(2700)	
40	Vorochistoe	Amphibolite, light	1.0	.44	130	0.3529, 1949	5.729, 1936	1922 ± 42	2880	Bibikova et al., 1999
41	Mramorniy	Amphibolite, dark	98.0	38,9	374	0.3345, 1860	5.271, 1864	1869 ± 6.1	(2700)	
42	Zhemchuzhnaya	Gabbro-norite	Data from Kudryashov et al., 1999					1940		

[a] Ages in brackets are tentative.

Table 2
U–Pb isotope data for rutiles from the Belomorian belt, Eastern Baltic Shield

Locality, the locality numbers are as for the titanite sampling	Rock type	Concentrations in ppm		Mean 206Pb/204Pb	Atomic ratios and ages ±2σ, Ma			Titanite age Ma
		U	Pb	Ratio	206Pb/238U	207Pb/235U	207Pb/206Pb	
15 Hizovaara	Metatonalite	14.8	4.65	1120	0.3111, 1746	4.575, 1745	1743 ± 4.4	1770
23 Keret’	Gabbro-norite	10.1	3.28	737	0.3094, 1738	4.533, 1737	1736 ± 3.6	1780
33 Lyagkomina	Al-gneiss and metatonalite	Data from Skiöld et al., 1997, 1870					1750–1780 (4 analyses)	
31 Tupaya Bay	Metagabbro and Al-gneiss	Data from Skiöld et al., 1997, 1850					1740–1760 (4 analyses)	
34 Chupa	Al-gneiss	18.9	6.1	1660	0.3253, 1816	4.957, 1812	1808 ± 3.5	1850
40 Vorochistoe	Amphibolite	85.6	27.9	3780	0.3239, 1809	4.941, 1809	1810 ± 2.0	1920

From the quartz diorites of the Tavayarvi pluton, two generations of titanite have been analysed. One of these is most likely igneous and forms inclusions in hornblende, while the other, which is much lighter in colour, occurs in the matrix between the large crystals of plagioclase and hornblende. The latter type has extremely low contents of uranium. As indicated in Table 1 (Samples 4 through 6), the age difference between these two generations of titanite is ca. 60 Ma. The Concordia upper-intercept age of the zircons from the Tavayarvi quartz diorite is 2725 Ma (Bibikova et al., 1997), while the age of the titanites of the igneous-looking generation is ca. 2700 Ma. Similar age differences of ca. 25–30 Ma between igneous zircons and similarly igneous titanites also characterize the Ondozero diorite (Sample 8 in Table 1).

5.2. The Belomorian Mobile Belt

Solely Palaeoproterozoic but somewhat variable ages have been yielded by the dominantly metamorphic titanites of the Belomorian Belt.

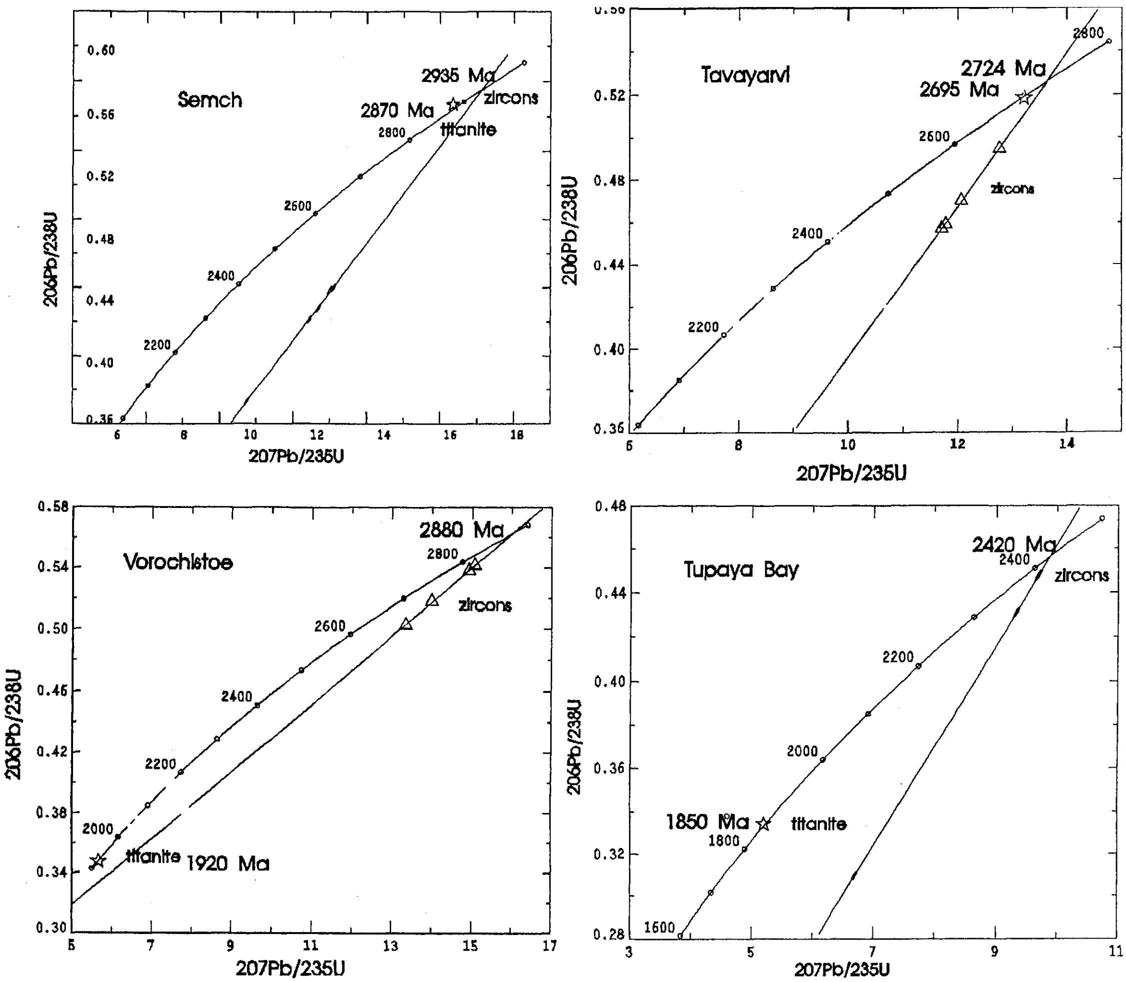

Fig. 2. Concordia diagrams for zircons and titanites from various rocks of the eastern Baltic Shield. The titanite ages obtained in the present study derived from: (a) the Semch dacite (Karelian Protocraton), with zircon data by Bibikova (1989)(b) the Tavayarvi quartz diorite (Karelian Protocraton),with zircon data by Bibikova et al. (1997)(c) the Vorochistoe dacite (Belomorian Belt), with zircon data by Bibikova et al. (1999)(d) the Tupaya Bay K-granite (Belomorian Belt) with zircon data by Lobach-Zhuchenko et al. (1993a).

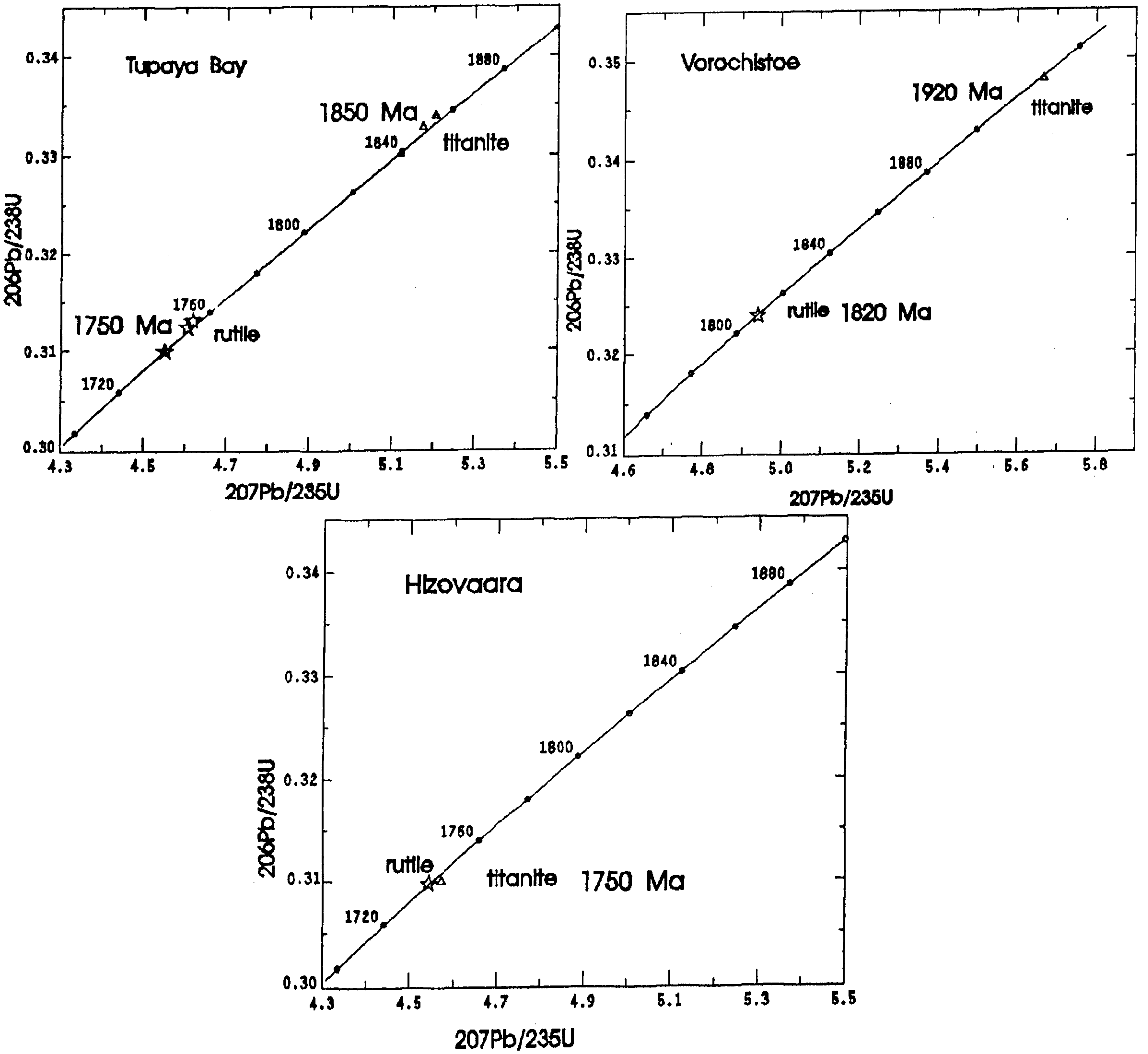

Fig. 3. Concordia diagrams for titanites and rutiles from various rocks in the Belomorian Mobile Belt and the junction zone between the Belomorian and Karelian Provinces. The sample sources are: (a) Tupaya Bay Al-gneisses; (b) Vorochistoje dacite; (c) Hizovaara tonalite.

Regardless of the ages of the host rocks, their volcanic or plutonic origins, metamorphic prehistories and tectonic positions, these ages are all within the time period between 2000 and 1815 Ma (Table 1 and Fig. 2c,d). Thus, for instance, in the Tupaya Bay locality the titanites from Al-gneisses, with zircon ages older than 2.8 Ga, from a ca. 2.7 Ga old gabbro and from 2.45 Ga potassic granites, all have virtually identical U–Pb ages of ca. 1.85 Ga.

5.3. The junction zone

In the junction zone between the Karelian Craton and the Belomorian Mobile Belt, a substantial proportion of the titanite ages are discordant in the sense of plotting between the ages of late Palaeoproterozoic resetting and Archaean or earliest Palaeoproterozoic origins (Figs. 3 and 4). In a 2.8 Ga tonalite from the Hizovaara greenstone belt, two generations of titanite are present. An older, magmatic one that coexists paragenetically with igneous plagioclase and biotite has discordant U–Pb ages between ca. 2300 and 1780 Ma (Sample 15 in Table 1), while a younger low-uranium generation associated with muscovite (Sample 16 in Table 1) has an almost concordant U–Pb age of 1770 Ma. Discordant U–Pb ages were also obtained for titanites from a sheared gneiss (Sample 19 in Table 1) and a charnockite (Sample 17 in Table 1).

5.4. Rutile ages

All the rutiles analysed in the present study stem from the Belomorian Belt and its junction zone with the Karelian Protocraton. Their ages vary between 1810 and 1740 Ma (Table 2 and Fig. 3), and thus mostly are ca. 50–100 Ma younger than those of the coexisting titanites.

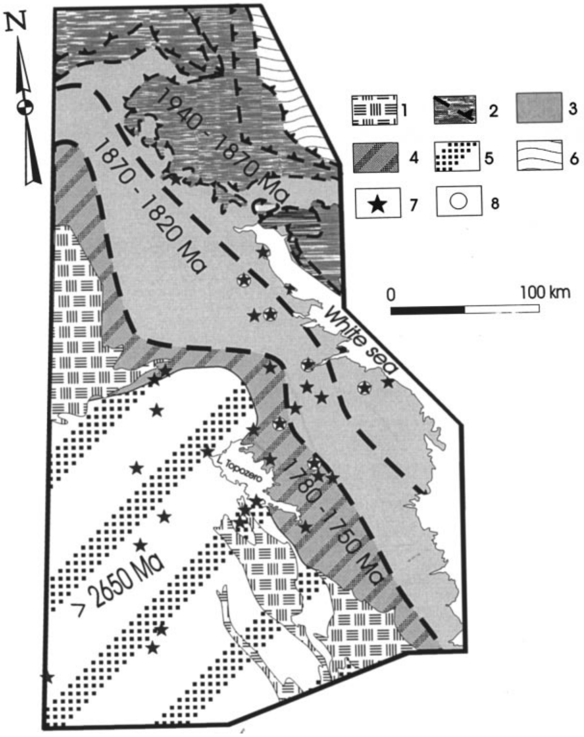

Fig. 4. General distribution of titanite ages in the region extending across the boundary between the Karelian Protocraton and the Belomorian Belt. The junction zone proper is marked by the lowest titanite ages. These mostly derive from titanites formed during late Palaeoproterozoic epizodes of shearing and recrystallization.

6. Discussion

From the titanite U–Pb ages obtained in this study (Table 1 and Table 2), it is obvious that the conditions of Palaeoproterozoic metamorphism were very different in the Karelian Protocraton and the Belomorian Mobile Belt.

In the Protocraton, the titanite ages are late Archaean, the only exception being a sample from a mafic igneous rock which is itself Palaeoproterozoic in age (Sample 14 in Table 1). From the Belomorian Belt, in contrast, not one single Archaean age has been obtained, even though most titanites analysed from that province were sampled in late Archaean rocks comparable to those in the Karelian Protocraton.

One of our principal findings is therefore that the Belomorian Belt had undergone thorough metamorphic reworking in the Palaeoproterozoic under relatively high temperature conditions (cf. Glebovitsky et al., 1996). Simultaneously, the temperatures in the Karelian Protocraton only occasionally exceeded the ca. 650°C required to open the titanite U–Pb systems. Despite substantial Palaeoproterozoic deformation and block faulting also in Karelia, high temperatures at that time appear to have been restricted to the immediate vicinity of late intrusions.

The junction zone between the Karelian Protocraton and the Belomorian Belt had its own, specific metamorphic development marked by the lowest titanite U–Pb ages in the entire region but also by incomplete age resetting of old, inherited titanites. Tectonic and/or hydrothermal processes in that zone therefore appear to have continued for a considerable time after the adjoining crustal provinces both in the west and the east had come to a relative rest.

As far as specific conditions within the principal crustal provinces and rock units of the investigated region are concerned, the following regularities apply.

In the Karelian Protocraton, it is notable that amongst the thirteen Archaean titanite ages

(Table 1) no less than eight plot within a relatively narrow time interval between 2.71 and 2.69 Ga. Since these titanite samples derive from six different localities distributed across a sizeable area and represent volcanic as well as plutonic rocks, their U–Pb ages appear to describe a period of regional crustal cooling when variously formed igneous and metamorphic titanites crossed the isotherms that marked the closure of their U–Pb systems. The cooling at ca. 2.70 Ga followed upon a series of igneous and metamorphic orogenic events, amongst which the ca. 2.74–2.72 Ga TTG Tavayarvi-Notozero magmatism has already been referred to in the description of the regional geological background.

In some of the TTG-type plutonic rocks, two different generations of titanite are seen under the microscope and can be distinguished further from their chemical compositions. The older titanite comprises dark-coloured crystals which mostly have moderate to high uranium contents and modes of occurrence, suggesting igneous crystallization. The younger generation, in contrast, is lightly coloured, typically low in uranium and appears largely to have grown within previously solidified rock.

Two of the light, presumably metamorphic titanites poor in uranium (Samples 6 and 9 in Table 1) have yielded U–Pb ages of 2.64 and 2.65 Ga. Together with two apparently igneous titanites of 2.64 and 2.62 Ga age (Samples 10 and 12), these crystals appear to date a period of heating associated with magmatism. During that time, new igneous and metamorphic titanites were formed, but no general resetting of the ages of the older titanite grains appears to have taken place. It is interesting that the new dating of a final Archaean tectonothermal event at ca. 2.65–2.62 Ga agrees well with the field observations of Systra and Semenov (1990), who found that the 2725 Ma Tavayarvi quartz diorite had been deformed and reheated during a tectonic episode before ca. 2.45 Ga.

Only one sample of titanite from the presently considered part of the Karelian Protocraton has yielded a U–Pb age older than 2.71 Ga (Sample 1 in Table 1). It remains unclear why that age had not been reset, but from Fig. 1 it is evident that the locality concerned is rather remote from the other sites of sampling. Therefore resetting of titanite U–Pb ages after the 2.74–2.72 orogenic phase may not have affected all of the studied area.

In the Belomorian Mobile belt, discordant isotopic plots showing incomplete resetting of older titanite U–Pb ages are uncommon except in the junction zone with the Karelian Protocraton. This indicates comprehensive Palaeoproterozoic reheating to temperatures above ca. 650°C and thorough metamorphic re-equilibration. Nevertheless, variation of the titanite ages across the Belomorian Belt is quite marked. Three different, somewhat indistinctly delimited age zones can be distinguished.

As indicated in Fig. 1, the highest ages ranging from ca. 1.88 to more than 1.90 Ga are encountered in a wide marginal zone outlining the large Lapland-Kola collisional thrust-and-nappe system that delimits the Lapland and Kolvitsa-Umba granulite terranes toward the south and southwest. Titanite U–Pb ages within the indicated range are here represented by Samples 26, 27, 29, 38, 39, 40 and 42 (Table 1), the only exception being Sample 28 which, however, has very wide limits of uncertainty and may have been affected by late shearing.

In the core part of the Belomorian Mobile Belt, which is not separated sharply from the northeastern marginal zone either agewise or lithologically, the titanite U–Pb ages are rather well concentrated to between 1.82 and 1.87 Ga, six of the nine samples (Samples 30 through 37 and 41 in Table 1) plotting at 1.84–1.85 Ga with low analytical errors. While some of the ages around or above 1.90 Ga in the northeast (e.g. Sample 26 in Table 1) may be related directly or indirectly to the formation of 1.94–1.91 Ga igneous mafic, dioritic and anorthositic rocks (cf. e.g. Bernard-Griffiths et al., 1984; Barling et al., 1997; Tuisku and Huhma, 1999), others clearly derive from late Archaean (2.7–2.8 Ga) or earliest Palaeoproterozoic (ca. 2.45 Ga) lithologies (Table 1) and must therefore be interpreted as reset ages or ages marking metamorphic growth of titanite.

The zonation of titanite ages across the northeastern and central zones of the Belomorian Belt must therefore have been created by the Lapland-Kola orogeny. Burial during that collisional event began ca. 1.91 Ga ago and was succeeded by uplift lasting past 1.87 Ga (Tuisku and Huhma, 1999).

Ages of cooling that are higher in the northeastern marginal zone of the Belomorian Belt than in its central part agree well with the higher tectonostratigraphic position of the former unit immediately beneath the Lapland and Kolvitsa-Umba allochthons. They also fit excellently with observations of metamorphic inversion in the immediate substratum of the Lapland Granulite Belt (e.g. Barbey and Raith, 1990) implying that part of the heat of metamorphism in that substratum had been brought in by the hot granulite nappes thrusted toward the southwest. Thus the heating associated with metamorphism in the northeastern marginal zone must have been a somewhat earlier, shorter event than the heating associated with deep burial in the central part of the Belomorian Belt.

At first sight, the relatively low U–Pb ages obtained from many of the titanites in the Karelian-Belomorian junction zone appear to continue the southwestwards-younging age zonation in the northeastern and central parts of the Belomorian Belt. However, a consideration of the characteristics of the respective titanite populations cautions against such extrapolation.

While most of the titanites in the main body of the Belomorian Belt are well equilibrated and age-reset originally igneous or metamorphic crystals that describe a reheating-cooling history, the titanites in the junction zone largely comprise other types.

In contrast to the rest of the Belomorian Belt, discordant, incompletely age-reset titanites are relatively common (Samples 15, 17 and 19 in Table 1), while the dominant fraction, the one principally responsible for the 1.78–1.75 Ga ages, consists of newly grown titanites. Most of these (Samples 16, 20, 22, 24 and 25 in Table 1) have characteristically low uranium (and lead) contents, whereas a low proportion may represent age-reset or recrystallized grains of igneous or metamorphic derivations (Samples 21 and 23, possibly also Sample 18).

This mineral set-up focuses attention on the performance and role of newly grown titanites specifically in shear zones and other structures like the Karelian-Belomorian junction zone.

While low-temperature, diagenetically grown titanites have been known for many decades, recent mineralogical and isotopic studies (e.g. Gromet, 1991; Resor et al., 1996) have particularly emphasized the growth of titanites in shear zones, where the easy passage of hydrothermal fluids (Bancroft et al., 1987; Pan et al., 1993; Frei et al., 1997) may lead to both extensive growth of new and complete recrystallization of older titanites. Under the influence of carbonate fluids, loss of Ca has been demonstrated as well as extensive removal of uranium and already accumulated radiogenic lead from older titanites. If the loss of radiogenic lead is complete and/or the titanites have been newly grown, U–Pb isotope analysis will date the process of hydrothermal reworking and indirectly that of the shearing. Ongoing experimental work on titanites, employing fluids under conditions of high pressure and temperatures, fully confirms the conclusions drawn from field observations (E. Bibikova, unpublished data).

Characteristically, the mean concentration of uranium in the titanites from the Karelian-Belomorian junction zone is 12 ppm, whereas it is much higher in the rest of the Belomorian Belt (ca. 50 ppm) and higher still (about 80 ppm) in the Karelian Protocraton.

Another line of evidence which stresses the important role of newly grown, hydrothermal, relatively low-temperature titanites expressly in the Karelian-Belomorian junction zone is comparison between the titanite and rutile ages (Table 2 and Fig. 1). Even though these are relatively few, there appears to be a tendency for the difference between the titanite and rutile ages to be ca. 50 Ma, practically less in the junction zone, and ca. 50–100 Ma in the main body of the Belomorian Belt (Table 1 and Table 2, Fig. 2 and Fig. 3). Since the average closure temperatures of titanites and rutile U–Pb isotope systems are ca. 650 and ca. 450°C, respectively, the data from the main part of the Belomorian Belt indicate slow cooling rates between 2 and 4°C/Ma, while within the junction zone the titanite and rutile ages are more similar indicating a close development of these minerals.

From these data, it can be inferred that thermal and hydrothermal reworking of the crust lasted much longer in the junction zone than in its surroundings. This gives the originally Neoarchaean suture the role of a specific zone of weakness during and after the Palaeoproterozoic Lapland-Kola orogeny. Intense late hydrothermal-fluid activity in the Karelian-Belomorian junction zone conforms well with the abundant occurrence of late Palaeoproterozoic pegmatites in the Belomorian Belt, the presence in that zone of kyanite-bearing metasomatites (e.g. Kozhevnikov, 1992) and the association of that zone with amphibolite-facies brecciation and mylonitization (e.g. Shurkin, 1974).

7. Conclusions

From the obtained data and their consideration as reported in the above discussion, the following principal conclusions are drawn:

1. Now exposed parts of the Archaean Karelian Protocraton and the Belomorian Mobile Belt were drastically different in their degrees of Palaeoproterozoic tectonothermal reworking related to the Lapland-Kola orogeny. In the Belomorian Belt. temperatures above 650°C prevailed throughout, and the titanite U–Pb ages were reset almost totally, while the studied part of the Karelian province temperatures above ca. 650°C were never reached except in the vicinity of Palaeoproterozoic intrusions.
2. No information pertaining to the Archaean development of the Belomorian Belt can be obtained from the U–Pb titanite and rutile data, but in the Karelian Protocraton a period of general cooling past 650°C at 2.71–2.69 Ga succeeded TTG-type magmatism at 2.74–2.72 Ga. A less comprehensive tectonothermal event at ca. 2.65–2.64 Ga appears to have been associated with some metamorphism and igneous activity but did not lead to general heating above 650°C.
3. In the Belomorian Belt, closure of the titanite U–Pb isotope system at ca. 650°C occurred at ca. 1.94–1.88 Ga in the northeastern marginal zone and at 1.87–1.82 Ga in its central part. This difference originated from the different tectonostratigraphic positions (levels) of those parts of the Belt during the syn-collisional and post-collisional stages of the Lapland-Kola orogeny.
4. The Karelian-Belomorian junction zone, the boundary zone between two of the principal Archaean crustal provinces of the Baltic Shield created originally in the Neoarchaean, played the role of a major zone of shearing and magmatism in the late Palaeoproterozoic in relation to the Lapland-Kola orogeny. In that zone, titanite with ages as young as 1.78–1.75 Ga are dominant, but a fraction with discordant ages caused by incomplete resetting is also prominent. Extensive hydrothermal activity is here evidenced by abundant newly grown titanite, loss of uranium and radiogenic lead, as well as rutile and titanite ages less different than in the Belomorian Belt and the Karelian Protocraton outside the junction zone.

Acknowledgements

This work was supported by the INTAS-RFFI project 95-1330 and RFFI project 97-05-65565. David Bridgwater has been an infallible source of inspiration, also much emphasizing the significance and necessity of the studies here presented. The results obtained are a contribution to IGCP-Project 371 COPENA and the SVEKALAPKO project of ESF's and ILP's EUROPROBE Programme. Two anonymous reviewers are thanked for corrections of the manuscript.

References

Amelin, Yu.V., Heaman, L.M., Semenov, V.S., 1995. U–Pb geochronology of layered mafic intrusions in the eastern Baltic Shield: implication for the timing and duration of Palaeoproterozoic continental rifting. Precambrian Res. 75, 31–46.

Balagansky, V.V., Glaznev, V.N., Osipenko, L.G., 1998. The Palaeoproterozoic evolution of the northeastern Baltic Shield: a terrane analysis. Geotektonika 2, 16–28 In Russian.

Bancroft, G.M., Metson, J.B., Kresovic, R.A., 1987. Leaching studies of natural and synthetic titanites using secondary ion mass spectrometry. Geochim. et Cosmochim. Acta. 51, 911–918.

Barbey, P., Raith, M., 1990. The Granulite Belt of Lapland. In: Vielzeuf, D., Vidal, P. (Eds.), Granulite and Crustal Evolution. Kluwer Academic Publishers, The Netherlands, pp. 111–132.

Bernard-Griffiths, J., et al., 1984. Isotopic data (U–Pb, Rb–Sr, Pb–Pb and Sm–Nd) on mafic granulites from Finnish Lapland. Precambrian Res. 23, 325–348.

Bibikova, E.V., 1989. Uranium–lead Geochronology of the Early Stages in the Development of Ancient Shields, Moscow, Nauka, p. 168 (in Russian).

Bibikova, E.V., Mel'nikov, V.F., Avakyan, K.Kh., 1993. Lapland granulites: petrology, geochemistry, isotopic age. Petrologija 1, 181–198 In Russian and English.

Bibikova, E.V., Skiöld, T., Bogdanova, S.V., 1996. Age and geodynamic aspects of the oldest rocks in the Precambrian Belomorian Belt, Baltic Shield. In: Brewer, T. (Ed.), Precambrian crustal evolution in the North Atlantic Region, vol. 112. Geological Society of London Special Publication, pp. 58–76.

Bibikova, E.V., Slabunov, A.I., Kirnozova, T.I., Makarov, V.A., 1997. U–Pb geochronology and major-element chemistry of a diorite-plagiogranite batholith in Northern Karelia. Geochemistry International 11, 1154–1160.

Bibikova, E.V., Slabunov, A.I., Bogdanova, S.V., Skiöld, T., 1999. Early magmatic events in the evolution of the Belomorian Mobile Belt (Baltic Shield): lateral zonation and isotope age. Petrologija (Petrology) 2, 115–125.

Bogdanova, S.V., 1996. High-grade metamorphism of 2.45–2.4 Ga age in mafic intrusions of the Belomorian Belt of the northeastern Baltic Shield. In: Brewer, T. (Ed.), Precambrian crustal evolution in the North Atlantic Region, vol. 112. Geological Society of London Special Publication, pp. 69–90.

Bogdanova, S.V., Bibikova, E.V., 1993. The 'Saamian' of the Belomorian mobile belt: new geochronological constraints. Precambrian Res. 64, 131–152.

Bridgwater, D., Marker, M., Mengel, F., 1992. The eastern extension of the Early Proterozoic Torngat orogenic zone across the Atlantic. In: Wardle, R.J., Hall, J. (Eds.), Eastern Canadian Shield Onshore-Offshore Transect (EC-SOOT). Lithoprobe report, vol. 27, pp. 76–91.

Bridgwater, D., Glebovitsky, V.A., Sedova, I.S. et al., 1994. Sub-horizontal stretching fabrics and high-grade metamorphic assemblages in 2.5–2.35 Ga syntectonic igneous suites from the Belomorian fold belt. Evidence of acid-basic igneous activity during extension in the deep crust. In: IGCP Symposium 275 and 371, Nottingham. Terra Nova, 6, Abstract suppl., 2, p. 4.

Cherniak, D.J., 1993. Lead diffusion in titanite and preliminary results on the effect of radiation damage on Pb transport. Chem. Geol. 110, 177–194.

Corfu, F., 1996. Multistage zircon and titanite growth and the inheritance in an Archean gneiss complex, Winnipeg River Subprovince. Ontario. Earth Planet Sci. Lett. 141, 175–186.

Dodson, M.H., 1973. Closure temperature in cooling geochronological and petrological systems. Contrib. Mineral. Petrol. 40, 259–274.

Dodson, M.H., 1979. Theory of cooling ages. In: Jager, E., Hunziker, J.C. (Eds.), Lectures in Isotope Geology. Spreinger-Verlag, Berlin, Heidelberg, New York, pp. 194–202.

Frei, R., Villa, I.M., Nagler, Th.F., et al., 1997. Single mineral dating by Pb–Pb stepleaching method assessing the mechanism. Geochim.et Cosmochim. Acta 61, 393–414.

Gaál, G., Gorbatschev, R., 1987. An outline of the Precambrian evolution of the Baltic Shield. Precambrian. Res. 35, 15–52.

Glebovitsky, V.A., 1993. Tectonics and Early Precambrian metamorphism in the Eastern Baltic Shield. Regional Geology and Metallogenesis 1, 7–24 In Russian.

Glebovitsky, V.A., Miller, Y.A., Drugova, G.M., Mil'kevich, R.I., Vrevsky, A.B., 1996. Structure and Metamorphism of the Belomorian-Lapland Collisional Zone. Geotektonika 1, 63–75 In Russian.

Gorbatschev, R., et al., 1987. Mafic dyke swarms of the Baltic Shield. In: Halls, H., Fahrig, W.F. (Eds.), Mafic Dyke Swarms. Geological Association of Canada Special Paper, Canada, pp. 361–372.

Gromet, L.P., 1991. Direct dating of deformational fabrics. In: Heaman, L., Ludden, J.N. (Eds.), Applications of radiometric isotope systems to problems in geology, Mineral. Assoc. Can, pp. 167–189.

Kozhevnikov, V.N., 1992. Geology and Geochemistry of the Archaean North-Karelian Greenstone Structures. Karelian Science Centre, Petrozavodsk, 199 pp. (in Russian).

Kratz, K.O. (Editor), 1978. The Earth's Crust of the Eastern Part of the Baltic Shield. Nauka, Leningrad, 232 pp. (in Russian).

Krogh, T., 1973. A low contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determination. Geochim. et Cosmochim. Acta. 37, 485–494.

Kudryashov, N.M., Balagansky, V.V., Apanasevich, E.A., Ryungenen, G.J., 1999. U–Pb age of gabbro-norites of the Zhemchuzhnyi massif: consequences for Palaeoproterozoic evolution of the Belomorian Mobile Belt. Geochemistry International 37 (3), 324–327.

Lobach-Zhuchenko, S.B., Bibikova, E.V., Drugova, G.M., 1993a. Geochronology and petrology of magmatic complexes of Tupaya Bay, North-West Belomorje. Petrologija (Petrology) 6, 657–677 in Russian and English.

Lobach-Zhuchenko, S.B., Chekulaev, V.P., Sergeev, S.A., Levchenkov, O.A., Krylov, I.N., 1993b. Archaean rocks from southeastern Karelia (Karelian granite-greenstone terrain). Precambrian Res. 62, 375–397.

Lobach-Zhuchenko, S.B., et al., 1995. Archaean magmatism in the Notozero area in northwestern Belomorje: isotopic geochronology and petrology. Petrologija (Petrology) 3, 539–566 in Russian and English.

Mezger, K., Hanson, G.N., Bohlen, S.R., 1989. High precision U–Pb ages of metamorphic rutile: application to the cooling history of high-grade terrains. Earth Planet Sci. Lett. 96, 106–118.

Mezger, K., Rawnsley, C.M., Bohlen, S., Hanson, G.N., 1991. U–Pb garnet, sphene, monazite and rutile ages: implications for the duration of high-grade metamorphism and cooling histories, Adirondack Mts., New York. Journal of Geology 99, 415–428.

Miller, Yu.V., 1997. Unique folds in the fold-and-thrust framework of the Belomorian Mobile belt. Geotektonika 4, 80–89 in Russian.

Miller, Yu.V., Mil'kevich, R.I., 1995. Thrust-fold structure of the Belomorian zone and its correlation with the Karelian granite-greenstone region. Geotektonika 6, 80–93 in Russian.

Mints, M.V., 1996. The Early Precambrian of the Northeastern Baltic Shield: Paleogeodynamics, crustal structure and evolution. Transactions of the Geological Institute of Russian Academy of Sciences, vol. 503. Nauchny Mir, Moscow, p. 287.

Mitrofanov, F.P., 1995. Geology of the Kola Peninsula (Baltic Shield)., Apatity, 145 pp.

Pan, Y., Fleet, M.E., MacRae, N.D., 1993. Late alteration in titanite ($CaTiSiO_5$): redistribution and remobilization of rare earth elements and implication for U–Pb and Th–Pb geochronology and nuclear waste disposal. Geochim.et Cosmochim. Acta 57, 355–367.

Pidgeon, R.T., Bosh, D., Bruuguier, O., 1996. Inherited zircon and titanite U–Pb systems in an Archaean syenite from southwestern Australia: implications for U–Pb stability of titanite. Earth Planet.Sci. Lett. 141, 187–198.

Puchtel, I.S., Zhuravlev, D.Z., Kulikova, V.V., et al., 1991. Komatiites of the Vodlozero block of the Baltic Shield. Doklady AN USSR B 317 (1), 197–202 in Russian.

Puchtel, I.S., et al., 1998. Oceanic plateau model for continental crustal growth in the Archaean: a case study from the Kostomuksha greenstone belt, NW Baltic Shield. Earth Planet. Sci. Lett. 155, 57–74.

Resor, P.C., Chamberlain, K.R., Frost, C.D., Snoke, A.W., Frost, B.R., 1996. Direct dating of deformation: U–Pb age of syndeformational sphene growth in the Proterozoic Laramie Peak shear zone. Geology 24, 1123–1126.

Rybakov, S.I., 1987. Sulphur Metallogeny in Early Precambrian of the Baltic Shield. Nauka, Leningrad, 266 pp. (in Russian).

Scott, D.J., St-Onge, M.R., 1995. Constraints on Pb closure temperature in titanite based on rocks from Ungava orogen, Canada: implication for U–Pb geochronology and P–T–t path determinations. Geology 23 (12), 1123–1126.

Shurkin, K.A. (Editor), 1974. Geology and Magmatism of the Junction Area Between Karelides and Belomorides. Nauka, Leningrad, 184 pp. (in Russian).

Skiöld, T., Bibikova, E., Slabunov, A., Bogdanova, S., 1997. The effect of Paleoproterozoic tectonothermal processes on titanite and zircon ages from the Karelian-Belomorian assemblage of the Baltic Shield. EUG 9 Abstract Supplement. Terra Nova 9, 129–130.

Sokolov, V.A., Heiskanen, K.J., 1985. Evolution of Precambrian volcanogenic-sedimentary lithogenesis in the southeastern part of the Baltic Shield. Geol. Survey Finland. Bull. 331, 91–106.

Stacey, J.S., Kramers, J.D., 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. Earth Planet Sci. Lett. 26, 207–221.

Stepanov, V.S., Slabunov, A.I., 1989. Amphibolites and Early Basite-Ultrabasites of the Precambrian in Northern Karelia. Nauka, Leningrad, 176 pp. (in Russian).

Systra, Y.J., Semenov, A.S., 1990. Geological complexes and tectonics on the western shores of Lake Pyaozero. In: Stenar', M.M., Stepanov, V.S., Shiptsova, N.I. (Eds.), Precambrian of Northern Karelia. Karelian Science Centre, Petrozavodsk, pp. 7–29 in Russian.

Taipale, K., 1983. The geology and geochemistry of the Archaean Kuhmo greenstone-granite terrain in the Tipasjärvi area, eastern Finland. Acta Univ. Oulu A 151, Geol. 5, 98.

Timmerman, M.J., Daly, J.S., 1995. Sm–Nd evidence for the Late Archaean crust formation in the Lapland-Kola Mobile belt, Kola Peninsula, Russia and Norway. Precambrian Res. 72, 97–107.

Tucker, R.D., et al., 1987. Uranium–lead zircon and titanite ages from the northern portion of the Western Gneiss region, south-central Norway. Earth Planet Sci. Lett. 96, 106–118.

Tugarinov, A.I., Bibikova, E.V., 1980. Geochronology of the Baltic Shield by Zirconometry. Nauka, Moscow, 130 pp. (in Russian).

Tuisku, P., Huhma, H., 1999. SIMS U–Pb dating of zircons from migmatite khondalites and enderbites from Lapland Granulite belt, Finland. J. Conf. Abs. 4, 710–711.

Zhang, L-Sh, Schaerer, U., 1996. Inherited Pb component in magmatic titanite and their consequence for the interpretation of U–Pb ages. Earth Planet Sci. Lett. 38, 57–65.

Verts, L.A., Chamberlain, K.R., 1996. U–Pb sphene dating of metamorphism: the importance of sphene growth in the contact aureole of the Red Mountain pluton, Laramie Mountains, Wyoming. Contrib. Mineral. Petrol., 657–677.

Volodichev, O.I., 1990. The Belomorian complex of Karelia: Geology and Petrology. Leningrad: Nauka, 248 pp. (in Russian).

Vuollo, J., Nykänen, V., Liipo, J., Piiranen, T., 1994. Mafic dyke swarms from 2.44 Ga to 1.97 Ga in eastern Fennoscandian Shield. In: Precambrian crustal evolution in the North Atlantic regions. Abstracts, Terra Nova 6 (2), 21–22.