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Age and ϵ_{Nd} constraints on the Palaeoproterozoic tectonic evolution in the Baltic-Sea region

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Abstract

The metamorphic Precambrian basement in the western part of the East European Craton (EEC) has previously been considered to be Archaean in age. Recent U–Pb and Sm–Nd studies in Estonia, Poland and Belarus have, however, revealed a vast area of Palaeoproterozoic crust. In order to survey the crustal ages in Latvia and Lithuania, and to establish the relationships of these territories with adjacent regions of the EEC, particularly those exposed in the Baltic and Ukrainian Shields, three new U–Pb zircon age determinations and 21 ϵ_{Nd} whole-rock analyses were performed.

In Latvia, a granodiorite yielded an intrusion age of 1816 ± 5 Ma and a felsic metavolcanic rock an age of metamorphism at 1810 ± 2 Ma, with indications of a minimum protolith age of ca. 1840 Ma. In Lithuania, a metasediment yielded a multigrain U–Pb zircon age of 2302^{+200}_{-100} Ma, very similar to multigrain zircon ages of Svecofennian metasediments in Scandinavia.

The ϵ_{Nd} survey of various rock types demonstrated relatively little variation, with depleted-mantle model ages between 2.4 and 1.9 Ga for the igneous rocks and between 2.5 and 2.0 Ga for the metasedimentary ones. This indicates only minor influence of Archaean crust but close isotopic similarity to rocks of the same lithologies in the Svecofennian Domain of Sweden and Finland.

Together with recent U–Pb and Sm–Nd results from other parts of the EEC, the present study suggests a close relationship between the Palaeoproterozoic crust in Estonia, western Latvia and western Lithuania, and the southern part of the Svecofennian Domain within the Baltic Shield. All these regions have U–Pb zircon ages of rock formation between 1.90 and 1.82 Ga, and were subjected to a major metamorphic event between 1.83 and 1.81 Ga. These ages contrast with ages between 2.0 and 1.9 Ga for similar rocks farther east and southeast, i.e. closer to the Ukrainian Shield. Altogether, the current results reaffirm an accretionary character of the Palaeoproterozoic crust in the western part of the EEC, as previously concluded by other investigators. In addition, there is basis to suggest that the crust in western Latvia and Lithuania was formed during the late stages of the Svecofennian orogeny and thus can be correlated with juvenile late Svecofennian crust in southeastern Sweden.

Keywords: U–Pb zircon dating; Sm–Nd; Palaeoproterozoic; East European Craton; Baltic shield

1. Introduction

The Precambrian basement of the East European Craton (EEC) is covered extensively by Neoproterozoic and Phanerozoic platform sediments, and is

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therefore known principally from geophysical investigations and a great number of drillholes.

The platformal part of the EEC comprises the region between the two major Precambrian shield areas in Europe, the Baltic and the Ukrainian Shields. Already during the 19th century, the crystalline basement in that part of the EEC began to be investigated by deep-well drillings. In the last decades, such studies have been complemented by various isotopic investigations of the drilling-core materials. Instrumental in that regard were various international research enterprises such as IGCP-projects 275 'Deep geology of the Baltic/Fennoscandian Shield', 314 'Rapakivi Granites and Related Rocks', 371 'North Atlantic Precambrian (COPENA)' and the EUROBRIDGE geophysical–geological transect. These studies, which largely relied on U–Pb zircon ages and Nd-isotopic surveys, have by now totally changed our views of the age of the Precambrian crust in the region and have indicated the presence of a vast domain of Palaeoproterozoic rocks between the two shields (Shcherbak et al., 1990; Shcherbak, 1991; Puura and Huhma, 1993; Bogdanova et al., 1994; Claesson et al., 1994; Bibikova et al., 1995, 1996).

The area in Latvia and Lithuania studied in particular in the present context has been suggested to be an orogen formed by the accretion of juvenile terranes between ca. 2.0 and 1.8 Ga ago (Bogdanova et al., 1994, 1996a; Claesson et al., 1994; Bibikova et al., 1996, 1997). A deeper understanding of its formation and position within the EEC, however, requires additional meticulous analytical work and correlation of the results with those from other areas, particularly such where the Proterozoic crust is well exposed. In the present paper, the author reports U–Pb age determinations on zircons and the results of a Nd-isotopic study of key rock assemblages. Possibilities of correlation with the Baltic Shield are also discussed. As a result, a tentative model of the crustal evolution of large regions in the northwestern EEC is proposed.

2. Geological background

The EEC is composed of three crustal segments (Bogdanova, 1993; Gorbatschev and Bogdanova, 1993), Fennoscandia in the north, Sarmatia in the south and Volgo-Uralia in the east (Fig. 1, cf. also Bogdanova et al., 1994, 1996b). Amongst these, Fennoscandia and its borderlands towards Sarmatia are in the focus of attention in the present paper.

Apart from an Archaean core in its northeastern part and the exposed Baltic Shield in the northwest, the Fennoscandian crustal segment comprises the subplatformal crystalline basement in Estonia, Latvia, Lithuania, Belarus, northeastern Poland and the westernmost part of Russia. Excluding post- to anorogenic intrusions and platform-cover supracrustal rocks, the metamorphic grades at the surface of this crust are invariably granulitic to upper amphibolitic. In the southern part of the area (Lithuania, Poland and Belarus) the granulite- and amphibolite facies rocks form belts with NNE–SSW orientation, whereas in Estonia they trend WNW–ESE (Fig. 1). Together, these differently orientated belts define an arcuate pattern that reflects crustal growth by accretion and associated collisions outward from two Archaean proto-cratons, one of these in northeastern Fennoscandia, the other in Sarmatia. Stephens and Wahlgren (1996) used the term 'bilateral collision' to describe that phenomenon. Reasonably regular alternation between amphibolite- and granulite-facies belts is particularly marked along the edge of Sarmatia, where these belts are younging from the southeast toward the northwest (Gorbatschev and Bogdanova, 1993; Bogdanova et al., 1994).

The following text provides a short review of these alternating granulite- and amphibolite-facies tectonic units, employing the nomenclature of Bogdanova et al. (1994).

The easternmost of the amphibolite-facies belts is the Osnitsk–Mikashevichi Igneous Belt (OMB), located atop and adjacent to the Archaean rocks of the Ukrainian Shield (Fig. 1). It principally comprises calc-alkaline magmatic rocks with U–Pb zircon ages between 2.02 and 1.97 Ga (Shcherbak et al., 1990; Shcherbak, 1991; Bibikova et al., 1995). Sm–Nd surveys yielding ϵ_{Ndt} values between +1.5 and +2.4 suggest formation mainly from juvenile mantle sources (Claesson et al., 1994; Bibikova et al., 1995).

Situated in Belarus north of the OMB is the high-grade Vitebsk Granulite Domain (VG). A U–Pb age determination on a monazite from that area has yielded 1.95 Ga which is interpreted as the age of peak metamorphism (Bibikova et al., 1995, 1996).

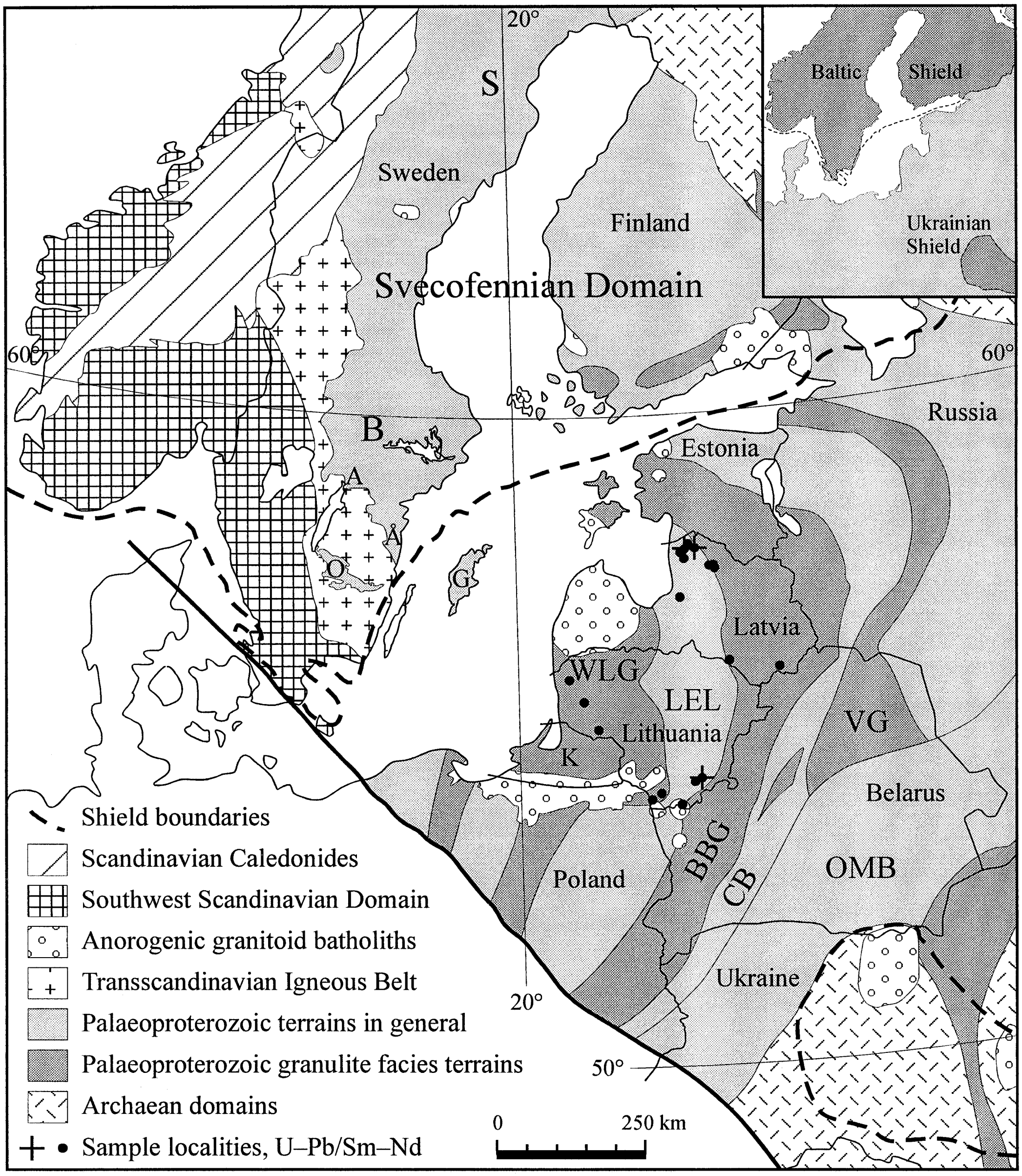

Fig. 1. Simplified geological map of the Precambrian crust in the Baltic Shield and the adjoining platform areas (compiled from Puura et al., 1978; Gaál and Gorbatschev, 1987; Bogdanova et al., 1994). BBG = Belarus–Baltic Granulite Belt, CB = Central Belarus Belt, LEL = Latvian–East Lithuanian Belt, OMB = Osnitsk–Mikashevichi Igneous Belt, VG = Vitebsk Granulite Domain, WLG = West Lithuanian Granulite Domain, A = Askersund, Å = the Åtvidaberg–Valdemarsvik area, B = Bergslagen, G = Gotland, K = Kaliningrad Enclave O = Oskarshamn–Jönköping Belt, S = Skellefte district. Inset map shows the location of the Baltic and Ukrainian Shields.

Farther to the west follows the Central Belarus Belt (CB), where the U–Pb zircon magmatic ages are between 2.0 and 1.9 Ga (Shcherbak et al., 1990; Bogdanova et al., 1994; Claesson et al., 1994; Bibikova et al., 1996). The initial ϵ_{Nd} values of these rocks range between +2.1 and +3.3, suggesting that juvenile mantle material was the main source of material (Bibikova et al., 1995; Claesson et al., 1994).

To its northwest, the CB is bordered by the Belarus–Baltic Granulite Belt (BBG). Across the separating inter-belt boundary there appears to exist an age discontinuity of ca. 0.1 Ga (Bogdanova, 1997). The BBG is composed of lenses of meta-igneous charnockites with minor metasedimentary units. Magmatic rocks in the BBG have U–Pb zircon ages between 1855 and 1790 Ma (Shcherbak et al., 1990; Bogdanova et al., 1994), while peak metamorphism appears to have occurred close to the end of that period, ca. 1.79 Ga ago (Bibikova et al., 1995). The isograds of metamorphism sometimes cut across the boundary between the CB and the BBG which suggests that these belts (and probably also the belts farther east) were brought together and accreted to the proto-craton before 1.8 Ga ago (Bogdanova, 1997).

West of the BBG there is a N–S to NNE–SSW trending belt of rocks in the amphibolite facies. That unit, the Latvian–East Lithuanian Belt (LEL), is composed of granitoids and metavolcanics, the latter most commonly mafic in composition. Small occurrences of sedimentary rocks are also present. A more detailed description of the LEL, which is a unit important in the context of the present paper, will be found in Section 3.

The West Lithuanian Granulite Domain (WLG) is the westernmost of the granulitic tectonic units east of the Baltic Sea. It occupies western Lithuania and western Latvia together with the Kaliningrad enclave in East Prussia (Fig. 1). The boundary between the LEL and the WLG is not only sharp and characterized by a discontinuity of metamorphic grade but also implies a drastic change from N–S and NNE–SSW trending tectonic grain in the east to E–W striking structures in the west (Skridlaite et al., 1997). Lithologically, the WLG consists of metasedimentary and meta-igneous charnockitic–enderbitic rocks together with minor migmatitic granites (Bogdanova et al., 1996a). The igneous rocks are calc-alkaline which suggests formation along a destructive plate margin, presumably in an island arc setting (Skridlaite et al., 1997). A U–Pb monazite age of ca. 1.8 Ga has been interpreted to represent the age of the granulite-facies metamorphism (Bibikova et al., 1996).

Precambrian rocks younger than the Palaeoproterozoic comprise Mesoproterozoic anorogenic, principally granitic intrusions and Meso- to Neoproterozoic platform-cover sediments. The boundaries of these rock units extend across those between the Palaeoproterozoic belts just considered.

Rapakivi-type granites plus mafic and anorthositic rocks form the ca. 1.58 Ga old Riga batholith in western Latvia and minor rapakivi stocks in Estonia. The latter have ages close to 1.63 Ga (Rämö et al., 1996). Another group of young granitoid rocks builds up small plutons in southeastern Lithuania and western Belarus (Sundblad et al., 1994), and the large Mazury granite complex in northern Poland (Ryka, 1993). All these have U–Pb ages around 1.50 Ga (Sundblad et al., 1994; Claesson et al., 1996). Terrigeneous Meso- to Neoproterozoic sediments was deposited predominantly in large aulacogens.

On the basis of the geochronological data and the alternation between rock belts in the amphibolite- and the granulite facies, the territory adjoining the Sarmatian crustal segment in the northwest can be subdivided into three major terranes, even ‘megaterranes’, each of these consisting of two sub-terranes containing rocks of the upper and lower crust, respectively (Bogdanova et al., 1997). Amongst the two boundaries between the megaterranes, the eastern is identical with the boundary between the CB and the BBG belts, whereas the western follows the very marked boundary between the LEL and the WLG. The three megaterranes appear to have been accreted successively onto the northwestward growing continental margin of Sarmatian (Bogdanova et al., 1997).

Although the available datings demonstrate a Palaeoproterozoic age of the crystalline platform basement in the region between the Baltic and the Ukrainian Shields, no immediate lithological correlation with the exposed parts of the Shields is obvious. The almost sole exception is the Jõhvi Zone in northeastern Estonia where felsic volcanic rocks with iron mineralizations have been correlated with the Svecofennian Bergslagen ore district in Sweden and its continuation into southern Finland (Sundblad and Kivisilla, 1991). Volcanic areas, with iron formations identified from drillings and magnetic anomalies, can also be found in central Latvia.

In yet another attempt to find similarities, Ryka (1993) related the Mazury granite complex in northeastern Poland to the Transscandinavian Igneous Belt (TIB) in Sweden. Such correlation, however, appears untenable in the light of an age difference of more than 150 Ma (ca. 1.50 Ga for the Mazury as compared with ages between 1.85 and 1.66 Ga for the TIB; cf. Larson and Berglund, 1992; Persson and Wikström, 1993).

3. Geology of the areas sampled in Latvia and Lithuania

The crystalline basement in Latvia is the least well investigated Precambrian area in the Baltic countries, which is partly due to an overlaying Phanerozoic platform cover ranging between 600 and 2000 m in thickness. Early attempts at interpretation led to a subdivision into five orogenic 'cycles' with suggested ages from the early Archaean to the middle Proterozoic. Such modelling was largely based on K–Ar analyses not considered in regard to excess argon and, apart from that, age identification with Archaean granulite areas in the Kola Peninsula and elsewhere (Bogatikov and Birkis, 1973; Vetrennikov, 1991; Vetrennikov pers. comm., 1992). The rock units assumed to be the oldest comprise metasedimentary and mafic igneous lithologies metamorphosed to the granulite facies. They occur in eastern as well as southwesternmost Latvia. Central Latvia, however, which is mostly metamorphosed in the amphibolite facies, is mainly composed of the Staicele–Inchukalns felsic and mafic metavolcanic rocks. Within the felsic of these units, large stratiform iron deposits have been identified e.g. at Staicele in northern Latvia (Vetrennikov et al., 1986). Small granodiorite plutons such as the Mazsalaca granodiorite ca. 20 km east of Staicele occur among the supracrustals, while microcline granites, probably migmatitic in origin, are located in high-grade metamorphic terrains. Particularly in eastern Latvia, which is a part of the BBG, these rocks dominate the bedrock. Western Latvia, in contrast, is totally dominated by the large anorogenic Riga rapakivi batholith (Bogatikov and Birkis, 1973).

Important in the Precambrian bedrock of southeastern Lithuania is the Marcinkonys igneous complex which comprises granitoids varying from dark, gneissic granodiorites to light-red true granites. Within these granitoids there are occurrences of mafic and metasedimentary rock units metamorphosed in the amphibolite facies. These presumably represent megaxenoliths of older crustal materials. Further to the east, along the border with Belarus, granulite-facies rocks belonging to the BBG comprise charnockites and enderbites occasionally surrounded by migmatitic materials. The youngest igneous rock in the region is a red granite which is part of the Marcinkonys igneous complex. That rock, the Kabeliai granite, has I-type chemical characteristics. It has been dated by the U–Pb zircon method to 1505 ± 11 Ma (Sundblad et al., 1994).

The Precambrian crust in eastern Lithuania resembles the southeast Lithuanian crust in lithological character, but in northeasternmost Lithuania granulite-facies rocks occur along the border with Latvia.

Western Lithuania comprises metasedimentary and mafic igneous rocks metamorphosed in the granulite-facies, together with migmatite granites. It has been defined as WLG.

4. Sample description

Since the basement particularly considered in the present study is dominated by metasedimentary and mafic metavolcanic lithologies at high metamorphic grades, rocks suitable for U–Pb dating of the formation of the crust are rather difficult to find. However, two acceptable samples could be obtained from the Staicele area in north central Latvia, where there occur felsic volcanics as well as a granitoid pluton:

(1) Sample 92041 is a gray, fine-grained, sparsely quartz-porphyritic rhyodacite. It was collected from drillcore GK-1KC at Staicele (57.83°N, 24.80°E), at the depth level between 843 and 849 m.

(2) Sample 92042 represents a grayish-red granodiorite with up to three cm large microcline megacrysts. That rock belongs to the Mazsalaca pluton and was collected from the 761–778 m depth level of drillcore GK-4P at Rujena (57.83°N, 25.12°E).

The zircons of the Staicele metavolcanic rock vary from colorless and transparent to light brown and translucent. They form short prismatic crystals with rounded corners and corroded faces. Only a few grains exhibit oscillatory zoning. Fractured zircons are rare, but there occur small, radially oriented fractures in the interior parts of some of the grains. Between a third and half of the zircons contain minute dark inclusions. Some of the grains appear composed of small fragments of older crystals overgrown by new zircon substance.

In the Mazsalaca sample, the zircons are colorless to very light pink and transparent. They form short, prismatic crystals with smooth faces and sharp to slightly rounded corners, and contain very few fractures and inclusions. About 5–10% of the crystals exhibit minute cores, the overall core volume, however, representing less than one percent of the total volume of the zircons. Approximately half of the crystals show oscillatory zoning.

In Lithuania, the rocks hitherto sampled for U–Pb isotopic analysis derive from the southeastern part of the country, where the geology of the Precambrian bedrock is known best. A dating of the Kabeliai granite, the youngest granite in that area, has been published previously (Sundblad et al., 1994), while the work now done concerned the supposedly oldest rock unit.

Analyzed sample 90034 was collected from drillcore 403 at 54.34°N, 24.91°E. This is a gray, fine-grained rock mainly composed of plagioclase, quartz and biotite. Initially, it was believed to be an intermediate volcanic by the surveying geologists, but the U–Pb data presented below and a new, more thorough petrographical examination coupled with chemical data all suggest that the rock is a metagraywacke. Its zircons are generally light colored, ranging from brownish gray to colorless, and are cloudy to transparent. The length to width ratios are mainly between two and three to one, but a few needle-shaped zircons also occur. The crystal surfaces appear corroded and abraded, and the edges are rounded. Almost all the grains are fractured and a relatively large amount of crystal fragments is present in the separated fractions. More than half of the zircons exhibit oscillatory zoning, while a few have small cores. The overall core volume contributes less than one percent to the total zircon volume. A few crystals also contain small grayish inclusions of unknown composition.

The ϵ_{Nd} investigation was planned to cover as large an area and as wide a range of rock compositions as possible. In the first place, rocks with determined U–Pb ages were sampled, and altogether thirteen samples from Latvia and eight from Lithuania were analyzed. The rock types and sample locations are listed in Table 1 and shown graphically in Fig. 1.

5. Methods of analysis

The U–Pb samples were crushed and milled, and non-magnetic fractions of heavy minerals were obtained by standard methods. The heavy-mineral concentrates, which were mainly composed of zircons, were thereafter divided into size fractions. From these fractions, the zircons were subsequently handpicked under a binocular microscope. From some of the size fractions, sub-samples were picked and abraded in air employing the technique of Krogh (1982). From these sub-samples, in turn, second fractions were handpicked. The results were as follows: the Staicele volcanic rock yielded nine fractions of which two were air abraded, and only transparent colorless to lightly-colored zircons were picked by hand. From the Mazsalaca granitoid, one abraded and five unabraded zircon fractions were picked. The selected crystals were all transparent with well-developed crystal faces. From the metasedimentary unit in southeastern Lithuania, six fractions were separated of which two were abraded in air.

After handpicking, the zircons were prepared according to a procedure modified from Krogh (1973). The crystals were dissolved in hydrofluoric acid in 0.35 ml teflon beakers inside a teflon capsule. After uranium and lead spiking, lead was separated from the aliquots by an HBr ion-exchange procedure adapted after Manhès et al. (1978). Uranium was separated employing a modified HCl ion-exchange procedure adapted from Krogh (1973). Lead was loaded with H_3PO_4 and silica gel, and uranium was loaded with nitric acid. Analyses of lead and uranium were performed on a Finnigan MAT 261 mass-spectrometer equipped with multiple Faraday cups. The blank values for lead varied between 50 and 100 pg, while they were less than 10 pg for uranium. Mass-discrimination, determined by frequent standard analyses, was 0.11%/a.m.u. for lead and 0.1–0.2%/a.m.u. for uranium. The common-lead correction figures for samples 90034 and 92041, as adapted from the isotopic compositions of juvenile Svecofennian ore-lead (Sundblad, 1994), were: $^{206}Pb/^{204}Pb = 15.6$, $^{207}Pb/^{204}Pb = 15.25$ and $^{208}Pb/^{204}Pb = 35.2$. For the 92042 sample, the corresponding figures were 15.8, 15.35 and 35.3, as derived from the initial isotopic compositions of 1.8 Ga granitoids in southeastern Sweden (Mansfeld, 1991). Calculation and

Table 1
Investigated U–Pb and Sm–Nd samples from Latvia and Lithuania

Sample	Drillcore	Rock type	Metamorphic grade	Location
Belarus–Baltic Granulite Belt				
92043	3-Strenci, Latvia	Mafic	Granulite	57.38°N/25.65°E
92047	GK-11K, Valmera, Latvia	Mafic	Granulite	57.57°N/25.50°E
92050	GK-12PR, Strenci, Latvia	Metasediment	Granulite	57.55°N/25.65°E
92051	GK-12PR, Strenci, Latvia	Mafic	Granulite	57.55°N/25.65°E
92062	Subate-2A, Latvia	Felsic metavolcanite	Granulite	56.07°N/25.80°E
92063	N42, Pulkule, Latvia	Felsic metavolcanite	Granulite	57.73°N/24.85°E
92066	104-Kraslava, Latvia	Felsic metavolcanite	Granulite	55.88°N/27.33°E
LEL				
90033	M-4, Lithuania	Kabeliai granite		53.98°N/24.30°E
90034	403, Lithuania	Metagraywacke	Amphibolite	54.34°N/24.91°E
91003	404, Lithuania	Amphibolite	Amphibolite	54.31°N/24.79°E
91070	Staicele-1, Latvia	Felsic metavolcanite	Amphibolite	57.82°N/24.75°E
92041	GK1-KC, Staicele, Latvia	Felsic metavolcanite	Amphibolite	57.83°N/24.80°E
92042	GK-4P, Mazsalaca, Latvia	Mazsalaca granodiorite		57.83°N/25.12°E
92055	GK-9P, Mazsalaca, Latvia	Felsic metavolcanite	Amphibolite	57.87°N/24.97°E
92056	GK-2P, Incukalns, Latvia	Granitoid	Amphibolite	57.12°N/24.68°E
92060	GK-2P, Incukalns, Latvia	Metasediment	Amphibolite	57.12°N/24.68°E
WLG				
91002	Darius-1, Lithuania	Mafic	Granulite	55.59°N/21.89°E
93008	Vol 1, Vidmantai, Lithuania	Enderbite	Granulite	55.93°N/21.51°E
93009	L-32, Lithuania	Metapelite	Granulite	54.03°N/23.58°E
93010	L-5, Lauksargiai, Lithuania	Metapelite	Granulite	55.13°N/22.24°E
93011	P-3/6, Pociai, Lithuania	Metapelite	Granulite	55.76°N/21.65°E

regression analysis followed Ludwig (1991a,b) using the decay constants of Steiger and Jäger (1977).

For the Sm–Nd analyses, whole-rock materials were used, the sample sizes varying between 0.09 and 0.16 g. Before chemical preparation, the samples were spiked with a mixed ^{147}Sm/^{150}Nd tracer solution. Dissolution was performed in hydrofluoric acid and a small portion of nitric acid placed in closed teflon containers for a week at 205°C. Rare-earth elements were extracted by standard cation ion exchange with HNO_3 after washing with HCl. Sm and Nd were subsequently separated from each other and from the other REE:s in a second ion exchange with hydroxyisobutyric acid at pH 4.5 and under a slight overpressure. Sm and Nd were loaded as nitrates on Re filaments and analyzed on the MAT 261 spectrometer in the multiple Faraday-cup mode. For Nd, mass discrimination was monitored using measured ^{146}Nd/^{144}Nd values corrected to the standard value of 0.7219. Sm-interference was monitored by measurements at mass 149. After analysis, the measured and mass-discrimination corrected ^{143}Nd/^{144}Nd-values were increased by 0.0001 in order to correct for apparatus bias in the mass spectrometer. This value of 0.0001 was determined from more than 200 La Jolla Standard analyses during the period of analyses from January 1993 to March 1995. Mass discrimination for Sm was corrected using the ^{149}Sm/^{152}Sm value of 0.51686; Nd-interference was checked by measurements at mass 146. The blank values were less than 0.5 ng for Nd and less than 0.3 ng for Sm.

6. Results

The results of the U–Pb zircon analyses are presented in Table 2 and Fig. 2. For the Staicele volcanic rock, the nine zircon fractions yielded a poorly fitted discordia with an upper-intercept age of 1823 ± 11 Ma, a lower intercept at 67 ± 277 Ma, and a MSWD-value of 88 (Fig. 2(A)). The ^{207}Pb/^{206}Pb ages of the fractions vary between 1810 and

Table 2
U–Pb analytical data for the investigated rocks (absolute errors are given at the 2σ-level. abr = air abraded fraction, cl = totally transparent and colorless grains)

Fraction (μm)		Concentrations (ppm)			Atomic ratios					Age (Ma)
		U	Pb_{rad}	Pb_{init}	$^{206}Pb/^{204}Pb^{a}$	$^{208}Pb/^{206}Pb^{b}$	$^{206}Pb/^{238}U^{b}$	$^{207}Pb/^{235}U^{b}$	$^{207}Pb/^{206}Pb^{b}$	
92041 Staicele metavolcanic rock, Latvia										
1	< 74	363	115.6	0.53	12600	0.0517	0.3170 ± 15	4.886 ± 24	0.11180 ± 14	1829 ± 2
2	74–106	244	79.7	1.73	2540	0.0925	0.3082 ± 21	4.727 ± 36	0.11125 ± 32	1820 ± 5
3	74–106 2	261	77.6	1.56	2720	0.1014	0.2800 ± 12	4.283 ± 19	0.11095 ± 44	1815 ± 7
4	74–106 3	199	60.3	1.16	2870	0.0872	0.2888 ± 22	4.436 ± 51	0.11140 ± 96	1822 ± 16
5	74–106 4	286	94.5	1.23	4380	0.0610	0.3242 ± 33	4.961 ± 60	0.11098 ± 72	1816 ± 12
6	74–105 abr	553	178.0	0.30	35000	0.0490	0.3217 ± 11	4.986 ± 18	0.11242 ± 9	1839 ± 1
7	74–106 cl	162	54.6	0.24	12400	0.1020	0.3190 ± 51	4.898 ± 102	0.11135 ± 145	1822 ± 24
8	> 106	184	59.9	0.17	19000	0.1062	0.3106 ± 16	4.754 ± 25	0.11101 ± 15	1816 ± 2
9	> 106 abr	326	109.4	1.19	5180	0.0777	0.3246 ± 25	4.951 ± 39	0.11061 ± 12	1809 ± 2
92042 Mazsalaca granodiorite, Latvia										
1	45–74	219	74.7	0.80	5100	0.1324	0.3151 ± 12	4.818 ± 29	0.11091 ± 48	1814 ± 8
2	74–106 abr	224	75.9	0.13	33000	0.1349	0.3153 ± 26	4.829 ± 44	0.11107 ± 39	1817 ± 6
3	106–150	185	61.3	0.24	14000	0.1311	0.3093 ± 17	4.737 ± 29	0.11106 ± 26	1817 ± 4
4	150–210	212	66.3	0.35	10000	0.1356	0.2897 ± 10	4.432 ± 26	0.11096 ± 46	1815 ± 8
5	> 210	270	90.8	0.29	17000	0.1306	0.3140 ± 11	4.796 ± 30	0.11080 ± 51	1813 ± 8
6	> 210	208	70.0	0.24	16000	0.1297	0.3148 ± 13	4.816 ± 26	0.11095 ± 34	1815 ± 6
90034 Metagraywacke, southeastern Lithuania										
1	45–74	436	153	0.98	1100	0.1220	0.3215 ± 8	6.012 ± 17	0.13461 ± 16	2172 ± 2
2	74–106	516	174	0.73	1700	0.1066	0.3155 ± 8	5.695 ± 17	0.13093 ± 17	2111 ± 2
3	74–106 abr	470	191	0.48	2900	0.1221	0.3740 ± 9	7.161 ± 21	0.13885 ± 22	2213 ± 3
4	100–150	430	153	0.32	3400	0.1226	0.3292 ± 8	5.951 ± 16	0.13111 ± 14	2113 ± 2
5	100–150 abr	415	169	0.46	2700	0.1372	0.3697 ± 9	7.184 ± 25	0.14094 ± 30	2239 ± 4
6	> 150	361	130	0.33	2800	0.1324	0.3292 ± 10	5.998 ± 20	0.13212 ± 17	2126 ± 2

[a] Atomic ratio corrected for blank and mass discrimination.

[b] Atomic ratios corrected for blank, mass discrimination and initial lead. Age is the $^{207}Pb/^{206}Pb$ age.

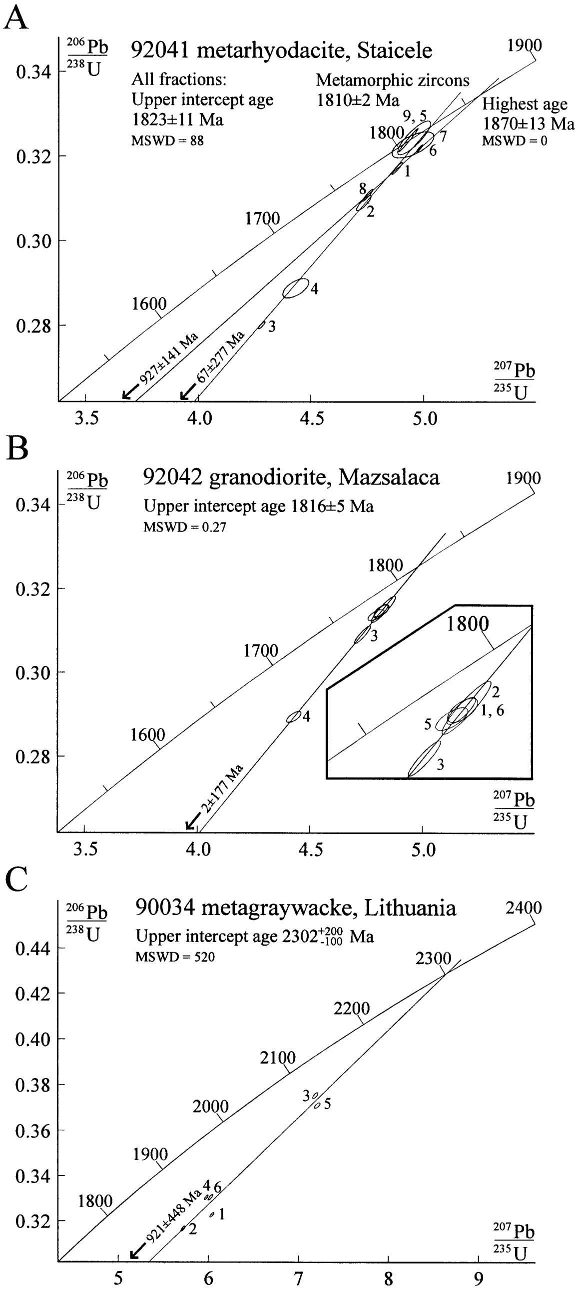

Fig. 2. U–Pb concordia diagrams for (A): the 92041 Staicele metavolcanic rock, (B): the 92042 Mazsalaca granodiorite, (C): the 90034 Lithuanian metasediment. Error envelopes and uncertainties are quoted at the 2σ level. The numbers of the zircon fractions are the same as in Table 2.

1839 Ma, where the youngest represent two fractions consisting of short and clear zircon grains. These concordant analyses yielded together an age of 1810 ± 2 Ma (Fig. 2(A)). A discordia calculation based on the three least discordant of the other fractions (nos. 1, 6, and 8) yielded an upper intercept at 1870 ± 13 and a lower at 927 ± 141 Ma (Fig. 2(A)).

The Mazsalaca granodiorite with its six analyzed zircon fractions has yielded an upper-intercept age of 1816 ± 5 Ma and a lower intercept at 2 ± 177 Ma, with a MSWD-value of 0.27 (Fig. 2(B)). The low scatter and the nearly concordant plots of the zircon fractions, as well as the igneous looks of both rock and zircons suggest that the 1816 Ma age marks the time of crystallization from a melt.

The multi-grain analysis of the metagraywacke from Lithuania yielded an upper-intercept age of 2300 + 200/ − 100 Ma with very substantial scatter around the discordia as evidenced by a MSWD-value of 520 (Fig. 2(C)). That age cannot therefore be geologically meaningful. In order to investigate if the large scatter was due to mixing of zircons with significantly different ages, one zircon crystal was dated by the Pb–Pb evaporation method (Kober, 1987) yielding an age of 2673 ± 8 Ma.

The rocks analyzed in regard to the Nd isotopic system can be subdivided into a magmatic and a metasedimentary group. The magmatic group exhibits a narrow range of depleted-mantle model ages (DePaolo, 1981) between 2.4 and 1.9 Ga, and ϵ_{Nd} values ranging between +4 and −2 for $t = 1.9$ Ga (Table 3). The rocks from the granulite-facies regions, in contrast, have larger spread of both ϵ_{Nd} values and model ages. That could either suggest more heterogeneous sources for these rocks or higher REE mobility during metamorphism, or both. At present, neither of these explanations can be excluded, but the larger scatter does not affect fundamentally the general picture outlined above. The metasedimentary units investigated are characterized by a somewhat wider scatter of the Nd-data, with depleted-mantle model ages between 2.5 and 2.0 Ga, and ϵ_{Nd} values at $t = 1.9$ Ga between +3 and −3 (cf. Table 3).

7. Discussion

The Precambrian platform basement in the western, Baltic–Belarus part of the EEC is dominated by rocks in the granulite or upper amphibolite metamorphic facies. It also features a high proportion of mafic lithologies. In both these regards, that basement differs significantly from the Proterozoic Svecofennian crust in the Baltic Shield of Sweden and Finland, where granitoids, felsic metavolcanics and sedimentary rocks prevail. Present and previous work, nevertheless, invariably reports Palaeoproterozoic ages also for the crust in the Baltic–Belarus region (e.g. Shcherbak et al., 1990; Puura and Huhma, 1993; Bogdanova et al., 1994; Claesson et al., 1994; Bibikova et al., 1995, 1997). In that part of the EEC, the U–Pb zircon ages of the igneous rocks are between 2.0 and 1.8 Ga, which despite substantial overlap suggests a somewhat earlier beginning of crust formation than in the Svecofennian Domain of the Shield. In the Svecofennian, very few ages older than 1.9 Ga have been noted so far. In conjunction with previous data, the new U–Pb zircon ages and whole-rock Sm–Nd analyses very definitely confirm that no significant amounts of Archaean crust exist in the territory between the Archaean Domain of the Baltic Shield and the Archaean torso of the Ukrainian Shield.

In general terms, the crystalline basement of Lithuania and Latvia has isotopic characteristics similar to those prevalent in Belarus, Poland and Estonia, i.e. the rest of the Proterozoic substratum beneath the platformal part of the Fennoscandian crustal segment.

The age of the oldest crust in Lithuania and Latvia is, however, difficult to assess directly in view of the very few rock units suitable for U–Pb zircon age determination.

The U–Pb analyze of the Staicele metavolcanic rock yielded an upper intercept ages of 1823 ± 11 and a MSWD-value of 88 when all nine fractions were included in the calculation. The large scatter indicates post-crystallization disturbance of the isotopic systems. Given the shapes of the zircon grains and the high metamorphic grades in the sampled area, it is suggested that some of the zircons have metamorphic overgrowths. The two concordant fractions which yielded an age of 1810 ± 2 Ma comprise the clearest zircons and are also the fractions which have the lowest $^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$ ages. For that reason, it appears reasonable to assume that they consist almost entirely of metamorphically grown zircon substance. If the assumption of dominantly metamorphic zircon in

Table 3
Sm–Nd analytical data for Latvian and Lithuanian Precambrian rocks (all ages are given in Ga)

Sample	Rock type	Sm (ppm)	Nd (ppm)	^{147}Sm/^{144}Nd[a]	^{143}Nd/^{144}Nd[b]	T_{DM}[c]	T_{CHUR}[c]	ϵ_{Nd}[d,e]	T
Belarus–Baltic Granulite Belt									
92043	Mafic rock	4.54	19.6	0.1402	0.511994 ± 9	2.17	1.73	+1.2 ± 0.5	1.9
92047	Mafic rock	3.62	15.8	0.1383	0.512057 ± 5	1.99	1.52	+2.9 ± 0.4	1.9
92050	Metasediment	7.57	29.9	0.1531	0.512059 ± 10	2.48	2.02	−0.7 ± 0.5	1.9
92051	Mafic rock	14.3	86.0	0.1008	0.511405 ± 12	2.21	1.95	−0.7 ± 0.5	1.9
92062	Felsic metavolcanic rock	11.8	64.3	0.1112	0.511668 ± 6	2.04	1.73	+1.9 ± 0.4	1.9
92063	Felsic metavolcanic rock	4.24	24.2	0.1058	0.511620 ± 11	2.00	1.70	+2.3 ± 0.5	1.9
92066	Felsic metavolcanic rock	8.03	43.6	0.1113	0.511655 ± 6	2.06	1.75	+1.7 ± 0.5	1.9
LEL									
90033	Kabeliai granite	9.88	70.9	0.08421	0.511303 ± 19	2.04	1.80	−4.4 ± 0.6	1.505
90033	Kabeliai granite	10.0	71.1	0.08511	0.511367 ± 3	1.98	1.73	−3.3 ± 0.3	1.505
90033	Kabeliai granite	10.2	71.5	0.08657	0.511383 ± 6	1.98	1.73	−3.2 ± 0.4	1.505
90034	Metagraywacke	6.81	34.5	0.1194	0.511622 ± 9	2.29	2.00	−1.0 ± 0.5	1.9
90034	Metagraywacke	4.16	19.6	0.1281	0.511687 ± 5	2.41	2.11	−1.8 ± 0.4	1.9
91003	Mafic metavolcanic rock	3.50	11.9	0.1778	0.512594 ± 16	1.90	0.36	+3.8 ± 0.6	1.9
91070	Felsic metavolcanic rock	6.99	34.5	0.1225	0.511786 ± 4	2.09	1.75	+1.5 ± 0.4	1.9
91041	Felsic metavolcanic rock	3.59	18.2	0.1190	0.511814 ± 16	1.97	1.61	+2.9 ± 0.6	1.9
92042	Mazsalaca granodiorite	23.1	122.0	0.1147	0.511724 ± 9	2.02	1.69	+1.3 ± 0.5	1.816
92055	Felsic metavolcanic rock	10.0	58.1	0.1041	0.511572 ± 12	2.04	1.75	+1.8 ± 0.5	1.9
92056	Granitoid	0.71	5.59	0.07697	0.511354 ± 11	1.88	1.63	+4.2 ± 0.5	1.9
92060	Metasediment	1.50	8.61	0.1052	0.511632 ± 11	1.97	1.67	+2.7 ± 0.5	1.9
WLG									
91002	Mafic rock	4.99	22.4	0.1347	0.511847 ± 3	2.30	1.94	−0.3 ± 0.4	1.9
93008	Enderbite	9.32	46.7	0.1207	0.511567 ± 13	2.42	2.14	−2.4 ± 0.5	1.9
93009	Metapelite	8.53	42.8	0.1205	0.511695 ± 9	2.20	1.88	+0.2 ± 0.5	1.9
93010	Metapelite	6.82	41.4	0.0997	0.511267 ± 6	2.37	2.15	−3.1 ± 0.4	1.9
93011	Metapelite	8.77	53.1	0.0997	0.511313 ± 8	2.31	2.08	−2.2 ± 0.4	1.9

[a] Estimated 2σ-error = 0.3%.

[b] Values normalized to ^{146}Nd/^{144}Nd = 0.7219. Absolute errors for the last digits are given at the $2\sigma_m$-level.

[c] DM = Depleted mantle of DePaolo (1981).

[d] Errors calculated from analytical errors of ^{147}Sm/^{144}Nd and ^{143}Nd/^{144}Nd.

[e] $\epsilon_{Nd} = [(^{143}\mathrm{Nd}/^{144}\mathrm{Nd}_{\mathrm{sample\ at}\ T})/(^{143}\mathrm{Nd}/^{144}\mathrm{Nd}_{\mathrm{CHUR\ at}\ T}) - 1]10000$. $^{147}\mathrm{Sm}/^{144}\mathrm{Nd}_{\mathrm{CHUR}} = 0.1967$, $^{143}\mathrm{Nd}/^{144}\mathrm{Nd}_{\mathrm{CHUR}} = 0.512638$.

the concordant fractions is correct, it follows that the remaining seven fractions must consist of mixtures of pristine zircon material formed during rock crystallization and subsequently formed metamorphic material. These populations have ^{207}Pb/^{206}Pb ages between 1815 and 1839 Ma, the oldest of which age must represent the minimum age of crystallization. The discordia obtained from the least discordant, non-metamorphic fractions has an upper intercept at 1870 ± 13 and a lower at 927 ± 141 Ma (Fig. 2(A)). That suspiciously high lower intercept, however, does not correspond to any geological event known from the area. In conjunction with the limited scatter of the ^{207}Pb/^{206}Pb ages, it rather suggests that the 1870 Ma age represents a maximum age, i.e. the highest possible crystallization age for the metavolcanic rock.

An alternative interpretation could be that the age of 1810 ± 2 Ma is the crystallization age and that the zircons with higher ages contain an inherited component. However, the young material appears to be only a minor component in the majority of the zircons, and the crystal habit with short, clear crystals together with the low ^{208}Pb/^{206}Pb ratios also indicate that the 1810 Ma age is a metamorphic one.

In view of the 1810 Ma metamorphic age of the Staicele rock, the 1816 ± 5 Ma age of the Mazsalaca granodiorite, also sampled in the vicinity of Staicele, suggests intrusion close to the peak of metamorphism, the slightly younger metamorphic age of the metavolcanite post-dating that peak (cf. Roberts and Finger, 1997).

If, on the other hand, the 1810 Ma age of the metavolcanic rock should represent its age of magmatic crystallization, the Mazsalaca granodiorite is the oldest so far dated rock in the region. However, even in that case the older zircon ages from the Staicele rock demonstrate the existence of older crustal materials and the Mazsalaca age cannot be other than an absolute minimum age for the crust formation in the considered area.

Regardless of the interpretation of the individual samples, the combined U–Pb zircon results from Staicele and Mazsalaca indicate that the crust was formed after 1.9 but before 1.82 Ga, and experienced a high-grade tectonothermal event at ca. 1.81 Ga.

The metasedimentary rock from southeastern Lithuania that was dated by multigrain-fraction zircon analysis belongs to the stratigraphically oldest units in the sampled area. While the obtained age of ca. 2.3 Ga lacks geological meaning, that analysis strongly resembles multigrain analyses previously carried out on metasedimentary units within the Svecofennian Domain. These have yielded age values of the same order of magnitude and have similarly large errors (cf. Kouvo and Tilton, 1966; Åberg, 1978; Huhma 1985; Huhma et al., 1991). The meaningless ages were eventually shown to be a result of the mixing of Archaean and Palaeoproterozoic zircons, the latter derived from 1.9–2.1 Ga old rocks (Claesson et al., 1993). The 2673 Ma Archaean age obtained by the Kober evaporation method from one single zircon grain in the meta-greywacke from Southeast Lithuania demonstrates that a similar interpretation is valid also in the present case. While some of its detrital zircons thus are Archaean, that rock as such is far from being Archaean in age.

The whole-rock ϵ_{Nd} values obtained from Latvia and Lithuania vary between +4.2 and −3.1 for $t = 1.9$ Ga, which corresponds to depleted-mantle model ages between 2.5 and 1.9 Ga. The average age-value for the metasedimentary units is ca. 0.3 Ga higher than that for the igneous rocks. These results confirm the absence of Archaean crust in the region and identify the detritus in the sedimentary rocks as the principal carrier of the Archaean zircon component.

The Nd-isotopic results are also similar to those found in Estonia and Belarus (Puura and Huhma, 1993; Claesson et al., 1994; Bibikova et al., 1997), and in addition resemble the data from the Svecofennian Domain in Sweden and Finland (Fig. 3(A)), where the crust is mainly juvenile Palaeoproterozoic, and Archaean influence is very limited (Patchett and Kouvo, 1986; Patchett et al., 1987). However, there is a minor but still clearly perceptible difference in that almost all the ϵ_{Nd} values are slightly more positive compared to analyses from the Svecofennian Domain (Fig. 3(B)). This could either indicate a slightly younger crust in Latvia and Lithuania or be the result of a smaller Archaean component than in Scandinavia.

According to present views (Bogdanova et al., 1994, 1997), the Proterozoic part of the Fennoscandian crustal segment within the EEC was formed by the accretion of various juvenile terranes composed of volcanic arcs and their deep-crustal equivalents (Bogdanova et al., 1994, 1997). That accretion was directed onto the Archaean cores of Fennoscandia in the present northeast and Sarmatia in the present southeast, in a process named bilateral collision by Stephens and Wahlgren (1996). In the Baltic–Belarus region, these accretionary and collisional events created a conspicuous NE- to NNE-trending structure of alternating, northwestwards younging, granulite- and amphibolite-facies rock belts along the margin of Sarmatia. However, the western and northern parts of that region may have a different appurtenance marked by more or less west-eastern tectonic grain particularly prominent in Estonia and in the WLG (cf. Skridlaite et al., 1997).

In the Baltic-Sea region, the westernmost part of the Baltic–Belarus crystalline basement borders in the west and north against the Svecofennian Domain of the Baltic Shield, of which the amphibolite-facies belt in northern Estonia appears to be a direct continuation (Puura and Huhma, 1993; cf. Öpik, 1935).

The Svecofennian Domain was mainly formed by the accretion and collision of volcanic arcs between 1.91 and 1.86 Ga (Gaál and Gorbatschev, 1987). That accretion and later deformation and metamorphism at 1.85–1.80 Ga is evident as mainly E–W to SE–NW-trending structures within the Svecofennian Domain (e.g. in the Skellefte district, the Bergslagen volcanic province, and the southern granulite belt in southwestern Finland, Fig. 1). To the south, southwest and west, the Svecofennian Domain is succeeded by

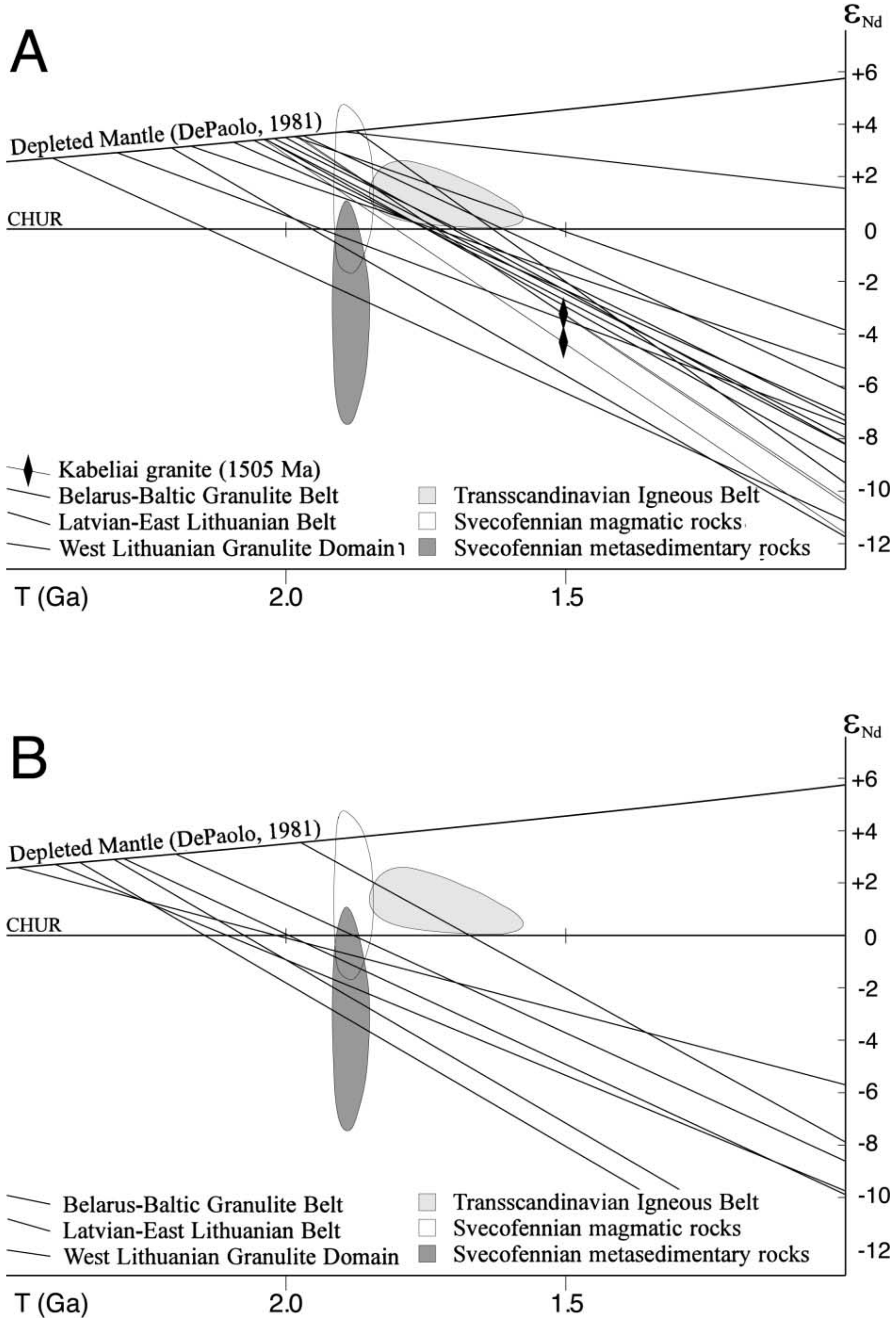

Fig. 3. Age versus ϵ_{Nd} diagram for the Latvian and Lithuanian samples. (A): magmatic rocks, black diamonds representing the U–Pb age determined from the Kabeliai granite, (B): metasedimentary rocks. The reference fields for the Svecofennian Domain are based on data compiled from Wilson et al. (1985), Huhma (1986), Patchett and Kouvo (1986), Claesson (1987), Huhma (1987), Patchett et al. (1987), and Welin (1987).

the TIB. Situated immediately to the northeast and east of the TIB is the Bergslagen volcanic province which, according to Lundström et al. (1998), was formed during less than 20 m.y. around 1.90 Ga ago. However, the Svecofennian Domain in a wider sense (or a southward, late continuation of that Domain, new terminology is as yet not firmly established here) does continue further to the south with remnants of volcanic arcs adjacent to the TIB or even located within the TIB. These small calc-alkaline arc areas are marked by comparatively large proportions of mafic rocks. They include the ca. 1.85 Ga Askersund area (Wikström, 1996), the equally aged Åtvidaberg area (Dobbe et al., 1995) and the ca. 1.83 Ga old Oskarshamn–Jönköping Belt (Mansfeld, 1996; Beunk et al., 1997). To these dated areas, the Precambrian basement of Gotland in the Baltic Sea should probably be added since it contains parts comparable to the Åtvidaberg–Valdemarsvik area dominated by mafic volcanic rocks (Sundblad and Gyllencreutz, 1999). All the named areas that continue the Svecofennian domain toward the south and southwest also feature numerous NW-trending mega-structures, similar in direction to the structures in the Svecofennian domain proper, i.e. farther to the north. It can thus be established definitely that the Svecofennian Domain continued to expand toward the southwest and south by the accretion of juvenile terranes until at least 1.83 Ga ago. Subsequently, that newly grown crust was deformed and metamorphosed before being intruded by the TIB 1 phase (cf. Larson and Berglund, 1992) of the TIB at 1.81–1.80 Ga.

The westernmost part of the Baltic–Belarus region and the rock belts continuing the Svecofennian Domain into southeastern Sweden are both composed of igneous formations with large proportions of mafic volcanic lithologies. Both areas also feature dominant W–E or NW–SE trending crustal structures. Even though there are still very few geochronological data, the available U–Pb zircon ages suggest similar timing of crust formation (ca. 1.85 Ga ago) and metamorphism (>1.81 Ga).

A fundamental inference must therefore be that the Precambrian crust in western Latvia, western Lithuania, southeastern Sweden and the Precambrian basement of Gotland belongs to a region that was formed between 1.85 and 1.83 Ga ago from juvenile volcanic arcs which were accreted toward the north or northeast at or before 1.81 Ga.

The boundary between the crust continuing the Svecofennian Domain toward the south and southwest, and the easterly crust grown by accretion onto Sarmatia is at present still difficult to pinpoint. Most probably it is located along the border between western and eastern Lithuania, along the tectonic break between W–E and NNE–SSW trending structures interpreted as a major crustal boundary by Skridlaite et al. (1997). An alternative site could be along the Belarus–Baltic Granulite Belt which exhibit signs of major collision before 1.79 Ga ago (Bogdanova et al., 1994).

8. Conclusions

A U–Pb zircon age determination of the Staicele metavolcanics in northern Latvia has yielded a scattered result with ^{207}Pb/^{206}Pb ages in the range 1839–1809 Ma. The youngest zircons are suggested to have been formed at or slightly after a high-grade metamorphic event in the region, while higher-aged fractions represent zircons only partly reset by that event. The relatively minor difference between the age extremes implies that there is no evidence of significantly older materials within the zircons. A minimum formation age of 1.84 Ga is therefore suggested to be close to the actual age of crystallization.

The Mazsalaca granodiorite, which is located close to Staicele, yielded an U–Pb age of 1816 ± 5 Ma. Together with indications of a metamorphic event at or before 1.81 Ga in the Staicele volcanite, that age may imply that the Mazsalaca intrusion was formed close to the peak of metamorphism.

A graywackoid metasedimentary rock in southeastern Lithuania that has yielded a geologically meaningless multi-grain zircon age of 2302 Ma. Similarly to rocks in the Svecofennian domain of the Baltic Shield, it is characterized by the mixing of zircons of Archaean and Proterozoic age.

Twenty-one whole-rock Nd-isotopic analyses from various rock assemblages and metamorphic terrains in Latvia and Lithuania indicate rather little variation of depleted-mantle model ages and ϵ_{Ndt}-values.

Magmatic rocks have model ages between 2.4 and 1.9 Ga, while in the metasedimentary units these ages vary between 2.5 and 2.0 Ga. This suggests a small to insignificant Archaean component in the continental crust of Latvia and Lithuania. Comparison with corresponding Svecofennian rock types reveals considerable similarity between the westernmost part of the Baltic–Belarus region and the Svecofennian Domain of the Baltic Shield.

The combined U–Pb and ϵ_{Nd} results suggest crust formation in Latvia and Lithuania after 1.9 but before 1.82 Ga ago, and a high-grade metamorphic event at or before 1.81 Ga. These ages and lithological similarity between the westernmost part of the Baltic–Belarus region and the late Palaeoproterozoic terranes in southeastern Sweden suggest a common history of crust formation in this part of the European Precambrian craton, and a continuous crustal province across the southeastern Baltic Sea. The boundary between that province in which the crust was accreted onto the Archaen core of Fennoscandia and the terranes grown outwards from Archaean Sarmatia must be a major crustal boundary. It appears to be located either along the border between the terranes of western and eastern Lithuania or farther to the east, along the Belarus–Baltic Granulite Belt.

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References

Åberg, G., 1978. Precambrian geochronology of south-eastern Sweden. Geol. Fören. Stockholm Förh. 100, 125–154.

Beunk, F.F., Page, L.M., Barling, J., Maaskant, P., Wijbrans, J.R., 1997. Magmatism, deformation, metamorphism and geochronology of the late Svecofennian SW continental margin of the Baltic Shield. Terra Nova, Abstract 9 (Suppl. 1), 131–132.

Bibikova, E.V., Claesson, S., Bogdanova, S.V., Naydenkov, I.V., 1995. Palaeoproterozoic age provinces in the southwestern part of the East European Craton. In: Glebovitsky, V.A., Kotov, A.B. (Eds.), Precambrian of Europe: Stratigraphy, structure evolution and mineralization. MAEGS 9 Russian Academy of Sciences, St. Petersburg, Russia, p. 12.

Bibikova E., Claesson, S., Mansfeld, J., Gorbatschev, R., Skridlaite, G., Taran, L., 1996. Isotope geochronological evidence of Palaeoproterozoic accretion in the western part of the East European Platform. Eurobridge workshop, Oskarshamn, Sweden, pp. 5–6.

Bibikova, E.V., Claesson, S., Bogdanova, S., Gorbatschev, R., 1997. Isotope geochronological evidence of Palaeoproterozoic accretion in the western part of the East European Craton. Terra Nova, Abstract 9 (Suppl. 1), 131.

Bogatikov, O.A., Birkis, A.P., 1973. Precambrian magmatism in western Latvia. Nauka, Riga, (in Russian).

Bogdanova, S.V., 1993. The three-segment hypothesis for the East European Craton. Terra Nova, Abstracts 5, 313–314.

Bogdanova, S.V., EUROBRIDGE geologists, 1997. Major crustal boundaries in the Eurobridge region: some implications for geological–geophysical modelling, Eurobridge workshop, Vilnius-Dubingiai, pp. 11–14.

Bogdanova, S.V., Bibikova, E.V., Gorbatschev, R., 1994. Palaeoproterozoic U–Pb zircon ages from Belorussia: new geodynamic implications for the East European Craton. Precambrian Res. 68, 231–240.

Bogdanova, S.V., Page, L.M., Skridlaite, G., Taran, L.N., 1996a. The Proterozoic tectonothermal history of the western part of the East European Craton: implications from ^{40}Ar/^{39}Ar geochronology. Geol. Fören. Stockholm Förh. 118 Jubilee Issue, A10–A11.

Bogdanova, S.V., Pashkevich, I.K., Gorbatschev, R., Orlyuk, M.I., 1996b. Riphean rifting and major Palaeoproterozoic crustal boundaries in the basement of the East European Craton: geology and geophysics. Tectonophysics 268, 1–21.

Bogdanova, S.V., Bibikova, E.V., Claesson, S., Gorbatschev, R., 1997. A Palaeoproterozoic accretional orogen in the East European Craton, COPENA conference. NGU, Trondheim.

Claesson, S., 1987. Nd isotope data on 1.9–1.2 Ga old basic rocks and metasediments from the Bothnian basin, central Sweden. Precambrian Res. 35, 115–126.

Claesson, S., Huhma, H., Kinny, P.D., Williams, I.S., 1993. Svecofennian detrital zircon ages — implications for the Precambrian evolution of the Baltic Shield. Precambrian Res. 64, 109–130.

Claesson, S., Bibikova, E., Mansfeld, J., Bogdanova, S., Reinfrank, R., 1994. Early Proterozoic development of the western part of the East European craton. The Eighth International Conference on Geochronology, Cosmochronology and Isotope Geology, Berkeley, California, p. 60.

Claesson, S., Sundblad, K., Ryka, W., Motuza, G., 1996. The Mazury Complex in N Poland, rapakivi granites and the SE-wards extension of the Fennoscandian Shield. The 22nd Nordic Geological Winter meeting, Turku, Finland, p. 30.

DePaolo, D.J., 1981. Neodymium isotopes in the Colorado Front Range and crust-mantle evolution in the Proterozoic. Nature 291, 193–196.

Dobbe, R.T.M., Oen, I.S., Verdurmen, E.A.T., 1995. U–Pb zircon ages of metatuffites and Older Granite from the Tunaberg area, SE Bergslagen, Sweden. Geol. Mijnbouw 74, 129–136.

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

Gorbatschev, R., Bogdanova, S., 1993. Frontiers in the Baltic Shield. Precambrian Res. 64, 3–21.

Huhma, H., 1985. Provenance of some Finnish sediments. Geologi 2, 23–24.

Huhma, H., 1986. Sm–Nd, U–Pb and Pb–Pb isotopic evidence for the origin of the Early Proterozoic Svecokarelian crust in Finland. Geol. Surv. Bull., Finland 337, 48.

Huhma, H., 1987. Provenance of early Proterozoic and Archaean metasediments in Finland: a Sm–Nd isotopic study. Precambrian Res. 35, 127–143.

Huhma, H., Claesson, S., Kinny, P.D., Williams, I.S., 1991. The growth of early Proterozoic crust: new evidence from Svecofennian detrial zircons. Terra Nova 3, 175–179.

Kober, B., 1987. Single zircon evaporation combined with Pb^+ emitter bedding for $^{207}Pb/^{206}Pb$-age investigations using termal ion mass spectrometry, and implications to zirconology. Contrib. Mineral. Petrol. 96, 63–71.

Kouvo, O., Tilton, G.R., 1966. Mineral ages from Finnish Precambrian. J. Geol. 74, 421–442.

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

Krogh, T.E., 1982. Improved accuracy of U–Pb zircon ages by the creation of more concordant systems using an air abrasion technique. Geochim. Cosmochim. Acta 46, 637–649.

Larson, S.Å., Berglund, J., 1992. A chronological subdivision of the Transscandinavian Igneous Belt — three magmatic episodes. Geol. Fören. Stockholm Förh. 114, 459–461.

Ludwig, K.R., 1991a. ISOPLOT A plotting and regression program for radiogenic-isotope data, version 2.53. Open-file report 88-557, U.S. Geological Survey.

Ludwig, K.R., 1991b. PBDAT 1.21 for MS-DOS: a computer program for IBM-PC compatibles for processing raw Pb–U–Th isotope data. Open-file report 88-542, U.S. Geological Survey.

Lundström, I., Allen, R.L., Persson, P.-O., Ripa, M., 1998. Stratigraphies and depositional ages of Svecofennian, Palaeoproterozoic metavolcanic rocks in E. Svealand and Bergslagen, south central Sweden. Geol. Fören. Stockholm Förh. 120, 315–320.

Manhès, G., Minster, J.F., Allègre, C.J., 1978. Comparative uranium–thorium–lead and rubidium–strontium study of the Saint Séverin amphoterite: consequences for early solar system chronology. Earth Planet. Sci. Lett. 39, 14–24.

Mansfeld, J., 1991. U–Pb age determinations of Småland-Värmland granitoids in Småland, southeastern Sweden. Geol. Fören. Stockholm Förh. 113, 113–119.

Mansfeld, J., 1996. Geological, geochemical and geochronological evidence for a new Palaeoproterozoic terrane in southeastern Sweden. Precambrian Res. 77, 91–103.

Öpik, A., 1935. Eine mögliche geologische Deutung der magnetischen Anomalien Estlands. Comptes Rendus de la Commission Géodesique Baltique réunie à Tallinn et Tartu 20–30 8, 287–288.

Patchett, J., Kouvo, O., 1986. Origin of continental crust of 1.9–1.7 Ga age: Nd isotopes and U–Pb zircon ages in the Svecokarelian terrain of South Finland. Contrib. Mineral. Petrol. 92, 1–12.

Patchett, P.J., Todt, W., Gorbatschev, R., 1987. Origin of continental crust of 1.9–1.7 Ga age: Nd isotopes in the Svecofennian orogenic terrains of Sweden. Precambrian Res. 35, 145–160.

Persson, P.-O., Wikström, A., 1993. A U–Pb dating of the Askersund granite and its marginal augen gneiss. Geol. Fören. Stockholm Förh. 115, 321–329.

Puura, V., Huhma, H., 1993. Palaeoproterozoic age of the East Baltic granulitic crust. Precambrian Res. 64, 289–294.

Puura, V., Apirubyte, R., Birkis, A., Gailius, R., Motuza, G., Ozolins, N., 1978. Geological map of the crystalline basement of the Soviet Baltic Republics (in Russian). Scale 1:500000.

Rämö, O.T., Huhma, H., Kirs, J., 1996. Radiogenic isotopes of the Estonian and Latvian rapakivi granite suites: new data from the concealed Precambrian of the East European Craton. Precambrian Res. 79, 209–226.

Roberts, M.P., Finger, F., 1997. Do U–Pb zircon ages from granulites reflect peak metamorphic conditions? Geology 25, 319–322.

Ryka, W., 1993. Crystalline basement of the Polish part of the Baltic Sea. Geol. Quart. 37, 329–344.

Shcherbak, N.P., 1991. The Precambrian subdivision of the Ukrainian Shield and their comparison with USSR and international scales. Geol. Zh. 4, 3–9 (in Russian with English summary).

Shcherbak, N.P., Pap, A.M., Bartnitsky, E.N., Zayats, A.P., 1990. Uranium–lead isotopic age of granitoids in Belorussia. Dokl. BSSR Acad. Sci. 34, 740–744 (In Russian).

Skridlaite, G., Bogdanova, S.V., Motuza, G., 1997. A major tectonic boundary in the basement of the East European Craton in Lithuania: implications from metamorphism. Terra Nova, Abstract 9 (Suppl. 1), 132.

Steiger, R.H., Jäger, E., 1977. Subcommission on geochronology:

convention on the use of decay constants in geo- and cosmochronology. Earth Planet. Sci. Lett. 36, 359–362.

Stephens, M.B., Wahlgren, C.-H., 1996. Thermal and mechanical responses to bilateral collision in the Svecokarelian orogen. Abstracts of the 22nd Nordic Geological Winter Meeting, Turku, Finland, p. 203.

Sundblad, K., 1994. A genetic reinterpretation of the Falun and Åmmeberg ore types, Bergslagen, Sweden. Miner. Deposita 29, 170–179.

Sundblad, K., Gyllencreutz, R., 1999. The Precambrian crust beneath the Baltic Sea. EUG 10, abstract volume. J. Conf. Abstr. 4 (1), 132.

Sundblad, K., Kivisilla, J., 1991. Evidence for the presence of Svecofennian stratiform oxide and sulphide ores in northeastern Estonia. Geology and mineral resources of Estonia. Symposium materials, Tallinn, Estonia, pp. 27–28.

Sundblad, K., Mansfeld, J., Motuza, G., Ahl, M., Claesson, S., 1994. Geology, geochemistry and age of a Cu–Mo-bearing granite at Kabeliai, southern Lithuania. Miner. Petrol. 50, 43–57.

Vetrennikov, V.V., 1991. Iron bearing silisic formations in the Precambrian of Latvia (in Russian), Riga, Latvia.

Vetrennikov, V.V., Petersell, V., Poldvere, A., 1986. Manganiferous iron ore formation of Precambrian of the northern Baltic area. Composition and origin of rocks in the crystalline basement of Belorussia and the Baltic states. Belorussian Academy of Sciences, Minsk, pp. 86–97 (in Russian).

Welin, E., 1987. The depositional evolution of the Svecofennian supracrustal sequence in Finland and Sweden. Precambrian Res. 35, 95–113.

Wikström, A., 1996. U–Pb zircon dating of a coarse porphyritic quartz monzonite and an even grained, grey tonalitic gneiss from the Tiveden area, south central Sweden. Radiometric Dating Results 2, Lundqvist, T. (Ed.), Geol. Surv. Sweden C828, 41–47.

Wilson, M.R., Hamilton, P.J., Fallick, A.E., Aftalion, M., Michard, A., 1985. Granites and early Proterozoic crustal evolution in Sweden: evidence from Sm–Nd, U–Pb and O isotope systematics. Earth Planet. Sci. Lett. 72, 376–388.