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BALTICA Volume 19 Number 2 December 2006 : 91-98

Mesoproterozoic events in eastern and central Lithuania as recorded by $^{40}Ar/^{39}Ar$ ages

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Skridlaite G., Bogdanova S., Page L., 2006. Mesoproterozoic events in eastern and central Lithuania as recorded by $^{40}Ar/^{39}Ar$ ages. Baltica, Vol. 19 (2), 91-98. Vilnius. ISSN 0067-3064.

Abstract To assess the Precambrian evolution of the western East European Craton (EEC), seven new $^{40}Ar/^{39}Ar$ amphibole age determinations have been carried out for the rocks along the Mid Lithuanian Suture Zone (MLSZ) and adjacent East Lithuanian Domain. They confirm the strong reworking of the Palaeoproterozoic crust by.1.57–1.45 Ga events, most likely due to late/post– orogenic AMCG (Anorthosite-Mangerite-Granite-Charnockite) magmatism and associated shearing. Cooling and reworking of the crust between 1.57–1.47 Ga characterise the southern ELD, while farther west, similar processes appear to have occurred later at 1.46-1.42 Ga.

Keywords *40Ar/39Ar dating, geochronology, East European Craton, AMCG magmatism, Mesoproterozoic of Lithuania.*

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INTRODUCTION

The western part of the East European Craton (EEC) is made up of distinct domains and belts brought up together by the end of the Palaeoproterozoic (Bogdanova *et al.* 2001, 2006). In the crystalline basement of Lithuania (Fig. 1), the West Lithuanian Granulite (WLG) domain and East Lithuanian domain (ELD) have been distinguished by means of geophysics and drillings (Skridlaite, Motuza 2001). They are separated by the so–called Mid Lithuanian Suture Zone (MLSZ).

Like the other tectonic units in this part of the EEC, the ELD and WLG were completely juxtaposed ca. 1.71–1.66 Ga (Bogdanova *et al.* 2001, 2006). The MLSZ is a 30 to 50 km wide transition zone where the WLG is thrust on the ELD (Skridlaite, Motuza 2001). This zone is characterised by a chain of positive and negative gravity and magnetic anomalies against subdued background of the surrounding country rock. The zone appears to be a complex suture once formed and reactivated several times.

Current work is a continuation of the Ar-Ar isotope studies of the Precambrian basement in the western part of the EEC by collaborators from Sweden, Lithuania and Belarus (Bogdanova *et al.* 2001). In the present study, we have been mostly concentrated on the dating of the youngest events in the MLSZ and the adjacent ELD. Their tectonothermal evolution is important for understanding of the belt formation and the tectonic significance of crustal boundaries in the entire western part of the EEC. Hornblendes from several varieties of mafic rocks have been exposed to the $^{40}Ar/^{39}Ar$ method to assess the time of crust forming and reworking processes in the Proterozoic.

GEOLOGICAL SETTING AND SAMPLE DESCRIPTION

Alternating metasedimentary and metavolcanic granulites of 1.84–1.81 Ga age intruded by various igneous rocks compose the **WLG** (Fig.1). These granulites have been suggested to characterise a

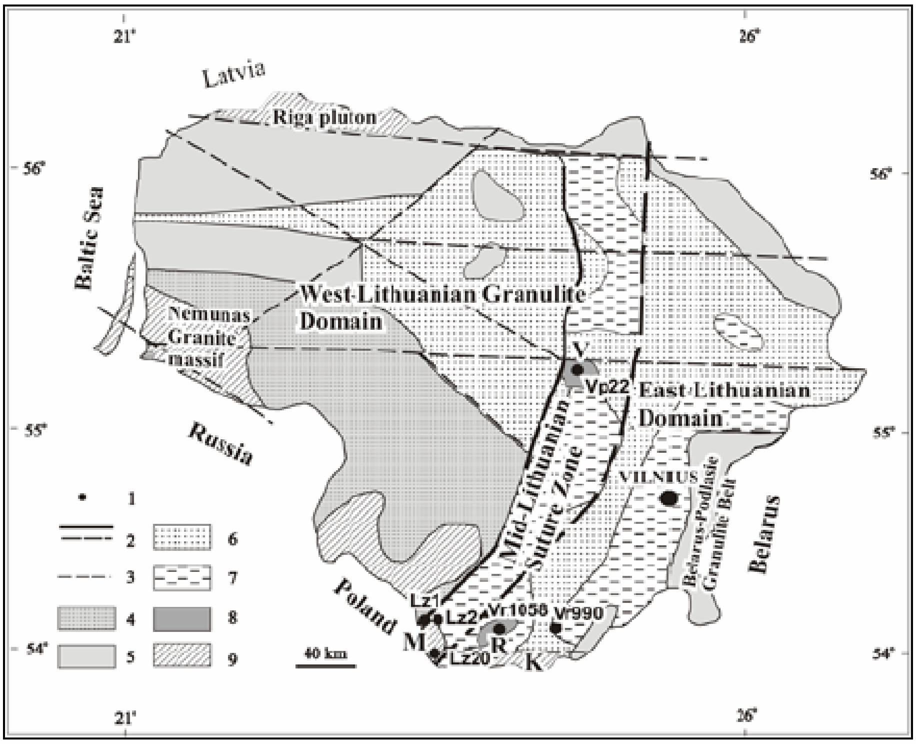


Fig. 1. Geological map of Lithuania (modified after Skridlaite and Motuza, 2001). Legend: (1) investigated boreholes; (2) boundary between the WLG and ELD, (3) faults; (4) metasedimentary and metavolcanic granulites, granites and migmatites; (5) enderbites and charnockites, mafic granulites; (6) migmatites and granites; (7) gneisses, amphibolites; (8) mafic intrusions; (9) rapakivi-type intrusions. Bold letters: K – Kabeliai granites, M – Mazury complex, R – Randamonys massif, V- Vepriai intrusion. For the borehole abbreviations see the text.

volcanic arc tectonic setting (Skridlaite, Motuza 2001) or an active continental margin. Hornblende bearing rocks are almost absent there.

The ELD is dominated by c. 1.9 Ga old amphibolite facies metavolcanics and metasediments, various migmatites and igneous rocks (Fig. 1). Occurrences of biotite gneisses and amphibolites are marked by elongated (up to 40 km long) magnetic anomalies, trending north-south. Several bodies of gabbro–norites, gabbros, gabbro-diorites and tonalites in the western part of the ELD are assembled into the 40x30 km Randamonys massif. There are also smaller bodies of mafic magmatic rocks traced by magnetic anomalies and drillings.

The Randamonys gabbro–norites are made up of plagioclase, hypersthene, minor clinopyroxene, hornblende and biotite, ilmenite, magnetite, and apatite. Some fine-grained varieties (Vr1058/492) possibly representing chilled margins (Fig. 2a) have similar composition. Pale green hornblende replaces both clinopyroxene and hypersthene along grain margins, and occasionally form small patches along the cleavage in the pyroxenes. Chemical composition of the fine–grained gabbro–norite is given in Table 1. The gabbro–norites display MORB-type as well as fractionated, LREE-enriched patterns (Rimsa et al. 2001).

Sample Vr990/313 has been taken from a gabbro body of 2x2 km size in the southern ELD (borehole 990 in Fig. 1). There is 70 m thick section of massive gabbro, which is crosscut by a few granitic veins. The gabbro preserves igneous textures and did not undergo any metamorphism except for the replacement of clinopyroxene by hornblende. The coarse–grained gabbro (sample Vr990/313, Fig. 1) consists of hornblende (up to 40%), minor pyroxene, mostly clinopyroxene (3-10%), plagioclase, magnetite, apatite, titanite, zircon with minor secondary carbonates and sericite replacing plagioclase. The hornblende gabbro is dominant (Fig. 2b) and rich in Ca and Al, poor in Fe (Table 1, Vr990/313). It has very low contents of trace elements and very primitive Rare Earth Element (REE) distribution (Fig. 3, Vr990/313). The rock is of calc-alkaline affinity and may represent a volcanic arc setting.

The **MLSZ** features mostly amphibolite facies rocks with some granulite relics along its western boundary (Fig. 1). Numerous intrusions of different composition make up this zone.

The Vepriai gabbro intrusion is situated in the **central part of the MLSZ** (Fig. 1), close to its western boundary, in the intersection of NW and N–S trending faults. In the north, the intrusion is limited by an E–W striking fault, likely belonging to the Polotsk—Kurzeme wide E–W shear zone farther north (Fig. 1). This intrusion is reflected by a 30x20 km magnetic anomaly, and is confirmed by tens of drillings. There are two varieties of gabbro, one being massive and other sheared. In the second (sample Vp22/786), oriented hornblende grains indicate shearing. The sheared hornblende gabbro of sample Vp22/786 is composed of hornblende, plagioclase, opaques, with minor biotite, titanite, epidote, apatite and zircon. Up to 5 mm elongated hornblende grains are clearly oriented. Epidote replaces hornblende. The chemistry is typical for hornblende gabbro enriched in Fe-and Ca (Table 1, Fig. 3, Vp22/786). The primitive REE distribution (Fig. 3, Vp22/786) indicates a mantle source and tholeitic origin. Since the age of this rock is unknown, it can belong to the 1.84 Ga Randamonys-type intrusions or related to the later, ca.1.6–1.5 Ga event.

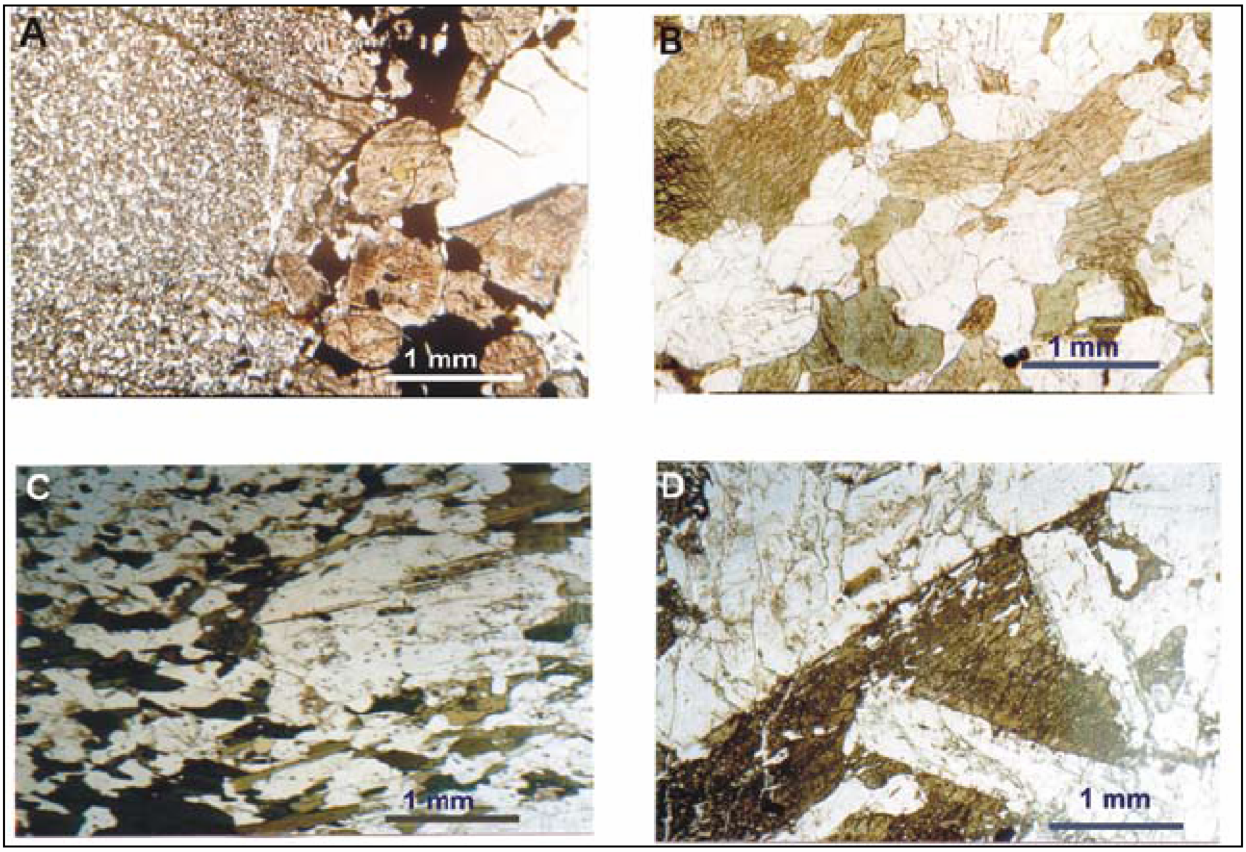


Fig. 2. Microphotographs of rock texture and composition in the investigated rocks: (A) Sample 1058/492 showing the contact between micro gabbro-norite (left side) and gabbro-norite (right side). Micro-grained matrix consists of white plagioclase, greenish brown pyroxenes and minor hornblende. On the right side, white plagioclase grain is surrounded with brown clinopyroxene and black opaque grains. Darker patches indicate hornblende and biotite replacing clinopyroxene. Black ilmenite and magnetite compose the opaques. . (B) Hornblende gabbro of Vr990/313 sample displaying typical gabbroic texture. Green hornblende grains with small pyroxene relics are surrounded by plagioclase with simple and polysynthetic twins. (C) Fine-grained monzonitic gabbro resembling jotunite with slightly deformed, twinned, porphyritic plagioclase (sample Lz2/568). Fine-grained matrix consists of yellow and green hornblende, grey and white plagioclase and overgrowing biotite flakes defining a week foliation.(D) Coarse-grained leucogabbro (sample Lz20/382) with euhedral twinned plagioclase. Hollows between the plagioclase are filled with mixture of clinopyroxne being replaced by hornblende and opaque minerals.

The southern part of the MLSZ is dominated by an anorthosite–mangerite–charnockite–granite (AMCG) suite with subordinate supracrustal rocks (Skridlaite *et al.* 2003). Granulite facies relics are preserved in borehole Lz1 in the south-westernmost part of the MLSZ (Fig. 1). The upper part of this 350 m thick cross-section consists mainly of mafic rocks where those of plutonic (gabbroic) origin alternate with metavolcanic ones. Sample Lz1/680 represents a metagabbro–norite, which consists of hypersthene, minor clinopyroxene, hornblende, biotite, plagioclase, opaques, apatite with minor quartz. Hornblende, quartz and opaque intergrowths have been formed mostly at the expense of clinopyroxene and, in places, of hypersthene. Hornblende, in turn, is replaced by biotite, quartz and magnetite. The gabbro–norite is slightly metamorphosed, however has inherited gabbroic texture. It is rich in Ti (Table 1, Lz1/680), has low incompatible trace element contents, and displays quite primitive REE distribution (Fig. 3, Lz1/680). Those rocks are underlain by enderbites and charnockites with relics of felsic granulites.

Amphibolite facies granitoids with mafic enclaves (sample Lz1/726) dominate the lowermost part of the Lz1 cross–section. Some of the angular and rounded enclaves are gabbroic, others are gneissose and sheared mafic rocks. The rock in general resembles magmatic breccia or mingling relationships. Sample Lz1/726 comes from a 5x4 cm mafic relic enveloped by granitoids. It is composed of hornblende and biotite, plagioclase, opaques, apatite with minor quartz, clinopyroxene and zircon. Hornblende is a major rock–forming mineral here. Biotite defines a slight foliation. The rock may represent the subsolidus gabbro of AMCG suite (Table 1).

Dioritic, monzodioritic and granodioritic varieties of the AMCG suite make up the log of borehole Lz2 (Fig. 1). There are intervals of fine-grained monzonitic

Table 1. Major, trace and rare earth element contents for the investigated samples from eastern and central Lithuania (wt.%).

Sample	Lz1/726	Lz1/680	Lz2/586	Lz20/382	Vr1058/492	Vr990/313	Vp22/786
SiO2	50.28	49.89	50.99	51.94	44.33	49.09	50.5
TiO2	1.03	0.82	1.45	1.2	2.46	0.33	0.7
Al2O3	15.92	16.1	17.02	20.55	15.65	17.51	11.83
FeO	11.73	10.75	11.73	8.36	15.58	6.5	10.89
MnO	0.271	0.25	0.21	0.133	0.16	0.06	0.25
MgO	5.13	6.55	3.35	5.03	6.25	7.62	10.78
CaO	8.7	10.21	7.87	8.11	9.42	15.42	10.63
Na2O	2.97	3.35	3.94	3.86	2.8	1.6	2.15
K2O	1.09	0.79	1.53	0.85	0.32	0.67	0.75
P2O5	0.10	0.17	0.55	0.33	1.11	0.17	0.14
LOI	0.01	0.97	0.71	0.9	1.43	0.54	1.2
Total	97	100	99	100	100	100	100
Ba	224	123	383	312	195	71	72
Ga	21	20	19.9	19			13.6
Hf	6	1.73	4.8	2.3	1	4	1.5
Nb	11	7.52		3	2	3	2.5
Ni	39	71.5	14				
Rb	52	16.71	63	19.5	11	16	11
Sr	213	203	492	547.5	533	335	233.3
Ta	1.5	1.04	0.92	0.1	1	1	0.2
Th	1.5	0.69	10.4	1	1	1	1.1
U	1.5	1.78	2.54	0.3	1	1	0.3
V	190	202	212	146			203
Zn	234	199	149				19
Zr	93	65.8	189	80.3	29	22	51.9
Cs		0.403	1.3	0.6			0.5
Pb	36	12.9	15.4		3	1.5	1.5
La	21	8.42	41.1	15.9	14	4	2.2
Ce	36	21.47	90	35.3	10	9	5.8
Nd		11.95	50.1	19.2		6	4.7
Sm		3.25	10.4	3.9		3	1.7
Eu		1.06	2.74	1.26		0.6	0.82
Gd		3.09	8.8	3.32		1	2.45
Tb		0.59	1.37	0.47		0.8	0.47
Dy		3.71	7.5	3.07		1.5	3.42
Er		2.27	4.2	1.62		0.9	2.08
Yb		2.59	3.7	1.46		0.8	1.82
Lu		0.41	0.51	0.2		0.2	0.28
Y	45	24.5	40.3	14.8	8	16	19.4

gabbro resembling jotunite with porphyritic plagioclase (sample Lz2/568). Some contacts with surrounding granodiorites are sharp. The rock can be considered as either the most mafic member of the AMCG suite or its host rock. Sample Lz2/568 (Fig. 2c) represents an 8-m thick layer of the porphyritic fine–grained metagabbro among quartz–monzodiorites of the AMCG suite. It is made up of hornblende, biotite, plagioclase, magnetite, titanite, apatite with minor clinopyroxene, zircon and quartz. Hornblende replaces clinopyroxene. There are few large (up to 4 mm) parallel oriented biotite flakes overgrowing hornblende and feldspars. Up to 10 mm large porphyritic plagioclase is randomly distributed in a fine-grained matrix (Fig. 2c). The gabbro is Fe–rich. Mg–poor enriched in K (Table 1, Lz2/568). It has the highest contents of incompatible and compatible

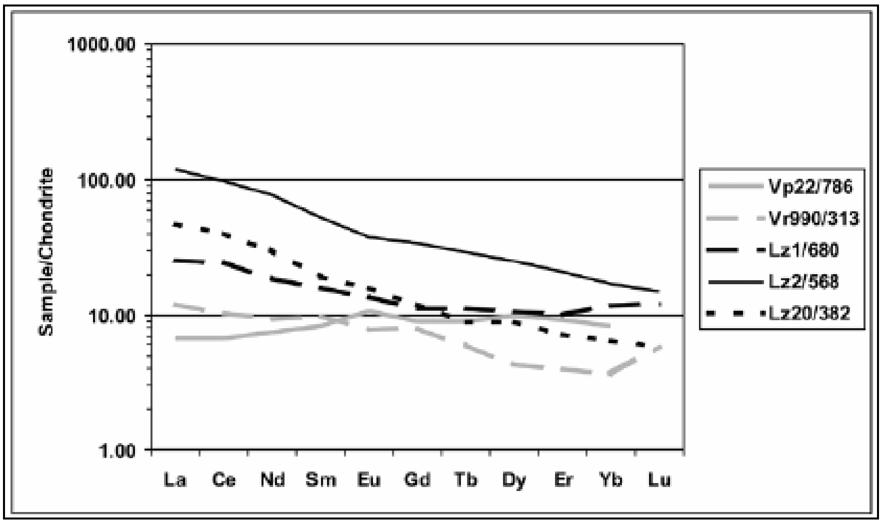


Fig. 3. REE composition of the investigated samples. Normalizing coefficients are after Boynton (1984).

trace elements (Table 1), and highly fractionated REE patterns (Fig. 3, Lz2/568). Its geochemistry suggests that this is the most mafic member of the fractionated AMCG series.

A gabbroic body recorded by a 2x1 km positive magnetic anomaly against the negative granitic background (Fig. 1) has been penetrated by borehole Lz20. Coarse grained leucogabbro (sample Lz20/382) exhibits well defined igneous texture with euhedral plagioclases. No metamorphic minerals have been found except for the subsolidus replacement of clinopyroxene by hornblende. Coarse–grained pegmatitic granite cut the gabbro in the upper part of the section. This coarse-grained gabbro contains hornblende with minor biotite and quartz, substituting clinopyroxene (Fig. 2d). In places, hornblende is replaced by biotite. Euhedral plagioclase crystals reach the size of 10 mm. The gabbro is rich in opaques and apatite. This is a calc–alkaline gabbro, Al–rich, with high trace element contents (Table 1, Lz20/382) and has fractionated REE distribution (Fig. 3, Lz20/382).

ANALYTICAL TECHNIQUES

The seven samples were crushed and sieved to a 0.15–0.25 mm size fraction, and hornblende was separated using standard magnetic and heavy liquid techniques.

30-50 mg of hornblende was irradiated along with the flux monitor MMhb-1 (Samson, Alexander 1987) and synthetic salts to permit corrections for interfering nuclear reactivations in the McMaster University reactor. Incremental step–heating analyses using a vacuum furnace were performed at the Laboratory for Isotope Geology, Vrije University, Amsterdam, the Netherlands. A MAP 215–50 mass spectrometer was used for the isotope analyses. 10–13 steps were

Table 2. The results of 40Ar/39Ar age determination for the Vr1058/492 micro gabbro-norite.

Results	40(r)/39(k)	Age±2σ	MSWD	39Ar(k)	K/Ca
	±2σ	(Ma)		(%, n)	±2σ
				59.96	
Error plateau	±0.8094	±15.47	14.36		40.059±0.003
	74.3598	1566.38			
	±1.09%	±0.99%			
		External error±34.94			
		Analytical error±11.4			
	±0.213	±11.29			
Total fusion age	82.7562	1680.88			80.028±0.003
	±0.26%	±0.67%			
		External error±35.46			
		Analytical error±2.81			

run on the hornblendes. Correction factors for interfering isotopes were measured on CaF_2 and K_2SO_4 salts. Ages were calculated using the isotopic ratios and decay constants listed in Steiger and Jäger (1977).

McDougall and Harrison (1988) discuss the generally accepted criteria for determination of a plateau in an age spectrum (cf. Dalrymple and Lanphere 1974; Fleck *et al.* 1977; Lanphere and Dalrymple 1978). One important criterion involves a minimum of three contiguous steps representing a significant proportion (usually >50%) of the total ^{39}Ar released with concordant ages. Ages are concordant if they do not differ at the 95% confidence level. Isotope peak heights and errors were calculated by least-squares linear regression of six cycles to the time at which the mass spectrometer was equilibrated with the inlet section. K/Ca ratios were calculated for each increment from the $^{39}Ar/^{37}Ar$ ratios.

DISCUSSION

The seven dated rocks from the ELD and MLSZ record the age between 1.57 and 1.42 Ga. All the estimated ages fall into three categories older than 1500 Ma (e.g. 1570–1530 Ma), and younger than 1500 Ma, the groups of 1490–1470 Ma and of 1460–1420 Ma.

The group older than 1500 Ma. In the ELD, the oldest age of 1569±12 Ma yielded the fine–grained gabbro–norite (Vr1058/492). The small quantity of hornblende was insufficient to build the plateau that is because the data is presented only in Table 2. It seems that hornblende formation started after some fluid influx into a dry system, and hornblende formation stopped after a short time. Since it is known that most felsic members of the Randamonys intrusion crystallised at 1830 Ma (Rimsa *et al.* 2001), it cannot be a cooling, post–magmatic age. This suggests that the gabbro–norites were affected by 1.57 Ga tectono-thermal event, and a new hornblende can have grown during this event or the earlier magmatic hornblende was reset. The similar age in the region is that of the Riga rapakivi pluton (Rämo *et al.* 1996) and the c. 1.56 Ga ore mineralisation in the Suwalki gabbro norites in northern Poland (Morgan *et al.* 2000). However this relationship is somewhat ambiguous and not well supported by other data. Some more possible relationships should be looked after.

The hornblende from the Vepriai gabbro (Vp22/786) in central part of the MLSZ and nearby an E–W trending tectonic zone (Fig. 1) records an age of 1534 ±11 Ma (Fig. 4). Hornblende in these gabbros is one of major rock–forming minerals, elongated and aligned in some parts. The age of gabbroic magmatism is unknown. The intrusion may belong to the chain of intru-

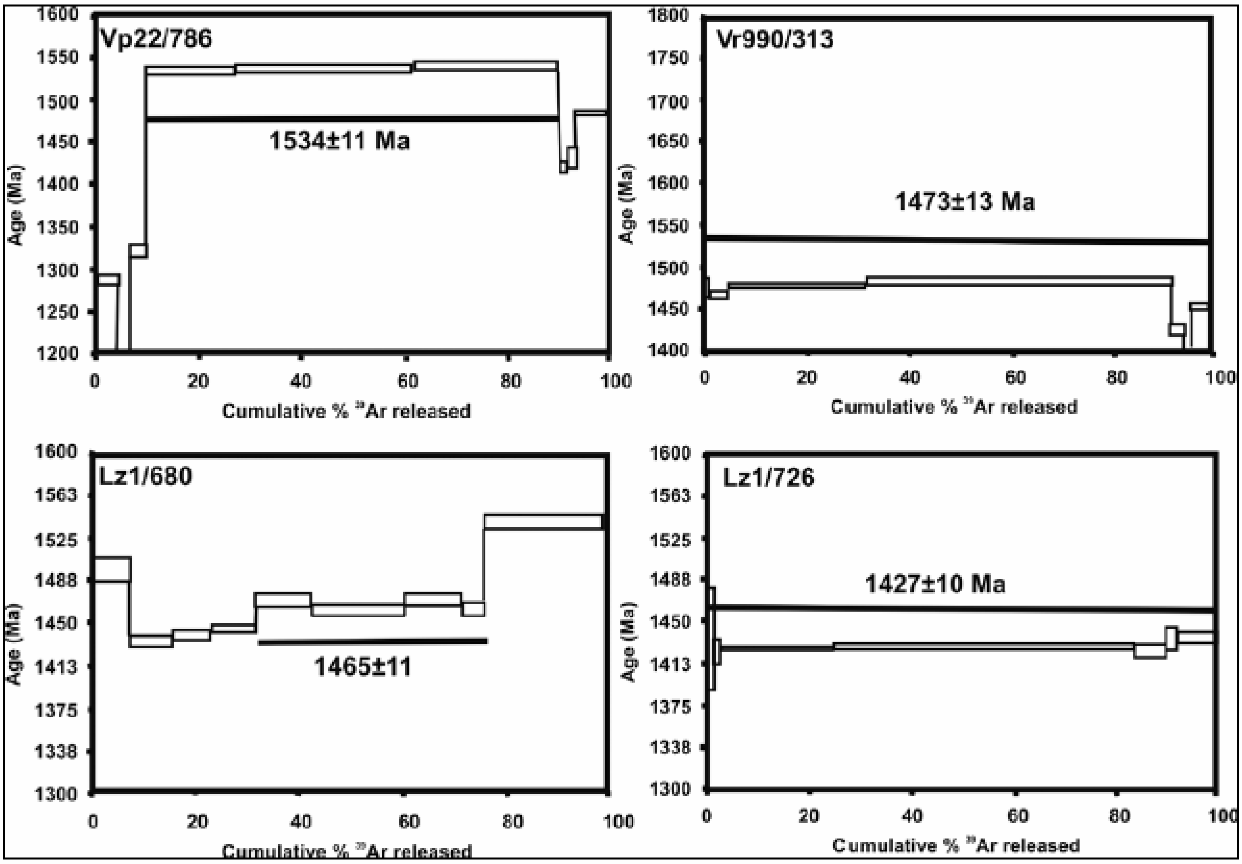


Fig. 4. 40Ar/39Ar amphibole age spectra from the investigated rocks in eastern and central Lithuania.

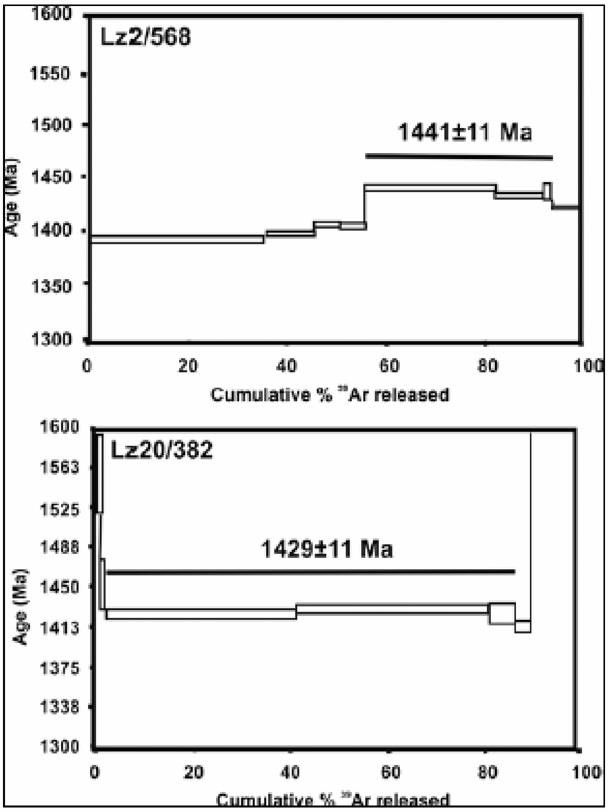
sions of volcanic island arc affinity of c. 1.85–1.82 Ga known in the MLSZ. It seems that the shearing of the gabbros accompanied by hornblende growth occurred much later, at 1.53 Ga and falls in the age range for the Mazury AMCG suite, i.e. 1.53–1.50 Ga (Dörr *et al.* 2002). Alternatively, the Vepriai intrusion may also be a part of the AMCG suite of the similar age.

The group of 1490–1470 Ma. The obtained hornblende age of 1473±13 Ma from the Vr990 gabbro (Fig. 4) is consistent with cooling ages of 1469±6 Ma for the amphibolite (borehole 982) and 1491±8 Ma for the metadiabase (borehole 423; Bogdanova *et al.* 2001). Porphyry type Mo mineralisation in the Kabeliai granites was dated to be formed at 1.48 Ga (Re-Os method; Stein *et al.* 1999). Since the obtained ages postdate this granitic magmatism of 1505 Ma (Sundblad *et al.* 1994) only by 10–30 myr, they might have been related to the latter event.

The group of 1450 Ma and younger. It is remarkable that somehow younger ages are characteristic for the southern part of the MLSZ (the Lazdijai area). It appears that metagabbro–norite (sample Lz1/680) from borehole Lz1 was cooled at 1465±11 Ma (Fig. 4), while hornblende from a gabbroic relic (sample Lz1/726) from the same borehole is 30 myr younger (Fig. 4). The plausible scenario would be as following: the Lz1/680 hornblende started to form with first fluid emanations from ascending granitoid magma when the rock was still at great depth. The hornblende formation did not proceed to greater extent there. The second (1427±10 Ma) hornblende might have originated at shallower depth when the fluid influx was sufficient for the overall hornblende growth in these small mafic enclaves. The scenario is supported with geological observations. The Lz1/680 gabbro–norite in the upper part of the borehole can represent a host rock affected by the ascending AMCG magmatism, since the lower part of this borehole is composed of the c.1.53-1.51 Ga AMCG suite (Skridlaite *et al.*, subm). The sample Lz1/726 came from gabbroic enclaves in granitic rocks resembling magmatic breccia, and possibly belonging to the same suite. Thus, the 1427±10 Ma hornblende may record the youngest age limit of the cooling.

The Lz2/568 gabbro cooled at 1441±11 Ma, while the cooling of the Lz20/382 gabbro proceeded until 1429±11 Ma. Both gabbros occur within the Mazury and Veisiejai AMCG complex (Fig. 1).

To sum up, the data from the southwestern MLSZ (Lazdijai area) are at least 40 but more often 60-70 myr (Fig. 4) younger than the 1.53–1.50 Ga AMCG magmatism (Dörr *et al.* 2002). The new hornblende growth or reactivation may indicate a separate magmatic and related shearing event rather than cooling after the c. 1.53–1.50 Ga magmatism. This is very close in time to granitic magmatism of ca 1.46–1.45 Ga in western and central Lithuania (Motuza *et al.* 2006; Skridlaite *et al.*, subm.).



CONCLUSIONS

The numerous $^{40}Ar/^{39}Ar$ amphibole ages of c. 1.57–1.43 Ga range, recorded by various metamorphic and magmatic mafic rocks from the ELD and MLSZ, are in a close time span with c. 1.60–1.45 Ga late/post–orogenic AMCG magmatism. Such a strong and widespread reworking of the Palaeoproterozoic rocks suggests the regional extent of this magmatism as it is known in the Baltic Shield (Rämö and Haapala 2005).

The somewhat younger cooling and shearing ages of 1.46–1.43 Ga in southwestern MLSZ (Lazdijai area) than those in the adjacent southern ELD (1.5–1.47 Ga) confirm a westward younging of the tectonothermal events.

The 1.46–1.43 Ga cooling and reworking ages may indicatea separate, younger than 1.5 Ga magmatic event, which had reactivated hornblende Ar–Ar systems and led to the overall hornblende formation. The granitoids of c. 1.46–1.45 Ga are found in western and central Lithuania (Motuza *et al.* 2006; Skridlaite *et al.*, subm.).

Acknowledgements

Funding from the Swedish Royal Academy of Science (KVA), the international VISBY-programme elaborated by the Swedish Institute (SI), and the Lithuanian State Science and Study Foundation (LSSF) are highly acknowledged. Authors are grateful to Dr. Bogusław Bagiński, Poland, and Dr. Ludmila Taran, Belarus for the valuable comments.

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