Precambrian domains in Lithuania: Evidence of terrane tectonics

Article *in* Tectonophysics · September 2001

DOI: 10.1016/S0040-1951(01)00035-X

2 authors:

Grazina Skridlaite
Nature Research Centre, Vilniu, Lithuania

Gediminas Motuza
Vilnius University

ELSEVIER

Tectonophysics 339 (2001) 113–133

TECTONOPHYSICS

www.elsevier.com/locate/tecto

Precambrian domains in Lithuania: evidence of terrane tectonics

Grazina Skridlaite*, Gediminas Motuza

Institute of Geology, T. Sevcenkos 13, LT-2600 Vilnius, Lithuania

Received 13 February 1998; revised 2 December 1999

Abstract

The West Lithuanian Granulite (WLG) and East Lithuanian domains (ELD) form the Proterozoic basement of Lithuania and can be distinguished on the basis of differing structural patterns, lithologies, and evolutionary histories. They are juxtaposed along the Mid-Lithuanian Suture Zone (MLSZ).

In the WLG, the main lithotectonic complexes comprise felsic and intermediate, mostly metasedimentary granulites in the south-west and mafic metaigneous granulites in the north-east. The former are interpreted as marine metapelites, while most of the mafic ones have been derived from island-arc tholeiites. These rock complexes trend NW–SE and are marked by contrasting gravity and magnetic anomalies. NE- and E–W-striking faults and shear zones complicate the potential-field patterns. Sets of NW-trending anomalies also extend from Lithuania across the Baltic Sea to south-central Sweden and indicate that the WLG complexes continue into the Baltic/Fennoscandian Shield. Voluminous anatectic granites alternate with the metapelites, whereas the mafic granulites occur together with enderbites and charnockites.

In the ELD, the main structures produce strong, NNE–SSW-oriented gravity and magnetic anomalies which trend parallel to the Belarus-Baltic Granulite Belt (BBG) and other terranes situated still farther east. The ELD is composed of metasedimentary rocks interpreted as one-time graywackes, shales and dolomites accumulated in continental-margin arc and shallow-water basinal environments. Amphibolites and gabbros with MORB and IAT characteristics, and voluminous granitoids are also present. The coexistence of juvenile mafic rocks with continental-margin and shelf sediments suggests an oceanic back-arc setting.

The two Lithuanian basement domains display contrasting metamorphic histories that suggest separate developments before the eventual amalgamation. In the WLG, the metapelites indicate peak metamorphism at high temperatures (up to 850–900°C) and moderate pressures (8–10 kbar). This was followed by cooling and reheating, and then an uplift event. Repeated magmatic underplating accompanied the metamorphism. In the ELD, in contrast, the rocks have been subjected to comprehensive metamorphism under moderate, amphibolite-facies conditions. That metamorphism, however, was not uniform throughout. The metasediments in the east have recorded pressures similar to those in the neighbouring BBG (7–8 kbar) but lower temperatures (650–680°C), while in the central and western parts of the ELD, metamorphism occurred at ca. 480–580°C with pressures increasing from 3–4 kbar in the centre, to 6 kbar close to the western boundary. Reheating to 700°C due to a ca. 1.5-Ga magmatic event is characteristic.

The MLSZ, which separates the two Lithuanian basement domains from each other, is a N–S-oriented, ca. 30–50 km wide, westward-plunging crustal discontinuity marked by magnetic and gravity highs, mafic and felsic intrusions, and sheared rocks. Crustal thicknesses change from 42–44 km in the west to 50 km in the eastern side of the Zone, which also truncates a crustal low-velocity layer characteristic of the WLG. The amalgamation of the WLG and ELD along the MLSZ occurred at ca. 1.71–1.66 Ga, after which time both domains were affected by the same post-kinematic, anorogenic magmatism ca. 1.58–1.45 Ga

---

* Corresponding author. Tel.: +370-2-235906/233595; fax: +370-2-236710.
E-mail addresses: grazina@geologin.lt (G. Skridlaite), gmotuza@geologin.lt (G. Motuza).

PII: S0040-1951(01)00035-X

ago. That event and related shearing were responsible for some ultimate refragmentation of the Lithuanian basement terranes.

Keywords: terrane tectonics; metamorphism; geochemistry; Proterozoic; Lithuania; East European Craton

1. Introduction

In Lithuania, unmetamorphosed, weakly deformed Neoproterozoic to Quaternary sediments overlie the crystalline basement. The thickness of this sedimentary cover ranges from 200 m in the east to 2300 m in the west; information on the structure and composition of the basement is derived from potential fields, deep seismic sounding (DSS) profiling, and drilling. Surface gravity and airborne magnetometry mapping of the entire country and offshore is available at a scale of 1:200 000 and, additionally, approximately 40% of Lithuania has been mapped at a scale of 1:50 000. Numerous boreholes have been drilled for geological mapping, iron ore exploration, geothermal energy, and oil and gas resources. Drillcore material from approximately 500 wells is available for petrological investigation (e.g. Motuza and Skridlaite, 1994; Puura et al., 1978, 1980; Gailius and Ciucelis, 1980).

In 1995 and 1996, the DSS EUROBRIDGE experiment was carried out in Lithuania. The results have provided new information on the deep crustal structure. The subdivision of the basement of Lithuania into two main tectonic domains, namely the West Lithuanian Granulite (WLG) and East Lithuanian domains (ELD), with an intervening structure called the Mid-Lithuanian Suture Zone (MLSZ), was previously recognised from potential field anomalies and a sharp break in metamorphic grades. This general picture of the Lithuanian basement has been confirmed by the results of the EUROBRIDGE transect (EUROBRIDGE Seismic Working Group, 2001–this issue).

The aim of the present paper is to compare the geological characteristics of the two Lithuanian basement domains in relationship to the new seismic profiling and other up-to-date geophysical and petrological data.

2. Description of the crystalline basement in Lithuania

The two principal basement domains, the WLG and the ELD (Fig. 1), display distinct potential-field patterns (Figs. 2 and 3; Popov and Sliaupa, 1997a,b) and differ in lithological composition (Motuza and Skridlaite, 1996). They are also dissimilar in terms of crustal thickness and seismic velocity structure, as evident from the recently acquired seismic refraction data (EUROBRIDGE Seismic Working Group, 2001–this issue).

2.1. The WLG

The WLG occupies the entire western part of Lithuania and also lies beneath the Baltic Sea, where the position of its western border is not yet established. Based on the north-west continuation of potential field anomalies, especially magnetic, across the Baltic Sea into Sweden (e.g. Wybraniec et al., 1999), it is likely to continue into the Baltic/Fennoscandian Shield in south central Sweden. The presence of the WLG beneath the eastern part of the Baltic Sea has been confirmed by the seismic refraction data (EUROBRIDGE Seismic Working Group, 2001–this issue). In the north, the WLG is truncated by the huge, ca. 30 000 km^2, Riga pluton of rapakivi granites and anorthosites. To the south, the WLG continues in northern Poland (the Kaszuby and Ciechanow granulite belts; Kubicki and Ryka, 1982).

The WLG is characterised by subdued and moderately uniform potential fields, with variable orientation of magnetic and gravity anomalies, and smooth gradients (cf. Figs. 2 and 3). In its central part, anomalies are comparatively higher and more contrasting; E–W-, NW-, and NE-trending fault zones are identified. According to the new seismic refraction studies (EUROBRIDGE Seismic Working Group, 2001–this issue), the crust is 42–44 km thick and contains a low-velocity layer at a depths of 10–15 km, abruptly truncated by the MLSZ inter-domain boundary.

The lithology of the WLG appears to be dominated by granitoids and migmatites with supracrustal (metasedimentary and metavolcanic) granulites as relic bodies or as palaeosomes in the migmatites. Two litho-tectonic complexes have been distinguished in the WLG. Metasedimentary granulites with subordinate felsic and intermediate metavolcanic granulites

Nomenclature

Ab 3	Ablinga 3
Bl 96, 150	Bliudziai 96 and 150
Dr1	Darius 1
G199	Geluva 99
Gn1	Geniai 1
Gr	Girdziai
Gz105	Grauzai 105
Lk2, 3, 5	Lauksargiai 2, 3 and 5
Lz1, 2, 3, 4, 13, 32	Lazdijai 1, 2, 3, 3, 13 and 32
Ls 2	Lasai 2
Mr4	Marcinkonys 4
Pc1, 3	Pociai 1 and 3
Pk1	Palukne 1
Pl140	Pilviskiai 140
Rk1, 2	Rukai 1 and 2
Rs1	Rusne 1
Sk87	Sutkai 87
Sl2, 3, 4	Silale 2, 3 and 4
Sn1, 2, 3, 4	Salantai 1, 2, 3 and 4
Sp68	Siupyliai 68
Tl1	Toliai 1
Tr11	Taurage 11
Vd1	Vidmantai 1
Vz6	Vezaiciai 6
61	Barciai 61
400	Zagarine 400
401	Mamavys 401
403	Salcia 403
404	Valkininkai 404
414	Purvenai 414
416	Pakuliskes 416
423	Krukliai 423
980, 981, 982, 989	Varena 980, 981, 982 and 989
727	Tauzginenai 727

occupy its southern part, while mafic granulites predominate in the north (e.g. Gailius and Ciucelis, 1980; Motuza and Skridlaite, 1994; Fig. 1).

2.1.1. Supracrustal rocks

In the south, metasedimentary granulites are mainly garnet-bearing gneisses of pelitic composition. These gneisses contain garnet, biotite, sillimanite, opaques, plagioclase, K-feldspar, quartz, frequently cordierite, zircon, monazite, and pyrite with rare hypersthene. The gneisses are either lens-spotted, domain-like or fine-grained, foliated, often mylonitic with ribbon-quartz (Skridlaite, 1994). Cordierite-spinel and ilmenite–magnetite–rutile–spinel intergrowths are typical in these rocks.

Minor biotite and pyroxene gneisses alternating with garnet-bearing gneisses are fine-grained rocks composed of clinopyroxene and/or hypersthene, biotite, plagioclase and quartz, with opaque grains. They occasionally display plagioclase phenocrysts and other igneous textures indicating volcanic, felsic or intermediate protoliths (e.g. well BI 150; Fig. 1). The rest might be metasediments. Subordinate layers of mafic granulites/metavolcanics also occur among metapelitic rocks. They are most typical of the northern WLG where mafic granulites are widespread among enderbites and charnockites. The mafic granulites are composed of clinopyroxene, hypersthene, biotite, plagioclase, and opaques. Granulite metamorphism variably overprinted the primary features of these rocks; some of them still contain coarse subidiomorphic phenocrysts of plagioclase. Mostly, plagioclase is replaced by K-feldspar and pyroxene is replaced by biotite.

The age of the WLG supracrustal rocks, as estimated by the Sm–Nd whole rock method (Mansfeld, 1995), varies between 2.37 DM 2.20 Ga (T_{DM}), demonstrating a Palaeoproterozoic age for the crust of the WLG. A U–Pb monazite age indicates granulite metamorphism at ca. 1.8 Ga (Bibikova et al., 1997a).

2.1.2. Intrusive rocks

Voluminous anatectic granitoids and migmatites associated with metasediments have been produced mainly at the expense of the latter. These anatectites are composed of K-feldspar, plagioclase, quartz, biotite, and some amount of garnet, cordierite, or sillimanite. Opaques, zircon, and monazite are common accessories.

Tonalitic and trondjemitic granitoids have been discovered in the south-westernmost part of the WLG, in the so-called Nemunas Fault Zone (N in Fig. 1; e.g. well Rs 1). These slightly foliated rocks are composed of biotite, quartz, plagioclase, minor K-feldspar, opaques and zircon. According to a U–Pb

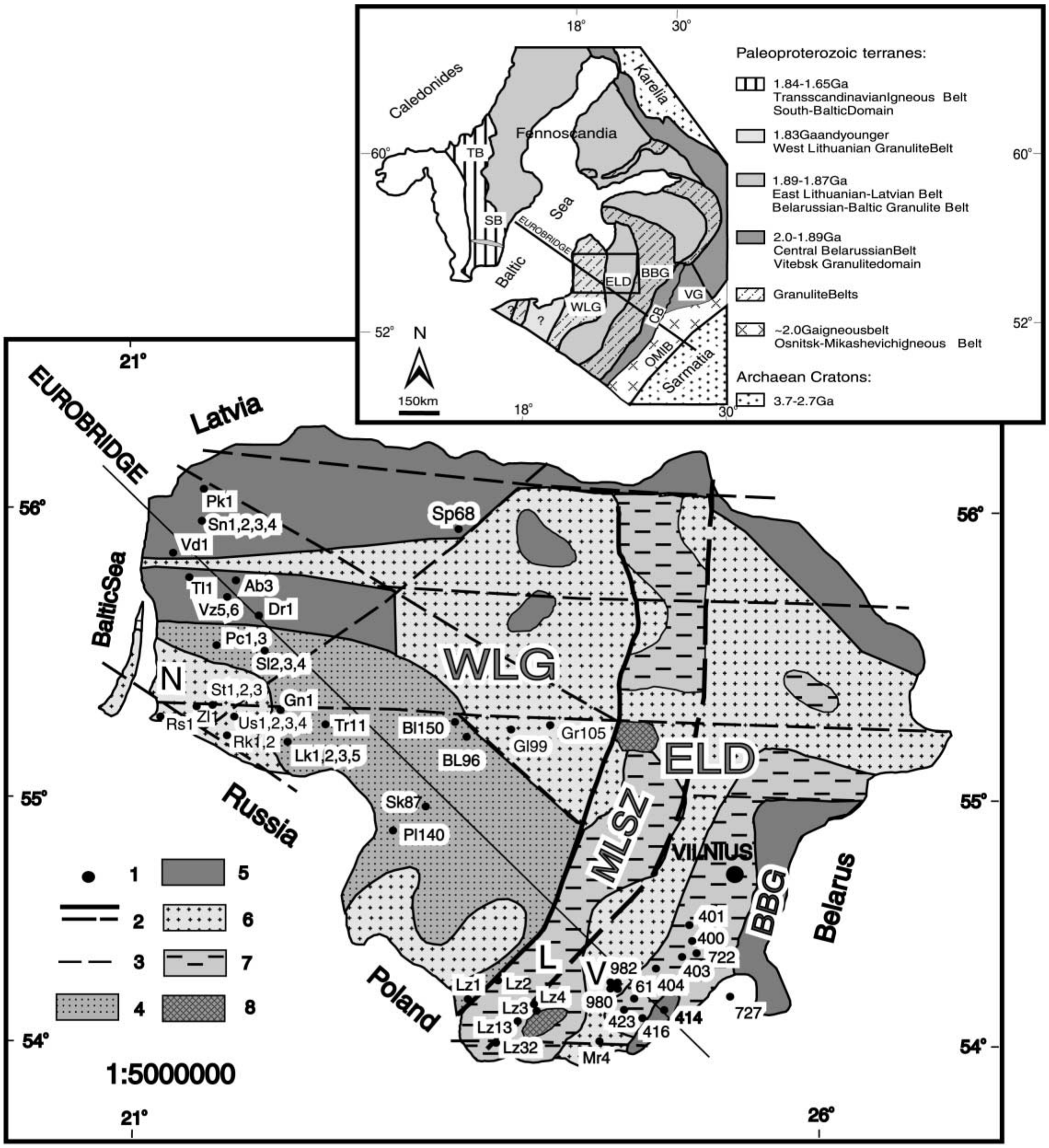


Fig. 1. Sketch map of the Precambrian basement of Lithuania. Legend: (1) drilling wells; (2) boundary between the WLG Domain and East Lithuanian Belt; (3) faults; (4) metasedimentary and metavolcanic granulites, granites and migmatites; (5) charnockites and enderbites with relics of mafic granulites; (6) migmatites and granites; (7) gneisses and amphibolites; (8) mafic intrusions. The solid line shows the course of the EUROBRIDGE DSS profile. The letter symbols are as follows: BBG — Belarus-Baltic Granulite Belt; ELD — East Lithuanian Domain; L — the Lazdijai area; MLSZ — Middle Lithuanian Suture Zone; N — Nemunas Fault Zone; V — Varena Iron Ore Zone, WLG — West Lithuanian Granulite Domain. Inset: The pattern of rock belts and terranes in the western part of the East European Craton acc. to Bogdanova et al. (1996). The study area is marked by the square; the solid line represents the EUROBRIDGE DSS profile.

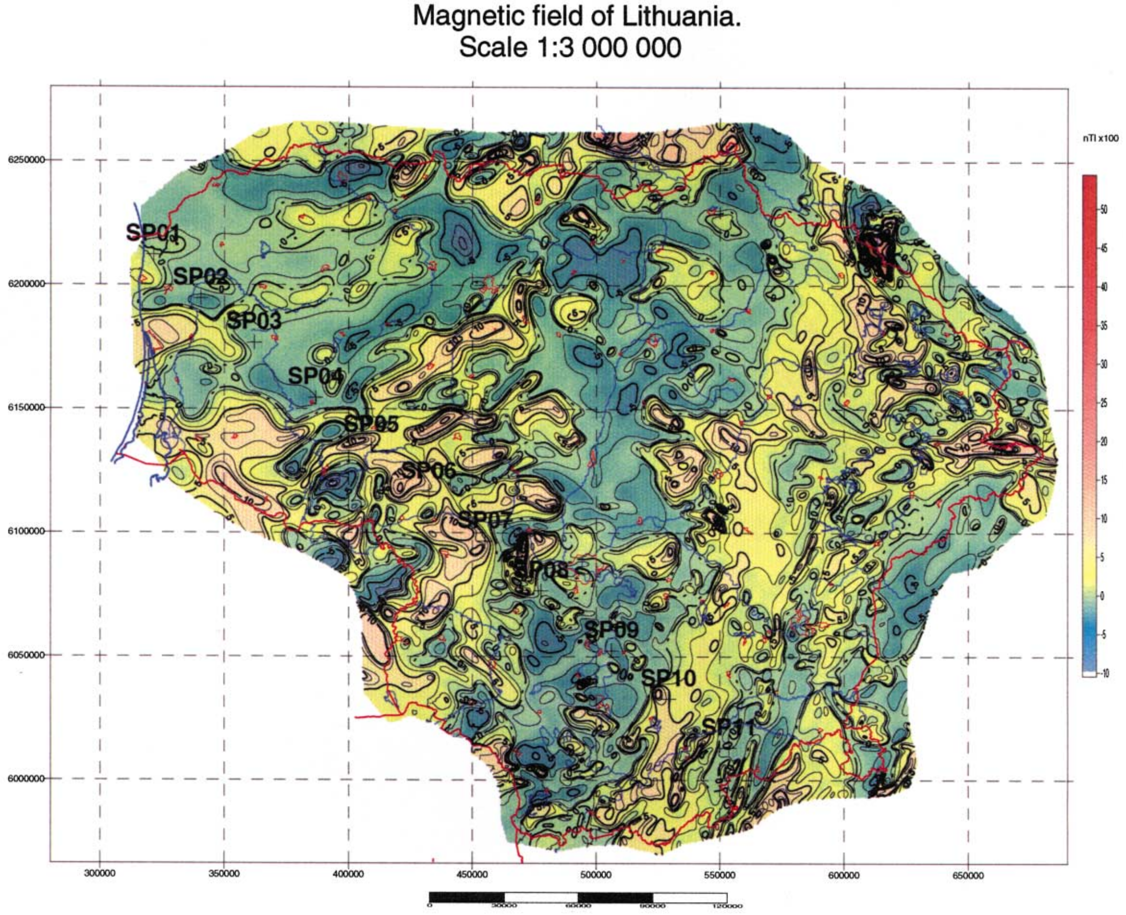


Fig. 2. The magnetic field of Lithuania. Scale 1:3 000 000.

zircon date, they are of ca. 1.81 Ga age (Claesson, 1996).

Enderbites and charnockites of magmatic appearance are very characteristic for the northern WLG. They are composed of hypersthene, biotite, plagioclase, K-feldspar, opaques, zircon, and frequently garnet. The enderbites and charnockites were partly recrystallised and reworked at granulite-facies conditions, and were sheared and retrogressed to amphibolite facies in some places (e.g. Vd1; Fig. 1). Mansfeld (1995) has obtained a Sm–Nd model age of ca. 2.4 Ga (T_{DM}) for the enderbites, while a preliminary U–Pb zircon dating of the same rocks gave ca. 1.82 Ga (Bibikova, pers. comm.).

Large areas of predominantly amphibolite-facies and undifferentiated granitic rocks occur along the north-eastern margin and in the central part of the WLG (Fig. 1). They produce low magnetic anomalies. Intensively brecciated, cataclased, and mylonitised rocks of various types form several-kilometre wide belts along the main fault zones.

2.2. The ELD

The ELD mostly comprises amphibolite-facies rocks and occupies eastern and southern Lithuania. The MLSZ separates the ELD from the WLG in the west. The crust of the ELD has thicknesses reaching 50–55 km and is thus 6–8 km thicker than that of the WLG (EUROBRIDGE Seismic Working Group, 2001–this issue). In the east, where granulites have been uplifted along numerous faults, the Belarus-Baltic

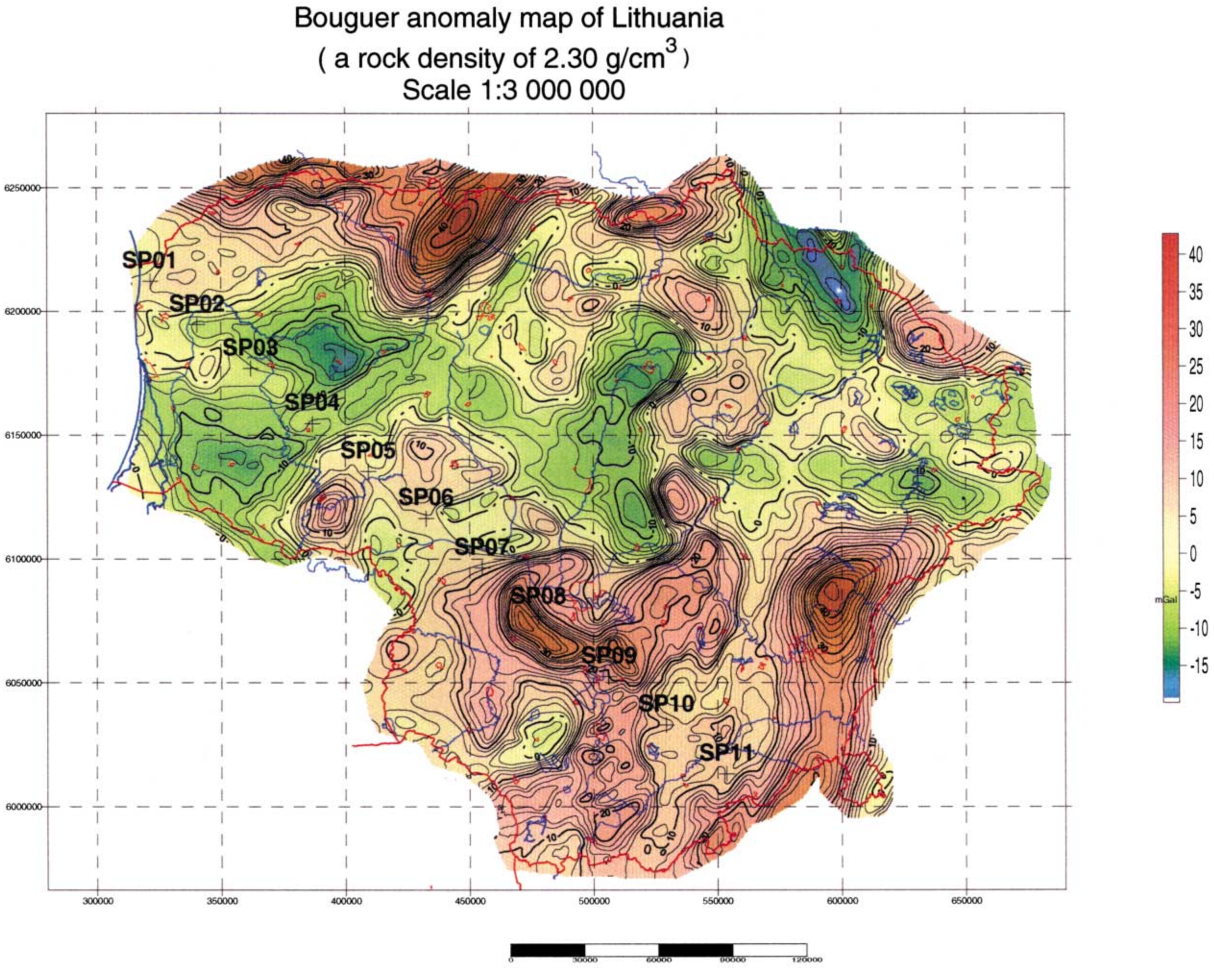


Fig. 3. The Bouguer anomaly map of Lithuania assuming rock density of 2.30 g/cm^3. Scale 1:3 000 000.

Granulite (BBG) belt borders the ELD. In the north, the ELD is abruptly cut off by an E–W-trending fault apparently belonging to the Polotsk–Kurzeme fault zone (cf. Garetsky et al., 1990). Towards the south-west, the ELD continues in the crystalline basement of north-eastern Poland, where it is known as the Masovian massif (Kubicki and Ryka, 1982).

In general, NNE-trending magnetic and gravity anomalies mark the ELD (Figs. 2 and 3). On a larger scale, against a subdued background, there are marked large-amplitude magnetic highs, each tens of kilometres long and 15–20 km wide. These correspond to various lithologies with contrasting magnetic properties, mainly gneisses and amphibolites, whereas granitoids dominate elsewhere in the domain. A chain of positive gravity and magnetic anomalies associated with numerous mafic bodies runs along the MLSZ (Figs. 2 and 3). In the southern part of the ELD, an area of high positive magnetic anomalies (up to 5000 nT) is produced by magnetite ores in the Varena Iron Ore Zone (VIOZ; V in Fig. 1).

2.2.1. Supracrustal rocks

Felsic gneisses tend to dominate the eastern ELD, whereas mafic rocks, mainly amphibolites, are more frequent in the west. Dolomitic and calcitic marbles alternate with gneisses and amphibolites in several places. Schists and quartzites are rare. Interbedding of these lithologies is observed in a few places.

Fine-grained biotite–quartz–plagioclase felsic gneisses with various amounts of K-feldspar, zircon (occasionally rounded), apatite, titanite and tourmaline are mostly metagraywackes. In a 100 m-long section of well 403 (Fig. 1), a stratigraphic sequence has been revealed where layers of several tens of centimetres thickness, discordant to gneissosity, may indicate primary graded bedding. Sm–Nd model ages for the metagraywackes vary between 2.41 and 2.29 Ga (T_{DM}, Table 1), indicating that the crust is mostly Palaeoproterozoic in age. The same metagraywackes have been dated by the U–Pb zircon method (Mansfeld, 1995), but no single meaningful ages could be obtained from multigrain fractions because various generations of zircon are present. The oldest, Archaean generation of zircon grains is thought to be detrital.

Similar results were obtained for rounded (detrital) zircons by the Pb–Pb evaporation method; here, the Archaean ages range between ca. 2.52 and 2.71 Ga (Marfin et al., 1987; Sumin, pers. comm.).

Gneisses and schists containing biotite, muscovite, sillimanite, plagioclase, quartz, minor K-feldspar, zircon and opaques occur in the easternmost part of the ELD, close to the BBG (e.g. wells 399, 400 and 722; Fig. 1). In places, they alternate with biotite–plagiocase gneisses, quartzites, amphibolites, and granite veins. Garnet is very rare and only found in a few drilling cores, e.g. among the sillimanite–muscovite–biotite schists and biotite–plagioclase gneisses of well 722 (Fig. 1). There are also garnet- and cordierite-bearing gneisses in the interior parts of the ELD (e.g. well 61, Fig. 1).

Layers of dolomitic marble, up to 100 m thick, are known in the Varena Zone. These layers may be relics of a single marble bed or of a sequence of several beds. A layer separating metagraywackes from amphibolites probably marks a particular stratigraphic level. Some marble beds have been torn apart tectonically (boudinaged) and partly substituted by metasomatic rocks, mainly iron–magnesium skarns. The skarns are composed of olivine that is mostly replaced by serpentine, and enstatite, diopside, amphibole, phlogopite, and magnetite (cf. Motuza et al., 1989; Skridlaite, 1993). The serpentinites with relics of olivine and spinel locally contain magnetite up to 100% and can then be considered serpentine–magnetite iron ores that form several deposits of potential economic interest. The surrounding amphibolites and gneisses have also been subjected to metasomatism.

The finely medium grained amphibolites form separate bodies or alternate with metasedimentary gneisses. They are composed of hornblende, biotite, plagioclase and opaques with minor quartz and K-feldspar. Some varieties, particularly those that are pyroxene-bearing, still preserve ophitic textures, while others are strongly foliated or mylonitised. An Sm–Nd model age (T_{DM}) for an amphibolite is ca. 1.9 Ga with an εNd value of +3.8 (Table 1).

An example of varied ELD lithologies is found in the Lazdijai area (wells Lz13 and Lz32, Fig. 1) where fine-grained biotite and hornblende–biotite gneisses alternate with amphibolites, amphibole–biotite schists, biotite–staurolite–garnet–quartz rocks, calcite marbles, and skarns. Metavolcanic garnet–biotite-, biotite-, amphibole- and clinopyroxene-bearing gneisses and schists preserving relic igneous textures also occur. These rocks have yielded Sm–Nd model ages between 2.08 and 2.2 Ga (T_{DM}), and are nearly juvenile to judge from their εNd values of +1.8 (Table 1).

2.2.2. Intrusive rocks

Several gabbroic and doleritic intrusions occur within the ELD, mainly along its western margin. The largest of these bodies occupies an area of several hundred square kilometres. The well-investigated Randamonys massif in southern Lithuania may either be a single body or a set of several minor, adjacent intrusive bodies consisting of norite, gabbro, diorite, and granodiorite. In the central parts of such intrusions, the rocks are massive, preserving igneous minerals and gabbroic textures, but in the more marginal parts, they are often amphibolitised, schistose and migmatised. Enrichment in ilmenite and magnetite occurs locally; dykes of microgabbro and diabase are common. According to ^{40}Ar/^{39}Ar hornblende age data (Table 1), the Randamonys massif experienced a tectonothermal event at ca. 1.67 Ga.

Ultramafic rocks are also present in the area. A thick harzburgite body, containing up to 70% orthopyroxene and 30% olivine, partly replaced by serpentine, actinolite, cummingtonite and micas, occurs in southern Lithuania (well 416; Fig. 1). Elsewhere,

Table 1
Isotopic and geochronological data for the Precambrian basement rocks in Lithuania

Domain	Data	Rock type (well)	Reference
The WLG	Sm–Nd (whole rock) — TDM: 2.42 Ga, εNd (1.9): −2.4 ± 0.5	Magmatic enderbites and charnockites (Vd 1)	Mansfeld (1995)
	TDM: 2.37 Ga, εNd: −0.3 ± 0.4	Mafic granulites (Dr 1)	Mansfeld (1995)
	TDM: 2.20 Ga, εNd: −3.1 ± 0.4	Metasedimentary granulites (Lk 5)	Mansfeld (1995)
	U–Pb (monazite): 1.79 Ga	Metasedimentary granulites (Lk 2)	Bibikova et al. (1997b)
	U–Pb (zircon): 1.81 Ga	Rusne tonalites (Rs 1)	Claesson (1996)
	Pb–Pb (monazite): 1.57 Ga	Rusne tonalites (Rs 1)	Claesson (1996)
	U–Pb (zircon): 1.58 Ga	Rapakivi granites and anorthosites of the Riga pluton	Rämö et al. (1996)
The ELD	Sm–Nd (whole rock)		
	TDM: 2.29–2.41 Ga, εNd (1.9): −1.0 to −1.8	Metagraywackes (403)	Mansfeld (1995)
	U–Pb (zircon): ca. 2.3 Ga	Metagraywackes (403)	Mansfeld (1995)
	Sm–Nd (whole rock)		
	TDM: 1.90 Ga, εNd (1.9): +3.8 ± 0.6	Amphibolites (404)	Mansfeld (1995)
	TDM: 1.98–2.04 Ga, εNd (1.5): −3.2 to −4.4	Kabeliai granites (Mr 4)	Mansfeld (1995)
	U–Pb (zircon): 1505 ± 11 Ma	Kabeliai granites (Mr 4)	Sundblad et al. (1994)
	Re–Os (molybdenite): ca. 1486 ± 5 Ma	Kabeliai granites (Mr 7)	Stein et al. (1998)
	^{40}Ar/^{39}Ar (hornblende)		
	1668 ± 9 Ma	Metagabbros (Lz 3)	Bogdanova et al. (this volume)
	1620 ± 10 Ma	Metagabbros (982)	Bogdanova et al. (this volume)
	1491 ± 8 Ma	Metavolcanics (423)	Bogdanova et al. (this volume)
	1469 ± 6 Ma	Mafic dykes (982)	Bogdanova et al. (this volume)
	1442 ± 7 Ma	Amphibolites (1064)	Bogdanova et al. (this volume)
The MLSZ	Sm–Nd (whole rock)		
	TDM: 2.2 Ga, εNd (1.9): +0.2	Metavolcanics (Lz 32)	Mansfeld (1995)
	TDM: 2.08 Ga, εNd (1.9): +1.8	Metavolcanics (Lz 13)	Mansfeld (1995)
	U–Pb (zircon): 1.50 Ga	Mazury rapakivi granites	Claesson et al. (1995)
	^{40}Ar/^{39}Ar (hornblende): ca. 1.45 Ga	Metasediments and metavolcanics (Lz 13 and Lz 32)	Bogdanova et al. (this volume)

layers of altered ultramafic rocks are preserved locally.

Various gneissic granitoids are found in the ELD. These are often anatectic migmatites formed at the expense of supracrustal rocks. They vary from plagioclase-rich to potassic granites, the latter often cutting the former. Biotite- and amphibole-bearing granites and migmatites usually contain relics of amphibolites.

2.3. The MLSZ

The position and nature of the MLSZ, the boundary between the WLG and ELD, is as yet not well constrained geologically. Geophysically, however, potential-field patterns change drastically in the middle of Lithuania, along a nearly N–S-trending zone of faulting where the mosaic-like, NW-, NE-, and E–W-trending geophysical anomalies of the WLG are truncated by the N–S-trending anomaly pattern of the ELD (Figs. 2 and 3). In southernmost Lithuania, in the so-called Lazdijai area (L in Fig. 1), the MLSZ boundary turns south-westward. It is here marked by sharp potential-field gradients, particularly of the magnetic field, which may coincide with zones of cataclastic crushing and mylonitisation.

According to the magnetic-field modelling of Popov and Sliaupa (1997a), the MLSZ dips westward to a depth of about 20 km, which suggests underthrusting of the ELD beneath the WLG. At the same time, however, the Moho boundary dips eastwards because of increasing crustal thicknesses toward the east (EUROBRIDGE Seismic Working Group, 2001–this issue).

Along the MLSZ, the structure of the crust changes within a 30–50 km wide transitional zone well seen in the EUROBRIDGE velocity model (EUROBRIDGE Seismic Working Group, 2001–this issue). The Moho subsides from 42 to 44 km in the WLG to 50 km in ELD. The seismic velocities in the crust of the ELD are higher than those in the WLG, which corresponds with the more mafic composition of the former. A low-velocity layer in the upper crust of the WLG is truncated by the MLSZ and does not reappear inside the ELD.

Direct geological evidence of a crustal domain boundary is observed in the south-western part of the MLSZ, in the Lazdijai area (L in Fig. 1), where rocks of different metamorphic grades and histories occur (cf. below), and ELD amphibolite-facies rocks are juxtaposed with granulites of WLG affinity in the west.

3. Comparative geochemistry and protolith origin

Major, trace, and rare earth (RE) element geochemistry has been used to infer the origins and probable geodynamic settings of the rocks in the Lithuanian basement. About 500 analyses were employed. Major-element analyses were made using wet chemistry at Vilnius University, the Lithuanian Institute of Geology, and the Geological Survey of Lithuania, in addition to which more than 70 samples were analysed using the plasma-emission-spectrometry facilities (ICP) at Luleå University, Sweden, and the Centre of Petrographical and Geochemical Research at Nancy, Vandoeuvre, France, as well as X-ray fluorescence (XRF) spectrometry at the Polish Institute of Geology in Warsaw. Trace and RE elements were surveyed by ICP-MS at Luleå and Vandoeuvre, and the former also by XRF in Warsaw.

The location of the wells from which samples have been analysed is shown in Fig. 1. Averages of chemical compositions for metasedimentary and metaigneous rocks are given in Table 2.

3.1. The WLG

3.1.1. Supracrustal rocks

Analyses of 30 metasedimentary granulites from the WLG (Table 2) indicate original compositions chemically similar to average oceanic clay (cf. Nichols et al., 1996), but there is some scatter due to high-grade metamorphism. In the classification diagram of Herron (1988), the results are plotted in the shale and Fe-shale fields (Fig. 4).

Similar to most rocks derived from clay, the WLG metapelites have higher concentrations of total REE than other metasediments (Fig. 5a). The patterns are similar to those of the ‘average European shale (ES)’ of Haskin and Haskin (1966). The observed enrichment in light REE in some samples can possibly be explained as an effect of migmatisation, whereas the garnet-rich samples generally have relatively elevated contents of heavy REEs (Fig. 5a).

More than 50 chemical analyses were employed to infer the origins and geodynamic settings of the mafic rocks in the WLG. In view of the mobility of many elements during high-grade metamorphism, all the available analyses were examined critically prior to their use for classification and discrimination. Following the approaches of Pearce and Cann (1973) and Pearce (1976), only mafic metavolcanics with contents of SiO_2 below 54% and CaO + MgO sums between 12 and 20% were considered suitable for use in the tectonic discrimination of the metabasalts.

A majority of the WLG mafic granulites correspond to low-*K* tholeiites of oceanic island-arc/ocean-island affinities (Fig. 6a and b). Some mafic granulites, however, plot in the field of the calc-alkaline basalt (Fig. 6b), while a metabasalt from the south-easternmost WLG can be assigned to the MORB and island-arc tholeiite fields according to the Ti–Zr–Y and Ti–Zr–Sr discriminations (Fig. 7a and b; cf. Pearce and Cann, 1973). As indicated in Fig. 5c, the latter metabasalt has a flat and unfractionated REE distribution, suggesting a quite primitive source.

The biotite- and pyroxene-biotite gneisses with relics of plagioclase phenocrysts have andesitic composition (Table 2) and highly fractionated REE distributions with marked depletion in heavy REE (Fig. 5d).

3.1.2. Intrusive rocks

The charnockites and enderbites from the northern WLG (e.g. from wells Vd1 and Lz1, Fig. 1), which have igneous textures and inclusions of mafic granulites, are enriched in REE and show fractionated REE patterns (Fig. 5b). The Rusne tonalitic–trondjemitic granites (Rs1, Fig. 1) have low REE values and

Table 2

Average chemical compositions of the Palaeoproterozoic rocks from the WLG and the ELD domains. Metavolcanics have been classified as island-arc tholeiites (IAT), calc-alkali basalts (CAB), ocean-island basalts (OIB) and ocean-floor basalts (OFB) according to the Pearce (1976) and Pearce and Cann (1973) discriminations. Number of analyses is shown in brackets

WLG

	Metabasalts			Metaandesites		Metasediments
	IAT (#7)	CAB (#5)	OIB (#1)	(#4)	(#2)	(#30)
SiO_2	51.52	54.00	47.88	57.52	58.38	61.09
TiO_2	1.47	1.42	2.72	1.89	0.89	1.02
Al_2O_3	15.75	18.39	15.00	15.28	18.00	18.9
$Fe_2O_3^*$	12.12	9.39	16.32	10.14	7.78	8.37
MnO	0.12	0.12	0.22	0.10	0.11	0.07
MgO	6.76	4.25	5.56	3.10	3.35	3.05
CaO	9.13	7.48	10.32	6.42	6.41	1.32
Na_2O	1.56	2.77	1.00	2.25	2.69	1.74
K_2O	0.89	1.05	0.33	2.88	1.42	3.62
P_2O_5	0.02	0.17	0.00	0.00	0.38	0.06
Total	99.63	98.88	99.45	99.86	99.64	99.76

ELD

	Metabasalts			Metaandesites			Metasediments	
	OFB (#8)	IAT (#11)	CAB (#10)	(#1)	(#3)	(#4)	(#22)	(#7)
SiO_2	49.01	49.67	50.88	58.69	56.30	65.87	70.4	63.12
TiO_2	1.66	0.96	1.12	0.59	1.01	0.44	0.38	0.64
Al_2O_3	14.37	15.51	17.79	13.53	17.01	16.74	14.31	17.55
$Fe_2O_3^*$	14.27	12.52	9.50	7.60	8.72	3.69	3.12	5.69
MnO	0.16	0.26	0.13	0.13	0.26	0.10	0.01	0.02
MgO	7.12	6.88	5.90	3.60	3.59	1.58	1.82	2.46
CaO	8.49	8.75	8.72	9.80	4.93	4.72	1.87	1.93
Na_2O	2.74	3.12	3.19	2.70	2.92	3.61	4.71	2.66
K_2O	0.34	1.04	1.06	2.80	3.22	1.49	2.66	3.06
P_2O_5	0.05	0.33	0.40	0.22	0.37	0.39	0.27	0.2
Total	98.92	99.94	99.58	100.36	99.30	100.13	100.04	99.8

markedly positive Eu-anomalies (Fig. 5b) typical of tonalites derived from tholeiitic sources (Hall, 1996).

3.2. The ELD

3.2.1. Supracrustal rocks

The ELD metasedimentary gneisses rich in plagioclase are mostly metagraywackes. There is some scattering of data, probably related to the metamorphism and Na–K metasomatism which affected the rocks in the south-central part of the ELD. Nevertheless, the average chemical composition with 69% SiO_2, 15% Al_2O_3, 4.1% Fe_2O_3 (total Fe), 1.9% MgO, 3.8% Na_2O, and 2.6% K_2O (Table 2), fits the average chemical composition of sandstones in 'active continental margin' tectonic setting (Bhatia, 1983). In the classification diagram of Herron (1988), the ELD metasediments mostly plot in the 'wacke' field (Fig. 4). Subordinate biotite gneisses from the interior parts of the ELD (e.g. in well 421), and gneisses from its westernmost margin plot in the arkose field of the same diagram.

The biotite- and sillimanite-bearing gneisses and schists from the easternmost ELD (wells 400 and 722, Table 2) have argillaceous composition and are assigned to the shale field (Fig. 4).

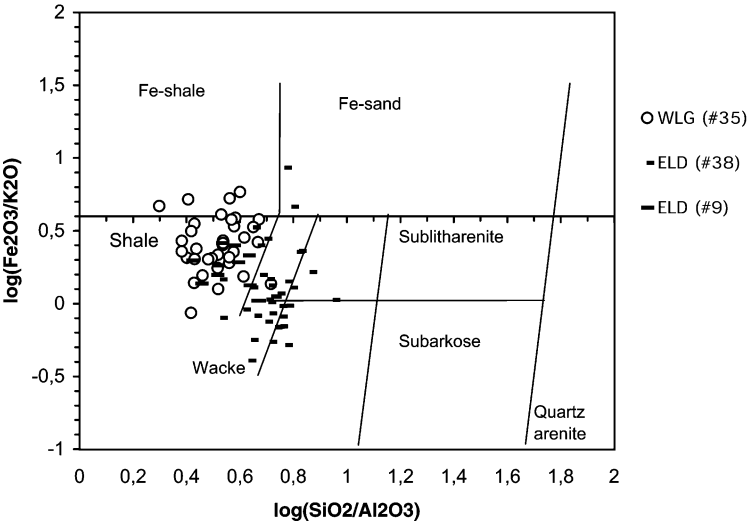


Fig. 4. Diagram according to Herron (1988) of the metasedimentary rocks from the crystalline basement of Lithuania. The open circles mark WLG metasedimentary granulites, the small bricks represent the ELD biotite plagioclase gneisses and the large bricks show biotite–sillimanite–muscovite gneisses and schists.

In the discrimination diagram of Bhatia (1983), the ELD metagraywackes plot in the 'active continental margin' field (Fig. 8a and b), while the argillaceous metasediments plot in the 'continental island arc' field. That could imply the presence of granitic materials in the source region or the detachment and incorporatation of fragments of the mainland into inter-arc, back-arc, and fore-arc basins (Bhatia, 1983). The REE patterns of the ELD metasediments are similar to those of the 'average Post-Archaean Australian sedimentary rock (PAAS)' of McLennan (1989) (cf. current Fig. 5a), even though the ELD metasediments have been more fractionated due to migmatisation.

The ELD metabasaltic amphibolites mostly correspond to low-*K* tholeiites and subordinately to calc-alkaline basalts (Fig. 6a and b). Some of them have MORB-type characteristics and display flat, unfractionated REE patterns, while the REE patterns of the others are fractionated (Fig. 5c). According to the Ti–Zr–Y and Ti–Zr–Sr discriminations (Fig. 7a and b), the analysed ELD amphibolites plot in the fields of very different tectonic settings.

The garnet–biotite, biotite-, amphibole-, and clinopyroxene-bearing gneisses from the Lazdijai area have andesitic or dacitic compositions (Table 2). Similar to the metaandesites in the WLG, they are depleted in heavy REE (Fig. 5d).

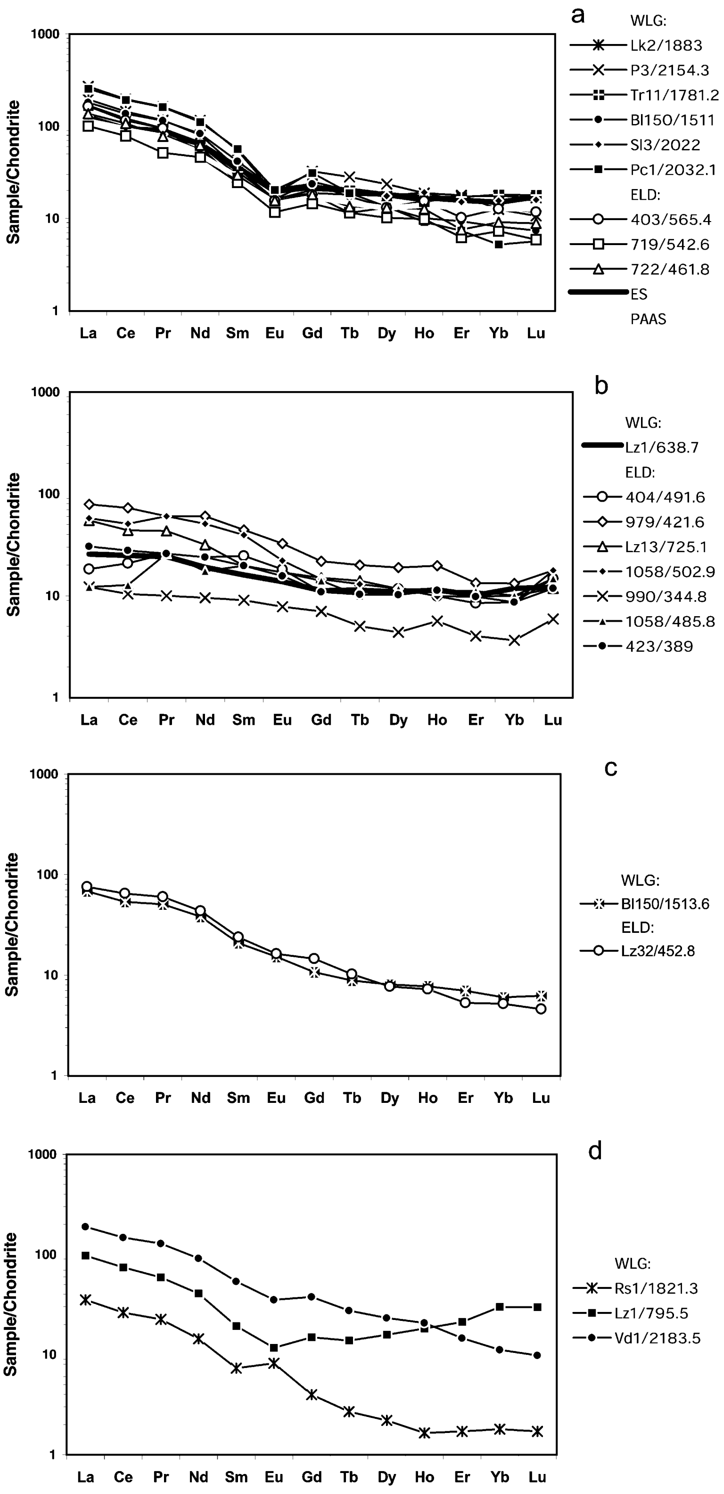
3.2.2. Intrusive rocks

According to their contents of major elements, the Randamonys gabbros and norites (e.g. those from wells 1058 and Lz3) plot in the OFB field, while the others scatter throughout the fields of low-*K* tholeiite and calc-alkaline basalt (Fig. 6a and b). In the Ti–Zr–Y and Ti–Zr–Sr discrimination diagrams (Fig. 7a and b), the gabbros and diabases are assigned to the fields either of undifferentiated MORB, island-arc tholeiite plus calc-alkaline basalt, or island-arc tholeiite. Some amphibole-rich Randamonys gabbros have differentiated REE patterns, whereas the subvolcanic gabbros (e.g. from well 990), metadiabases (well 423), and cutting diabase dykes (e.g. well 1058) display almost undifferentiated, flat REE distributions (Fig. 7c).

4. Metamorphism

4.1. The WLG

The recorded metamorphic conditions differ throughout the WLG. Peak conditions have


a
WLG:
Lk2/1883
P3/2154.3
Tr11/1781.2
Bl150/1511
Sl3/2022
Pc1/2032.1
ELD:
403/565.4
719/542.6
722/461.8
ES
PAAS
b
WLG:
Lz1/638.7
ELD:
404/491.6
979/421.6
Lz13/725.1
1058/502.9
990/344.8
1058/485.8
423/389
c
WLG:
Bl150/1513.6
ELD:
Lz32/452.8
d
WLG:
Rs1/1821.3
Lz1/795.5
Vd1/2183.5
Sample/Chondrite
1000
100
10
1
La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Yb Lu

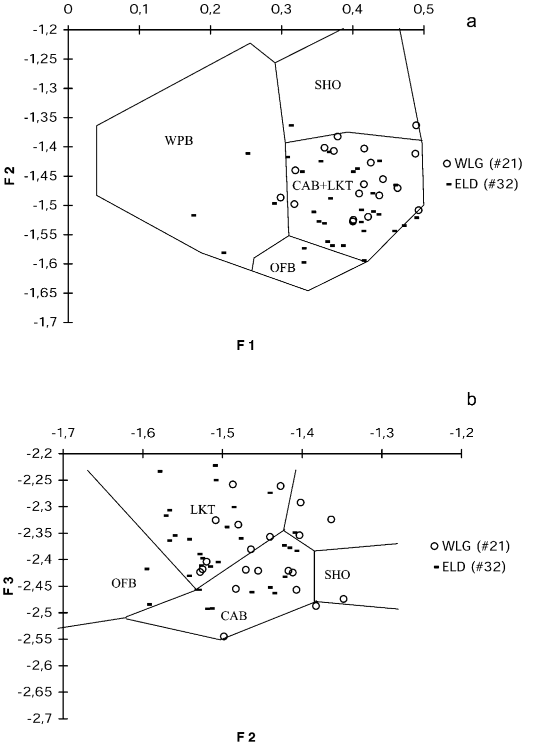


Fig. 6. Tectonic-setting diagrams for the metabasalts from the Lithuanian basement, employing plots of discriminant functions: (a) $F1$ versus $F2$ and (b) $F2$ versus $F3$, where $F1 = +0.0088\mathrm{SiO_2} - 0.0774\mathrm{TiO_2} + 0.0102\mathrm{Al_2O_3} + 0.0066\mathrm{FeO} - 0.0017\mathrm{MgO} - 0.0143\mathrm{CaO} - 0.0155\mathrm{Na_2O} - 0.0007\mathrm{K_2}O$; $F2 = -0.0130\mathrm{SiO_2} - 0.0185\mathrm{TiO_2} - 0.0129\mathrm{Al_2O_3} - 0.0134\mathrm{FeO} - 0.0300\mathrm{MgO} - 0.0204\mathrm{CaO} - 0.0481\mathrm{Na_2}O + 0.0715\mathrm{K_2}O$; and $F3 = -0.0221\mathrm{SiO_2} - 0.0532\mathrm{TiO_2} - 0.0361\mathrm{Al_2O_3} - 0.0016\mathrm{FeO} - 0.0310\mathrm{MgO} - 0.0237\mathrm{CaO} - 0.0614\mathrm{Na_2O} - 0.0289\mathrm{K_2}O$. The fields of ocean-floor basalts (OFB), low-potassium tholeiites (LKT), calc-alkaline basalts (CAB), shoshonites (SHO), ocean-island basalts (IOB) and continental basalts (CON) are shown according to Pearce (1976).

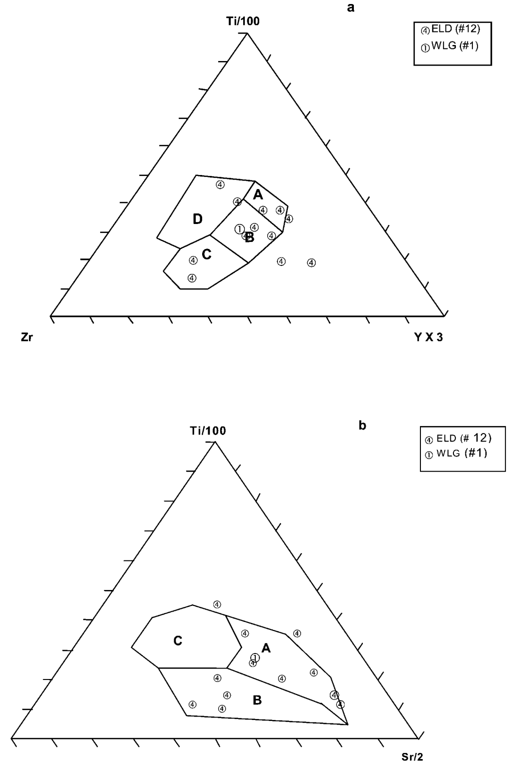


Fig. 7. (a) Ti–Zr–Y and (b) Ti–Zr–Sr discrimination diagrams according to Pearce and Cann (1973) for the metabasalts of the Lithuanian basement. In diagram (a), A is the field of island-arc tholeiites; C the field of calc-alkaline basalts, D the field of within-plate basalts, and B the field of MORB, island-arc tholeiites and, calc-alkaline basalts.In diagram (b), island-arc tholeiites plot in field A, calc-alkaline basalts in field B, and MORB in field C.

previously been estimated for a few drilling cores in its westernmost and south-easternmost parts (Skridlaite, 1994). In the west (e.g. wells Lk2, Lk5 and Tr11, Fig. 1), the metapelites were buried to depths of nearly 30 km and reached maximum temperatures of 850–900°C at 8–9 kbar (Fig. 9a) some time before 1.8 Ga. Approximately simultaneously, enderbites and charnockites were intruded farther to the north (U–Pb zircon ages; Bibikova, pers.com.). After initial cooling, there followed a nearly isobaric step of reheating and cooling documented by temperatures between 660 and 780°C at ca. 7.5 kbar, and subsequent decompression (Fig. 9a). The time of beginning

Fig. 5. Chondrite-normalised REE patterns for the basement rocks of Lithuania: (a) Metapelites the WLG (wells Lk2, P3, Tr11, Bl150, Sl3 and Pc1) and metagraywackes of the ELD (wells 403, 719 and 722), (b) WLG mafic granulites (well Lz 638.7), the ELD amphibolites (wells 404, 979 and Lz13), ELD gabbros (wells 1058 and 990) and ELD diabases (wells 1058 and 423), (c) Metaandesites of the WLG (well Bl150) and the ELD (well Lz32), (d) WLG tonalite (well Rs1) and enderbites plus charnockites (wells Lz1 and Vd1). The normalising of the data is according to Nakamura (1974. The composition of the Average European Shale (ES) is according to Haskin and Haskin (1966), and that of the Post-Archaean Average Australian Sedimentary Rock (PAAS) is according to McLennan (1989).

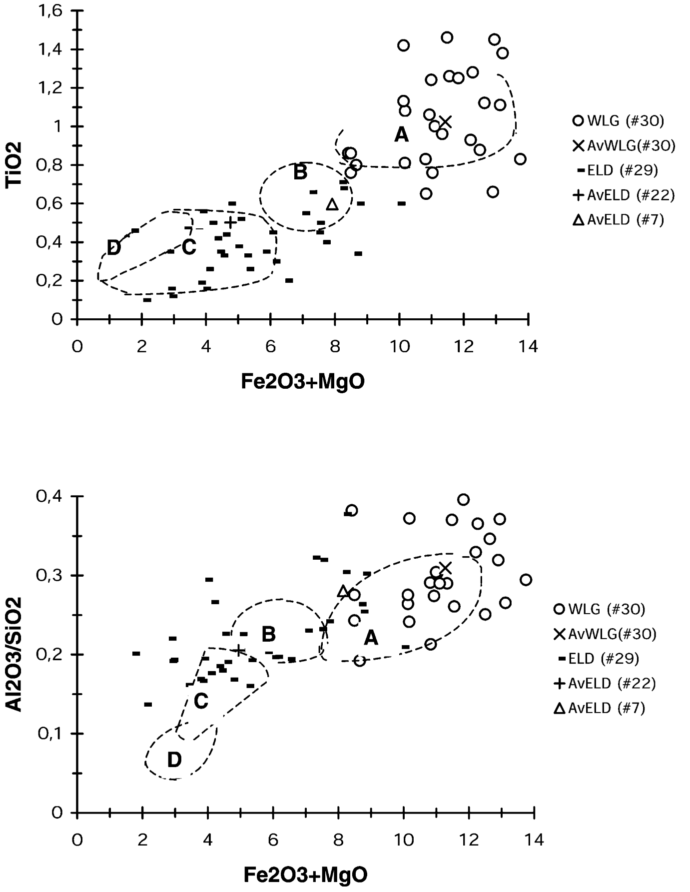


Fig. 8. Major-element compositions of metasediments from the basement of Lithuania as plotted in the discrimination diagram of Bhatia (1983) that indicates tectonic settings of sandstones. The fields for the various tectonic settings are: (A) oceanic island arc; (B) continental island arc; (C) active continental margin; (D) passive continental margins. Crosses mark the sites of the average ELD metagraywackes, and triangles those of the average ELD metapelites. Open circles represent the metapelitic granulites of the WLG, which are plotted in the diagram for comparison. The oblique cross marks their average composition.

thermal relaxation has been estimated using monazite formed during partial anatectic melting at 1.79 Ga (Bibikova et al., 1997b).

In the south-easternmost part of the WLG, inclusions of felsic granulites in enderbitic and charnockitic intrusions record a peak metamorphism at ca. 850–900°C and 10 kbar (e.g. in well Lz1, Fig. 9b). Together with the host rocks, these inclusions underwent a second granulite-facies event at ca. 800–850°C and 8 kbar, followed by later decompression.

In both parts of the WLG, the generally decompressional exhumation path was subsequently overprinted by a second reheating/cooling step at 550–800°C and ca. 4.5 kbar (Fig. 9a and b). That step may have been related to the emplacement of anorogenic granites at 1.58–1.50 Ga (Claesson et al., 1995; Rämö et al., 1996). The recorded metamorphic path terminates at ca. 500°C and 2 kbar throughout the WLG.

Similar evolutions can thus be inferred from rocks of different types in the WLG. The peak-metamorphic conditions recorded in the western and south-eastern parts of the WLG and the step-wise retrograde paths with alternating near-isobaric reheating/cooling and near-isothermal decompression steps (Fig. 9a and b) reveal a complex history of metamorphism.

4.2. The ELD

The rocks of the ELD have undergone amphibolite-facies metamorphism throughout. However, the presence of metamorphic zoning is revealed by some of the newly obtained data. The metagraywackes and metapelites from the part of the eastern ELD that is closest to the BBG (e.g. well 722, Fig. 1), record peak conditions at 650–680°C and 7–8 kbar, with later retrogression to 530°C at 4–5 kbar (Skridlaite, unpubl. data).

The metagraywackes, metavolcanics and metagabbros in the interior parts of the ELD have been metamorphosed at ca. 480–580°C and 3–4 kbar. This has been inferred from hornblende + plagioclase, biotite + tourmaline (e.g. wells 403 and 982 in Fig. 1; Motuza and Skridlaite, 1994), and garnet + biotite + sillimanite + plagioclase as well as garnet + cordierite (e.g. well 61, Skridlaite, unpubl. data) parageneses. Nevertheless, it is still unclear whether these conditions represent the peak of metamorphism. The reason is that associated migmatites and anatectic granites in the central ELD suggest that somewhat higher temperatures had been attained at one time. In some places in the Varena iron–magnesium-bearing skarns, an increase in temperature to 700°C at ca. 3 kbar has been recorded by clinopyroxene–hornblende assemblages (Skridlaite, 1993). However, the formation of skarns was presumably not a consequence of regional metamorphism, having more likely been related to a local heat source probably created by the emplacement of a body of anorogenic similar to the Kabeliai intrusion (cf. below).

In the south-westernmost part of the ELD, adjacent to the MLSZ, the garnet-bearing felsic, garnet–pyroxene, and amphibole-bearing mafic gneisses (e.g. wells Lz 13 and Lz 32, Fig. 1) had inferred pressures of ca. 6 kbar at 500°C and must therefore have been buried to depths of ca. 20 km. Subsequently, these rocks were heated to temperatures around 700°C and still later exhumed (Fig. 9c). Their recorded metamorphic evolution ceased at ca. 450°C and 1.5 kbar.

From the above representation, it follows that the

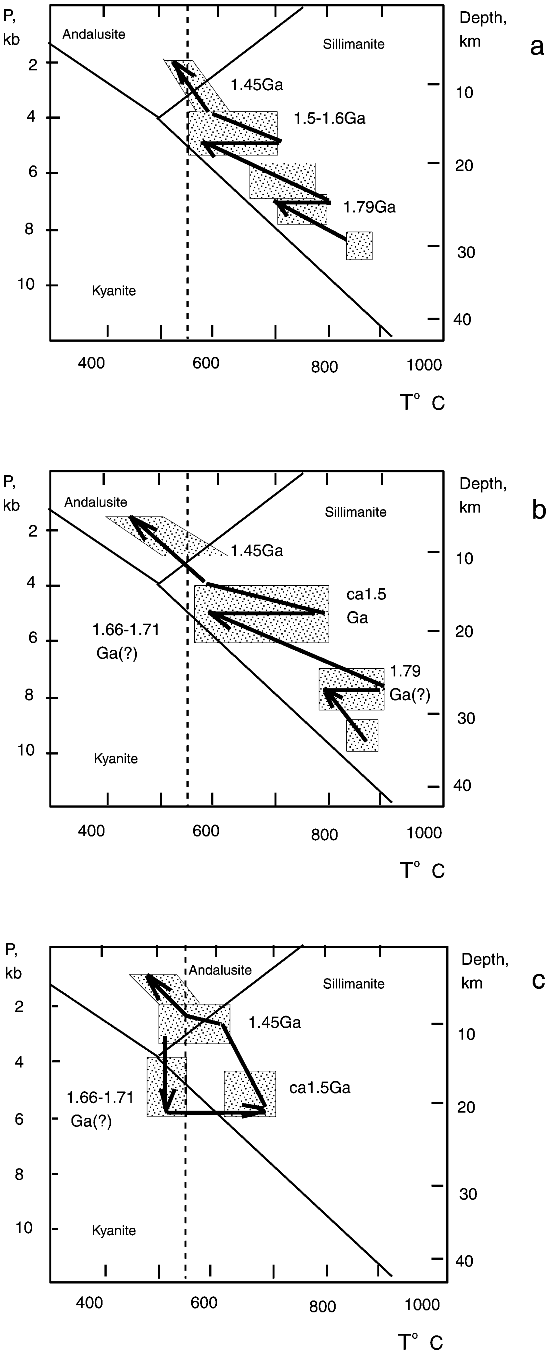


Fig. 9. *P–T–t* paths for the granulites (a) of the WLG, (b) of the western MLSZ, and (c) of the eastern MLSZ. The dotted fields in these diagrams mark parts of the *P–T–t* paths drawn according to *PT* estimates. The speculative parts of the paths are marked by thick solid arrow lines, while the thin solid lines delimit the stability fields for the aluminium silicates according to Holdaway (1971). The vertical dashed line indicates the 550°C Ar/Ar clossure temperature of hornblende. For ages, see Table 1.

rocks sampled from the eastern part of the ELD had undergone metamorphism at temperatures and pressures similar to but somewhat lower than those in the metapelites of the adjacent BBG. However, peak conditions occurred early during the metamorphic evolution of the eastern ELD, whereas Taran and Bogdanova (1997) indicate that the highest temperatures in the BBG were only reached during a second metamorphic episode, linked to intense post-collisional magmatism at ca. 1.79 Ga (cf. Bogdanova et al., 1994; Bibikova et al., 1997b). While such magmatism is also known from the eastern ELD, it was much less intense there and did not associate with a metamorphic top. The peak episode in the ELD, therefore, appears to correspond to the early episode in the BBG which took place a substantial time before 1.80 Ga.

Subsequently, the eastern ELD and the adjoining BBG were exhumed similarly, and for a while, the sampled parts of both domains remained reasonably stable at 530–580°C and 4 kbar.

As different from the eastern ELD, the sampled crustal level of the central ELD records peak metamorphism at 480–580°C and 3–4 kbar, i.e. at depths of only ca. 10–12 km. In contrast, the rocks sampled from the south-westernmost ELD were peak-metamorphosed at ca. 6 kbar and 580°C.

The now reported differences of metamorphic state and evolution within the ELD are consistent with Popov and Sliaupa's (1997a) model of the magnetic field, which shows westward dipping crustal boundaries in the ELD–BBG region and a thickened crust in the central ELD. Subsequent to metamorphism, the latter area had apparently undergone less uplift than the rest of the ELD. The metamorphic zoning in the ELD was thus mostly structurally controlled.

Like the BBG, the ELD underwent late tectonic and metamorphic reworking at 1.67–1.61 Ga, as indicated by the ^{40}Ar/^{39}Ar hornblende data listed in Table 1.

5. Anorogenic magmatism

After its consolidation, the Palaeoproterozoic crust in the entire Baltic-Belarus region was affected by post-kinematic, 'anorogenic' anorthosite-rapakivi magmatism associated with shearing along discrete, mostly E–W-trending tectonic zones (Bogdanova and Gorbatschev, 1997; Bogdanova et al., 2001–this issue). In Lithuania, the magmatism commenced ca. 1.58 Ga ago in the vicinity of the likewise 1.58-Ga Riga anorthosite-rapakivi pluton (Rämö et al., 1996), then continuing in various locations until approximately 1.50 Ga (Sundblad et al., 1994; Claesson et al., 1995). Attendant shearing and metamorphism of mafic and intermediate dyke lasted until ca. 1.45 Ga (Table 1).

The anorogenic magmatism has overprinted both the Lithuanian crustal domains. In the northern WLG, e.g. in well Ab3, Fig. 1, diorites with idiomorphic plagioclase phenocrysts partly replaced by K-feldspar may belong to the Riga pluton.

In the Nemunas Fault Zone of the southwestern WLG, which is characterised by the superposition of positive magnetic and negative gravity anomalies (Figs. 2 and 3), there are numerous occurrences of rapakivi granites as well as monzodiorites (e.g. in wells Rk1, Rk2, Us1, Us2, Us3, and Us4, Fig. 1). These are mainly porphyritic rocks composed of biotite, pyroxene, plagioclase, perthite, quartz, zircon, monazite, apatite, Fe–Ti oxides, and minor carbonates. Locally, these rocks have been mylonitised. A preliminary Pb–Pb monazite dating (Claesson, 1996) suggests an age of ca. 1.57 Ga.

Also within the WLG, a chain of bodies of porphyritic granites and associated mafic and intermediate rocks is linked to E–W-trending fault zones in the central part of that crustal domain (cut, e.g. by wells Gl99 and Gz105, Fig. 1). Locally, these rocks have been strongly sheared (e.g. in well Gz105).

In the Lazdijai area (Marfin et al., 1994), the Veisiejai complex of porphyritic potassic granites and related monzonitic–dioritic–gabbroic rocks overprints the MLSZ suture between the WLG and ELD, stitching these two domains. That complex is likely to be an extension of the Mazury and Suwalki complexes in north-eastern Poland; this interpretation is supported by the trends of geophysical anomalies (Krolikowski et al., 1999) and by similar mineral and chemical compositions (Rimsa et al., 1999; Wiszniewska et al., 1999).

In the southern ELD, finally, massive, inequigranular potassic granites form distinct bodies with numerous intrusive contacts. These rocks belong to the Kabeliai complex, U–Pb zircon dated at 1.505 ± 11 Ga by Sundblad et al. (1994). Chemically, they appear to be normal I-type granites or quartz-monzonites (Sundblad et al., 1994), mostly plotting in the 'within-plate granite' (WPG) field in respect to trace-element proportions (Cecys, 1998). Porphyry-type Cu–Mo mineralisations occur with Re–Os ages of 1.486 ± 5 Ga (Stein et al., 1998). The Kabeliai granites are comparable to anorogenic granites of the Mazury complex in Poland (Wiszniewska et al., 1999) and to some granites in southern Sweden (Cecys, 1998).

6. Discussion

6.1. Potential fields, composition and age of the Precambrian crust in Lithuania

The contrasting potential-field signatures, crustal velocity structures and thicknesses as well as the dominant lithologies of the WLG and ELD reflect independent tectonic histories for these terranes before their amalgamation along the MLSZ in the Palaeoproterozoic.

Although magnetic and gravity anomalies are generally subdued and only slightly differentiated in the WLG (Figs. 2 and 3), there is an obvious NW–SE fabric that is overprinted by the signatures of later NE- and E–W-trending faults and shear zones. These trends are probably also reflected in the distribution of the two main protolith complexes of the WLG, viz. the NW-trending contact between marine metapelites and metaandesites in the south-west, and island-arc tholeiites in the north-east, which partly coincides with a fault zone (cf. Fig. 1). According to the Sm–Nd isotope data (Mansfeld, 1995), the Palaeoproterozoic rocks of the WLG have εNd values between −3.1 and −0.3 (Table 1) indicating the involvement of some crustal material in the magmatism there. The main crust-forming events in the WLG appear to have occurred around 1.81–1.80 Ga (cf. Table 1). However, Mansfeld (1995) reports an igneous crystallisation age of 1.87–1.82 Ga for a metavolcanic granulite in the northern continuation of the WLG in Latvia.

The ELD is characterised by prominent gravity and magnetic anomalies that strike clearly in a NNE–SSW direction (Figs. 2 and 3). The geochemistry of amphibolites in the ELD suggests a protolith of mafic rocks with MORB, or IAT, characteristics (cf. above). This agrees with high positive εNd values between +1.8 and +3.8 for metavolcanics in the western ELD. Such primitive compositions are in contrast with the compositions of metasediments in the central ELD which appear, geochemically, to have been deposited in an active continental-margin tectonic setting. This also explains the high concentration of older, even Archaean, detritus in these sediments as indicated by zircons ages (Table 1; cf. also Mansfeld, 1995). Together, the combination of juvenile mafic volcanism with subordinate ultramafic rocks and continental-margin/shelf sediments in the ELD suggest an oceanic back-arc setting. Unfortunately, the precise age of the Palaeoproterozoic igneous event is not determined yet. However, the similarity of the early metamorphic evolutions of the eastern ELD and the BBG (cf. above) may suggest a similar crustal age for these two domains, i.e. probably older than 1.86 Ga (cf. Mansfeld, 1997).

6.2. Differences in character and timing of metamorphic evolution

In the WLG, peak metamorphism for the metapelites was attained at 850–900°C and 8–10 kbar ca. 1.8 Ga ago. This implies that sediments were buried to ca. 35 km, most likely to such a depth by subduction/accretion processes. Partial melting accompanying the peak metamorphism was followed by slow tectonic uplift and multiple emplacements of melts. Voluminous magmas produced by partial melting in the mantle and crust repeatedly, up to ca. 1.5 Ga, intruded the overlaying rocks (Fig. 9a).

The metamorphic development of the ELD is still poorly reconstructed. The rocks, in general, have experienced moderate to high amphibolite-facies metamorphism, which, however, has a different character across the domain. The metamorphic evolution of the eastern ELD is similar to that of the adjacent BBG. The latter, however, was affected by intense bimodal post-collisional magmatism and accompanying granulite metamorphism at 1.79 Ga (Taran and Bogdanova, 1997) that is not well expressed in the eastern ELD. Subsequently, both were affected by similar uplift trends. The central and western ELD are characterised by a lower grade of amphibolite facies, with temperatures of 480–580°C but with pressure increasing from 3–4 kbar to ca. 6 kbar near the WLG boundary. Another remarkable feature of the metamorphic evolution of the ELD is the increase of temperature with time up to ca. 700°C, suggesting significant heating of the crust in the vicinity of anorogenic, ca. 1.5 Ga intrusions in southern Lithuania and northern Poland. This is also recorded by 1.5–1.45 Ga Ar/Ar ages of amphiboles (Bogdanova et al., 2001–this issue).

6.3. Correlation of the WLG and ELD with Palaeoproterozoic complexes of the Baltic Shield and other tectonic belts in the EUROBRIDGE region

The geological complexes of the WLG can be compared to those in Sweden in order to assess the significance of a chain of magnetic and gravity anomalies that runs north-westwards from the WLG across the Baltic Sea, via Gotland to south-east Sweden (e.g. Wybraniec et al., 1999; Sundblad et al., 1998; Sundblad, pers.com.). The dominant NW–SE orientations of major structures and lithological trends are consistent in the WLG and south-east Sweden, for example in the Oskarshamn-Jönköping Belt (OJB; Mansfeld, 1997). Though the WLG metavolcanics and their associated metasediments suggest an island-arc tectonic setting, their possible counterparts in the OJB appear to belong to a back-arc setting (Beunk et al., 1996). According to the present age data, the main metamorphic and deformational events in western Lithuania occurred in the time span 1810–1450 Ma (Table 1); this is comparable with 1845–1550 Ma in south-east Sweden (Beunk et al., 1996).

Ages and lithologies in the WLG may also possibly be correlated with the Latvian–Estonian Granulite Domain (e.g. Puura et al., 1980; Mansfeld, 1995), even though the latter has previously been considered a continuation of BBG (Fig. 1, inset).

The major structures of the ELD strike in the same direction as the major terranes lying father to the east, e.g. the BBG, the Central Belarus Belt, and the Osnitsk–Mikashevichi Igneous Belt (Fig. 1, inset). These shared a common tectonic development along the north-west margin of the Sarmatian protocontinent (Bogdanova, 1999). The ELD appears to represent a terrane within this large-scale accretionary system. Accretion of the ELD onto the western edge of a network of Palaeoproterozoic arcs adjoining the Sarmatian nucleus (Bogdanova, 1996) might have caused the strong NNE–SSW orientation of ELD complexes developing in continental-margin arc and back-arc settings.

Thus, the WLG and ELD may be parts of separate terranes with distinct geological histories and structures not related only to simple subduction regimes. They may have been accreted and amalgamated to respectively different continents over a period of time, previously having travelled some distance independently. An additional contribution to contrasting crustal structures and metamorphic grades could have been derived from different degrees of exhumation and erosion subsequent to accretion onto the margin of Sarmatia (Bogdanova, 1996). However, the latter mechanism cannot explain the NW–SE oriented distribution of lithologies and the complicated stepwise retrograde metamorphism of the WLG. An independent evolution of domains prior to their final amalgamation must therefore have been the dominant control.

The 30–50 km wide, transitional MLSZ separates the two domains. A considerable change in crustal thickness, ranging from 42–44 km in the WLG to 50 km in the ELD (EUROBRIDGE Seismic Working Group, 2001–this issue), occurs in the MLSZ. That suture zone also truncates a low-velocity layer in the upper crust of the WLG. In its southern part, the MLSZ is steep near the surface of the crystalline basement, sloping westwards at depth (cf. Popov and Sliaupa, 1997a; Korabliova and Sliaupa, 1999). It is marked by a chain of gravity and magnetic anomalies that appear to correlate with mafic intrusions, granitoid bodies, and sheared zones (Figs. 2 and 3). It is surmised that the ELD has been underthrusted beneath the WLG along the MLSZ.

An important issue that remains is the time of juxtaposition of the WLG and ELD. It is possible that they were joined during the final closure of the Svecofennian ocean at ca. 1.82–1.79 Ga (Nironen, 1997; Mansfeld, 1997). However, according to the present metamorphic and isotopic studies (cf. above and Table 1), it is probable that both domains developed separately until ca. 1.71–1.66 Ga (Bogdanova et al., 1996, 2001–this issue). The age of their junction might be correlatable with the main period of compressional tectonics in the entire Baltic-Belarus region, viz. 1.71–1.66 Ga.

As far as the latest, 1.58–1.45 Ga magmatism associated with shearing is concerned, there may have been causal relationship with detachment, upward movement and juxtaposition of the different crustal slices along E–W-trending shears and faults, the MLSZ, and other tectonic zones. This process has affected the entire region and complicates the earlier structural fabric.

Thus, the final cratonisation of the crust in Lithuania was completed by 1.5–1.45 Ga. However, it is possible that even younger, ca. 1.0-Ga events, coinciding with the Sveconorwegian orogeny, may have affected the already stabilised crust and led to some of the observed shearing and mineralisation.

7. Conclusions

The following conclusions can be made:

(1) The WLG and ELD most probably represent parts of distinct terranes with their own structures and different developments before being amalgamated. Understanding their tectonic histories provides an important element in understanding the evolution and stabilisation of the Baltic-Belarus region and the entire East European Craton (Bogdanova, 1999).

(2) The WLG and ELD display contrasting metamorphic histories. Rocks in the WLG have undergone high-temperature and moderate-pressure granulitic metamorphism; the ELD in general has been subjected to moderate amphibolite-facies metamorphism. Repeated underplating by partial melts generated in the mantle and upper crust has accompanied metamorphism in the WLG.

(3) The MLSZ is a remarkable example of an accretionary boundary between suspected independent crustal terranes. These terranes (the WLG and ELD) were juxtaposed along a ca. 30–50 km wide, westward dipping crustal discontinuity at ca. 1.71–1.66 Ga.

(4) Post-accretionary fragmentation of the terranes is probably a consequence of subsequent extension that resulted in ca.1.6–1.45 Ga post-kinematic, anorogenic magmatism, controlled largely by E–W-trending shear zones.

Acknowledgements

This paper has resulted from collaboration within the framework of the ongoing ILP/ESF EUROPROBE project EUROBRIDGE and IGCP projects 275 'Deep Geology of the Baltic Shield' and 371 'North Atlantic Precambrian (COPENA)'. Funding from the Swedish Royal Academy of Science (KVA), the Swedish Institute (SI), and the Lithuanian Science and Study Foundation (LSSF) are strongly acknowledged. These organisations gave G.S. the opportunity to work in Lund, Sweden, several times between 1993 and 1998. Many special thanks to Roland Gorbatschev and Svetlana Bogdanova for valuable scientific and financial support, and for constructive criticism. The considerable help of colleagues from the Department of Geology of Lund University with analytical work and in the interpretation of analytical data are very much appreciated. The authors also wish to thank numerous EUROBRIDGE colleagues for many helpful and stimulating discussions. Geophysicists of the Lithuanian Geological Survey L. Korabliova and V. Nasedkin kindly made their geophysical maps available. G. Tamkeviciene and A. Rimsa provided valuable assistance in preparing the figures. Co-editors of this volume, Randell Stephenson (Amsterdam) and Roland Gorbatschev (Lund) revised the language in various versions of this manuscript.

References

Beunk, F.F., Page, L.P., Wijbrans, J.R., Barling, J., 1996. Deformational, metamorphic and geochronological constraints from the Loftahammar-Linköping Deformational Zone (LLDZ) in SE Sweden: implications for the development of the Svecofennian Orogen. Geol. Fören Stockholm Förh. 118, A9.

Bhatia, M.R., 1983. Plate tectonics and geochemical composition of sandstones. J. Geol. 91, 611–627.

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

Bibikova, E.V., Claesson, S., Bogdanova, S.V., Skridlaite, G., Taran, L.N., 1997. Isotopic ages and origin of granulitic belts in the Western part of the East European Craton. Fifth EUROBRIDGE Workshop. Geological Survey of Lithuania and Lithuanian Institute of Geology, Vilnius-Dubingiai, Lithuania, pp. 9–11.

Bogdanova, S., 1996. Palaeoproterozoic accretion of Sarmatia and Fennoscandia. In: Gee, D.G., Zeyen, H. (Eds.), Lithosphere. Uppsala University/ESF, Uppsala, pp. 81–89.

Bogdanova, S.V., 1999. The Palaeoproterozoic terrane pattern in the western part of the East European Craton. Seventh EUROBRIDGE Workshop. Polish Geological Institute, Suwalki, Poland, pp. 11–13.

Bogdanova, S.V., Gorbatschev, R., 1997. Major crustal boundaries of the East Eropean Craton cut by the TESZ. Terra Nostra 11, 24–28.

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

Bogdanova, S.V., Page, L.M., Skridlaite, G., Taran, L.N., 1996. 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, A11–A12 (jubilee issue).

Bogdanova, S.V., Page, L.M., Skridlaite, G., Taran, L.N., 2001. The Proterozoic tectonothermal history of the western part of the East European Craton: ^{40}Ar/^{39}Ar geochronological constraints. Tectonophysics 339, 39–66.

Cecys, A., 1998. The Kabeliai Granites (South Lithuania): a geochemical comparison with anorogenic granites in southern Sweden. Geophys. J. 20, 68–70.

Claesson, S., 1996. U–Pb age determinations from the Precambrian of Lithuania and Poland. Fourth EUROBRIDGE Workshop. Lund University, Oskarshamn, Sweden, p. 11.

Claesson, S., Sundblad, K., Ryka, W., Motuza, G., 1995. The Mazury complex — an extension of the Transscandinavian Igneous Belt (TIB) into the East European platform? Terra Nova, Abstr. 7, 107.

EUROBRIDGE Seismic Working Group, 2001. EUROBRIDGE'95: deep seismic profiling within the East European Craton. Tectonophysics 339, 153–175.

Gailius, R.P., Ciucelis, V.P., 1980. Metamorphic and magmatic complexes of the Precambrian in the western part of Lithuania (Metamorphicheskie i metasomatichieskie complexi dokembrije zapadnoj chasti Litwi). Nauchnie trudi vuzov Litovskoi SSR, Geologija 1, 3–14 (in Russian).

Garetsky, R.G., Apirubite, R., Dankevich, I.V., Karatayev, G.I., Pashkevich, I.K., Suveizdis, P., 1990. The horizontal Proterozoic displacements of large-scale blocks of the western part of the East European platform. Doklady AN USSR, Geological, Chemical and Biological Sciences, 6, pp. 6–8 (in Russian).

Hall, A., 1996. Igneous Petrology. Longman Group Limited, Harlow, 508 pp.

Haskin, M.A., Haskin, L.A., 1966. Rare earths in European shales: a redetermination. Science 154, 507–509.

Herron, M.M., 1988. Geochemical classification of terrigenous sands and shales from core or log data. J. Sediment Petrol. 58, 820–829.

Holdaway, M.J., 1971. Stability of andalusite and the aluminum silicate phase diagram. Am. J. Sci. 271, 97–131.

Korabliova, L., Sliaupa, S., 1999. 2.75-D gravity and magnetic modelling of anorogenic (1.5 Ga) granitoids of the Veisiejai complex in SW Lithuania. Seventh EUROBRIDGE Workshop. Polish Geological Institute, Suwalki, Poland, pp. 46–49.

Krolikowski, C., Petecki, Z., Korabliova, L., Jacyna, J., Nasedkin, V., 1999. New maps of the potential fields in the Polish–Lithuanian cross-border area. Seventh EUROBRIDGE Workshop. Polish Geological Institute, Suwalki, Poland, pp. 60–61.

Kubicki, S., Ryka, W., 1982. Geological Atlas of Crystalline Basement in Polish Part of the East European Platform, Wydawnistwa Geologiczne, Warsaw, 24 pp.

Mansfeld, J., 1995. Crustal evolution in the southeastern part of the Fennoscandian Shield. A Dissertation for the Doctor's Degree in Natural Science Thesis, Stockholm University, Stockholm, 128 pp.

Mansfeld, J., 1997. Palaeoproterozoic crustal growth in the southern part of the Baltic Shield and adjacent parts of the East European Craton. Fifth EUROBRIDGE Workshop. Geological Survey of Lithuania and Lithuanian Institute of Geology, Vilnius-Dubingiai, Lithuania, pp. 9–11.

Marfin, S., Motuza, G., Mitrofanov, F.P., Drubetskoiy, E.R., Nemchin, A.A., 1987. New radiologic data obtained from the crystalline basement rocks in south Lithuania. Lietuvos TSR aukstuju mokyklu mokslo darbai, Geologija 8, 3–9 (in Russian).

Marfin, S., Skripkina, T., Zvykas, A., Sliaupa, S., 1994. The diorite–granodiorite–granite complex in southwest Lithuania. Geologija, Vilnius 16, 28–33.

McLennan, S.M., 1989. Rare earth elements in sedimentary rocks: influence of provenance and sedimentary processes. In: Lipin, B.R., McKay, G.A. (Eds.), Geochemistry and mineralogy of rare earth elements. Rev. Mineral., 21, 169–200.

Motuza, G., Skridlaite, G., 1994. Classification of complexes of the Lithuanian crystalline basement and their correlation with those from the Baltic Shield and adjacent areas. Report. Institute of Geology, Vilnius, 70 pp. (in Lithuanian).

Motuza, G., Skridlaite, G., 1996. Geology of the Lithuanian part of EUROBRIDGE transect: Western Lithuanian Granulite Domain and East Lithuanian Belt. Fourth EUROBRIDGE Workshop. Lund University, Oskarshamn, Sweden, p. 27.

Motuza, G., Marfin, S., Skridlaite, G., Skripkina, T., 1989. The metasomatic rocks of the Varena Iron Ore Zone in Southern Lithuania. Metasomatites of Precambrian and their Mineralisation. Nauka, Moscow, (in Russian).

Nakamura, N., 1974. Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites. Geochim. Cosmochim. Acta, 38, 757–775.

Nichols, G.T., Wyllie, P.J., Stern, C.R., 1996. Experimental melting of pelagic sediment, constraints relevant to subduction. Subduction: Top to Bottom. Geophysical Monograph 96, American Geophysical Union, 293–298.

Nironen, M., 1997. The Svecofennian Orogen: a tectonic model. Precambrian Res. 86, 21–44.

Pearce, J.A., 1976. Statistical analyses of major element patterns in basalts. J. Petrol. 17, 15–43 Part 1.

Pearce, J.A., Cann, J.R., 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses. Earth Planet. Sci. Lett. 19, 290–300.

Popov, M., Sliaupa, S., 1997a. Deep-seated structural elements of Lithuania derived from magnetic field data. Fifth EUROBRIDGE Workshop. Geological Survey of Lithuania and Lithuanian Institute of Geology, Vilnius-Dubingiai, Lithuania, pp. 65–66.

Popov, M., Sliaupa, S., 1997b. Transformations of gravity field using terracing operator: implications for deep structure of Lithuania. Fifth EUROBRIDGE Workshop. Geological Survey of Lithuania and Lithuanian Institute of Geology, Vilnius-Dubingiai, Lithuania, pp. 67–69.

Puura, V., Apirubyte, R., Birkis, A., Gailius, R., Motuza, G., Ozolin, N., 1978. Geological map of the crystalline basement of the Soviet Baltic republics. Nedra, Leningrad, Russia (in Russian).

Puura, V., Birkis, A., Motuza, G., 1980. Geological map of the crystalline basement of the soviet Baltic republics: explanatory notes. Nedra, Leningrad, Russia (in Russian).

Rimsa, A., Skridlaite, G., Motuza, G., Cecys, A., 1999. Implications for rapakivi granite associations inn the crystalline basement of Lithuania. J. Conf. Abstr., EUG 10 4 (1), 686.

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.

Skridlaite, G., 1993. Metasomatism in the Varena Iron Ore Zone, Southern Lithuania. PhD Thesis. University of Vilnius and Institute of Geology, Vilnius, 163 pp.

Skridlaite, G., 1994. The metamorphism of metapelitic granulites from West Lithuania. Geologija, Vilnius 16, 21–28.

Stein, H.J., Sundblad, K., Markey, R.J., Morgan, J.W., Motuza, G., 1998. Re–Os ages for Archean molybdenite and pyrite Kuittila-Kivisuo, Finland and Proterozoic molybdenite, Kabeliai, Lithuania: testing the chronometer in a metamorphic and metasomatic setting. Mineralium Deposita 33, 329–345.

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. Mineral. Petrol. 50, 43–57.

Sundblad, K., Gyllencreutz, R., Flodžn, T., 1998. The Precambrian crust beneath the Baltic Sea. Geophys. J. 20, 121–124.

Taran, L.N., Bogdanova, S.V., 1997. Granulites of the Belarus-Baltic Granulite Belt. Terra Nova 9, 134 (supplementary volume).

Wiszniewska, J., Duchesne, J.-C., Claesson, S., Stein, H., Morgan, H.W., 1999. Geochemical constraints on the origin of the Suwalki Anorthosite Massif and related Fe–Ti–V ores, NE Poland. J. Conf. Abstr., EUG 10 4 (1), 686.

Wybraniec, S., Perchuc, E., Thybo, H., 1999. New views of the European gravity and magnetic fields. Seventh EUROBRIDGE Workshop. Polish Geological Institute, Suwalki, Poland, pp. 93–94.