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U–Pb single-grain dating of detrital zircon in the Cambrian of central Poland: implications for Gondwana versus Baltica provenance studies

P. Valverde-Vaquero [a,*], W. Dörr [a], Z. Belka [b], W. Franke [a], J. Wiszniewska [c], J. Schastok [a]

[a] *Institut für Geowissenschaften, Justus-Liebig Universtität, Senckenbergstrasse 3, D-35390 Giessen, Germany*
[b] *Institute of Geological Sciences, University Halle-Wittenberg, Domstrasse 5, D-06108 Halle, Germany*
[c] *Polish Geological Institute, Rakowiecka 4, PL-00975 Warszawa, Poland*

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Abstract

A provenance study of detrital zircon has been carried out in Middle Cambrian sandstones from the Lysogory Unit (Holy Cross Mountains) and the East European Platform (EEP, Baltica) to investigate the docking of terranes along the Trans-European Suture Zone (TESZ) during the Paleozoic. Paleontological evidence suggests that the Lysogory Massif is a peri-Gondwanan-derived terrane which did not reach the Baltic realm before Ordovician times. For a comparison with the adjacent sequence in the EEP, across the TESZ, we have analyzed samples from borehole Okuniew IG-1 (15 km east of Warsaw), which contains Baltic faunas. The age spectrum of the detritus in the Cambrian of the Lysogory Massif (19 analyses) reflects input of sources with ca. 600 Ma, ca. 1.8–2.0 Ga, and >2.5 Ga zircon ages. In the EEP (Okniew borehole; 19 analyses), the U–Pb data demonstrate input from sources with ca. 530–700 Ma, 1.0–1.2 Ga, 1.5 Ga, ca. 1.8–2.0 Ga, 2.2 Ga, and >2.5 Ga zircon ages. Additionally, in this borehole the crystalline basement has been dated at 1800 ± 6 Ma. These new data show that Late Neoproterozoic zircon ages are not restricted to peri-Gondwanan sources and that provenance studies across the TESZ are more complex than expected. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: geochronology; zircon; Cambrian; Precambrian; Poland

1. Introduction

The age spectra of detrital zircons in clastic sedimentary rocks can be quite useful in evaluating potential source regions for the sediment. This type of sediment provenance studies helps to define paleogeographic units (terranes) and their evolution from separation to docking, especially if one terrane records a major tectonic/orogenic event which is not present in the other. This would be the case of the ca. 550–650 Ma Avalonian/Cadomian events in northern peri-Gondwana [1,2] and the apparent absence of equivalents in Baltica [3]. According to this scheme, the pres-

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* Corresponding author. Fax: +49-641-9936019; E-mail: pablo.valverde@geolo.uni-giessen.de

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ence of Late Neoproterozoic zircon detritus in Cambrian sediments along the crustal blocks which border the Polish margin of the Eastern European Platform could potentially differentiate between Avalonian/Cadomian and Baltica-derived terranes. In this area the geophysical signatures of the Baltic crust abruptly terminate against the crustal blocks of the Teisseyre–Tornquist Zone [4]. This zone is part of one of the most significant lithospheric boundaries in Europe, the 2000 km long Trans-European Suture Zone (TESZ; Fig. 1A; e.g. [5,6]), which separates the older crust and mantle lithosphere of the Baltic Shield–East European craton from that of Central Europe. Current knowledge of the Central European crust indicates that it is mostly a collage of peri-Gondwana-derived terranes (e.g. [7]), with the possible exception of the crustal blocks between the Variscan deformational front and the Eastern European Platform in Poland: the Upper Silesian Massif, the Malopolska Massif, and the Lysogory Unit (Fig. 1; [8]). Trilobite faunas from the Upper Silesian [9] and the Malopolska [10] massifs indicate that these crustal blocks were in the vicinity of Baltica already in the Cambrian. In contrast, a recent provenance study of detrital micas in Cambrian rocks of the Lysogory Unit, coupled with fossil and ichnofossil evidence, has suggested that this unit is a Gondwanan-derived terrane which did not reach Baltica before the Early Ordovician times [11]. In order to test the Gondwanan affinities of the Lysogory Unit, we have sampled Cambrian sandstones from this unit and the western edge of the East European Platform (Baltica) for U–Pb dating of detrital zircon. The sample from the East European Platform comes from the Okuniew borehole, near Warsaw. The data from this borehole serve as a standard to which we compare the age of the zircon detritus from Lysogory. We have also dated the crystalline basement in this borehole, in order to constrain the age of the local sediment source.

This is the first zircon provenance study on early Paleozoic rocks from the EEP and surrounding areas in Poland. Our study shows that ca. 600 Ma zircons are present on both sides of the TESZ. This serves as a warning that detrital zircon alone is not sufficient for the identification

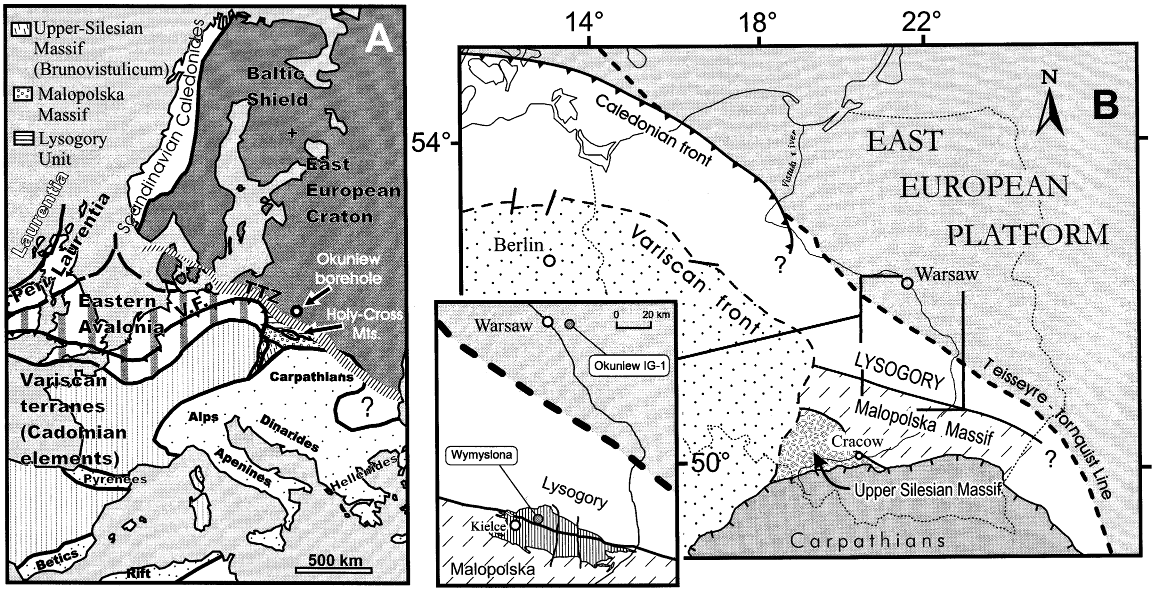

Fig. 1. A: Simplified map of the Paleozoic terranes of Western Europe, alpine areas excluded, showing the location of the terranes along the Trans-European Suture Zone (modified after [5,6]). Pattern: area with anomalous geophysical signatures along the margin of Baltica–East European Craton; TTZ: Teyssere–Tornquist Zone; V.F.: Variscan front. B: Suspected Paleozoic terranes in central Poland. Inset map: sample location; striped area, Holy Cross Mountains.

of terranes along the edge of the East European Craton.

2. Geological setting

The most prominent feature of the Polish crust is the Teisseyre–Tornquist Zone (TT Zone [4]). This is a 50–90 km wide zone characterized by anomalous geophysical properties, including an unusual crustal thickness of 50–55 km. It runs northwest–southeast across Poland along the southwest margin of the East European Craton (Fig. 1A). In northern Poland this zone is bounded against the East European Craton by the Teisseyre–Tornquist Line (TT Line; Fig. 1B), from which it takes its name. In southern Poland the trace of this lineament is uncertain [12]. The crustal domains west of the TT Line, i.e. the TT Zone, are part of the Trans-European Suture Zone [13]. In terms of paleogeography, the TT Line is considered to have represented the plate margin of Baltica until the Late Cambrian [11]. In central and southern Poland, at least three crustal blocks are located between the East European Craton and the core region of the Variscan Belt (Fig. 1B): the Lysogory Unit, and the Malopolska and Upper Silesian massifs [8]. These fault-bounded blocks represent the foreland of the Variscan Belt in southern Poland [7]. The Lysogory Unit and Malopolska Massif crop out in the Holy Cross Mountains where they constitute two separate lithotectonic units from which they take their names.

The Upper Silesian Massif constitutes the northern part of a larger block, the Brunovistulicum (Fig. 1; e.g. [7]), the Precambrian basement of which includes 580–590 Ma granitoids (e.g. U–Pb data [14,15]) and ca. 600 Ma amphibolite facies metamorphism (monazite chemical dating [16]). Because of these age data, the Brunovistulicum is conventionally being interpreted as a fragment of the Cadomian/Avalonian Belt [17].

The crystalline basement of the Malopolska Massif is unknown. The oldest rocks in the Malopolska are Vendian shales and siltstones with intercalations of greywackes, volcanic rocks and polymictic conglomerates with clasts of metamorphic, as well as, mafic and felsic igneous rocks [18,19]. Compston et al. [19] have dated a volcanic tuff at 549 ± 3 Ma (^{206}Pb/^{238}U SHRIMP age) from the top of this Vendian sequence. The large amount of arkosic material, the presence of clasts from volcanic and plutonic rocks, and the thickness of the sequence led Belka et al. [11] to interpret the Malopolska Massif as a Late Precambrian forearc–trench system linked to the Avalonian/Cadomian active margin.

While the previous data suggest that the Upper Silesian and Malopolska massifs were at the periphery of Gondwana during the Late Precambrian, the presence of Baltic trilobites in the Early Cambrian of Upper Silesia and Malopolska (Fig. 2; [9]) indicates a proximity to the Baltic realm during the Cambrian. In the case of Malopolska, this proximity is corroborated by the increasing importance of Baltic brachiopods during the Middle Cambrian [20]. A contrasting feature of the Malopolska Massif with respect to the neighboring crustal blocks is the evidence of Late Cambrian (pre-Tremadocian) non-penetrative deformation of the Cambrian and Neoproterozoic rocks (Fig. 2; e.g. [21]). This event might be related to the docking of Malopolska against Baltica. Paleomagnetic data [22] and sedimentary provenance studies [11] indicate that the Lysogory Unit and the Malopolska Massif were amalgamated into their current positions by the Silurian–Early Devonian.

The Lysogory Unit is located north of the Malopolska and lies next to the East European Platform (Fig. 1). In contrast to the Upper Silesian and Malopolska massifs, the Cambrian fauna and ichnofossils of the Lysogory Unit reveal affinity to Avalonia. This led Belka et al. [11] to consider the Lysogory as an exotic unit, because it is now set between a terrane with predominantly Baltic fauna during the Cambrian, the Malopolska Massif, and the East European Platform (Figs. 1, 2).

2.1. The Lysogory Unit

The Lysogory Unit crops out in the Holy Cross Mountains. It is separated from the southern unit of the Holy Cross Mountains, which belongs to the Malopolska Massif, by a brittle fault zone, the

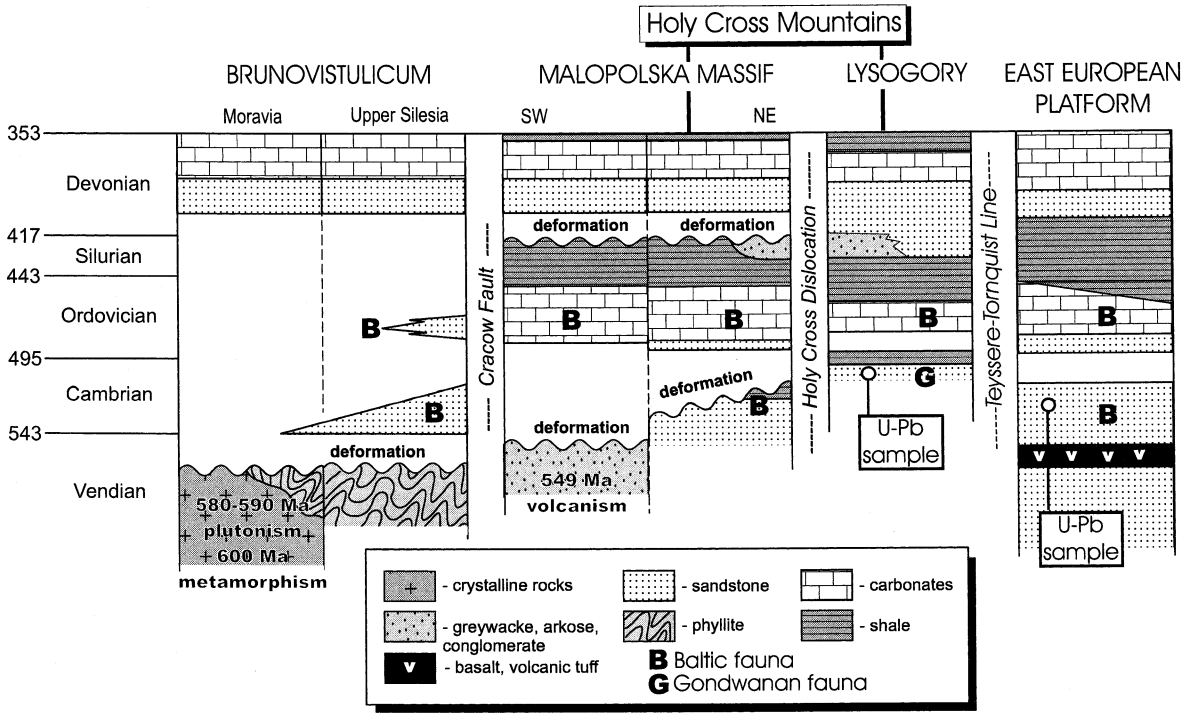

Fig. 2. Diagrammatic sections to show the geology of the Paleozoic suspect terranes in central Poland (modified after [11]). The stratigraphic position of the U–Pb samples from the Lysogory Unit and the East European Platform are indicated. See text for more details.

Holy Cross Dislocation (Figs. 1B, 2; e.g. [18]). Recent geophysical data indicate that the Lysogory Unit is about 30 km wide and is bounded to the north by a steep unexposed fault zone [23]. The paleogeographic affinities of the rocks set between this fault zone and the EEP are unknown.

The crystalline basement of the Lysogory is unknown. The oldest rocks are Middle Cambrian sandstones, which are well exposed in the northern part of the Holy Cross Mountains. They form part of a 1800 m thick clastic sequence, which extends into the Tremadoc and is lithologically similar to time-equivalent units of the East European Platform [24]. This sequence is dominated by sandstones with very mature compositions. However, detrital micas are abundant in the more shaly interbeds of the Middle Cambrian and have yielded a bimodal K–Ar age spectrum of ca. 600 Ma and ca. 1.7 Ga [11]. The Cambrian trilobite and inarticulate brachiopod fauna of the Lysogory is scarce, but the rocks are extremely rich in *Cruziana* [25,26]. This includes non-cosmopolitan Late Cambrian ichnospecies such as *Cruziana barbata* and *Cruziana semiplicata* which are restricted to the Gondwana realm [27,28]. This ichnocoenosis is identical to that of Gondwana and the peri-Gondwana microplates, but unknown from Baltica (cf. [28]). According to Jendryka-Fuglewicz (personal communication, [20]), the brachiopod fauna reveals a marked Avalonian affinity. Another significant and distinctive feature of the Lysogory with respect to the adjacent Malopolska Massif is the absence of angular unconformities in the pre-Carboniferous stratigraphy (Fig. 2; see [11]).

2.2. The East European Platform

As mentioned above, all the areas east of the TTZ in Poland belong to the East European Platform (EEP). Although the crystalline basement is

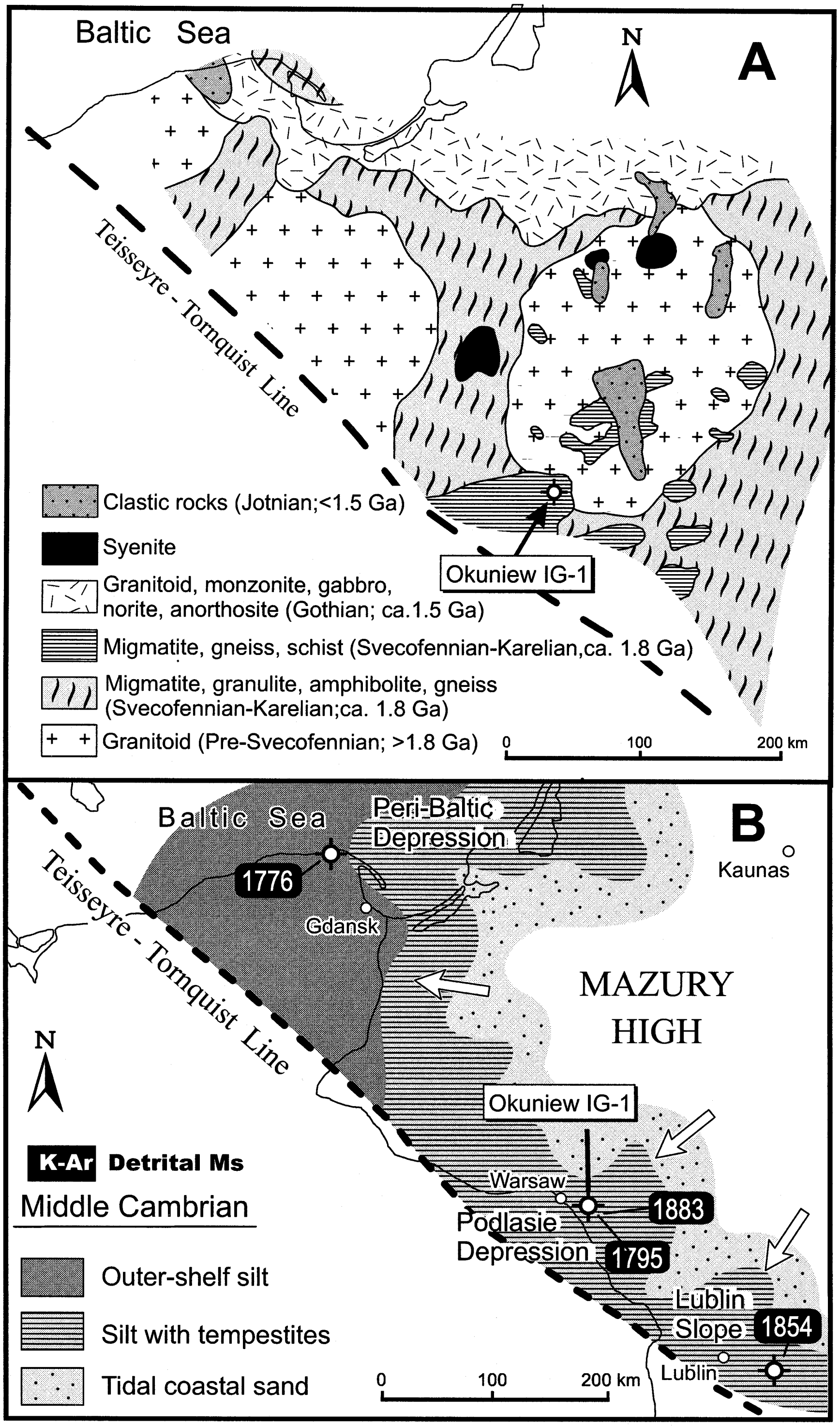

Fig. 3. East European Platform, Poland. A: Simplified geological map of the crystalline basement (modified after [29]). B: Paleogeographic reconstruction of the Middle Cambrian sedimentary facies (modified after [37]; K–Ar ages [11]).

Table 1

U–Pb data spiked with the ^{208}Pb–^{235}U isotopic tracer

Sample	Weight	Concentration			IC measurements[a]			Corrected atomic ratios[b]			Ages (Ma)			% *Discordia*
	(μg)	U (ppm)	Pbr (ppm)	Pbi (ppm)	$^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$	$^{208}\mathrm{Pb}/^{206}\mathrm{Pb}$	$^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$	$^{206}\mathrm{Pb}/^{238}\mathrm{U}$ ± 2σ	$^{207}\mathrm{Pb}/^{235}\mathrm{U}$ ± 2σ	$^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$ ± 2σ	$^{206}\mathrm{Pb}/^{238}\mathrm{U}$	$^{207}\mathrm{Pb}/^{235}\mathrm{U}$	$^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$	
Okuniew borehole: crystalline basement, granodioritic orthogneiss														
Z1 Lrg. P5 single pr. AB	17	100	34	0.3	3095	0.1311	0.11427	0.3225 ± 26	4.886 ± 40	0.10988 ± 52	1802	1800	1797	*−0.3*
Z2 Lrg. P5 single pr. AB	21	165	54	2.8	945	0.1460	0.12419	0.3133 ± 11	4.745 ± 18	0.10984 ± 43	1757	1775	1797	*2.6*
Z3 Lrg. P5 single pr. AB	12	109	35	1	1049	0.1448	0.12271	0.3079 ± 23	4.660 ± 36	0.10977 ± 49	1730	1760	1795	*4.1*
Z4 Lrg. P5 single pr. AB	26	148	44	0.9	1928	0.1357	0.11628	0.2825 ± 16	4.255 ± 24	0.10924 ± 45	1604	1685	1787	*11.6*
Z5 2 Lrg. P5 prisms AB	28	132	31	1.2	1011	0.1367	0.12052	0.2234 ± 11	3.298 ± 17	0.10706 ± 44	1300	1481	1750	*28.4*
Okuniew borehole: cover, Cambrian sandstone														
Bed at 3779 m depth														
Z3 Med. colourless NOAB	13	228	28	1.7	450	0.4895	0.09376	0.09537 ± 38	0.813 ± 12	0.06183 ± 92	587	604	668	*12.6*
Z14 Med. colourless NOAB	11	320	125	4.5	976	0.3177	0.19544	0.3084 ± 13	7.770 ± 34	0.18273 ± 75	1733	2205	2678	*40.1*
Bed at 3695–3701 m depth														
Z1 Med. colourless NOAB	22	466	49	1.2	1200	0.3846	0.07208	0.08623 ± 40	0.7145 ± 43	0.06009 ± 33	533	547	607	*12.7*
Z2 Med. pink-purple NOAB	31	41	5	1.5	122	0.6919	0.18378	0.09047 ± 51	0.838 ± 23	0.0672 ± 19	558	618	843	*35.2*
Z4 Med. light turbid NOAB	26	483	40	7.8	266	0.3173	0.15658	0.07436 ± 27	1.0795 ± 49	0.10527 ± 49	462	743	1719	*75.6*
Z6 Med. light pink NOAB	15	82	15	4	175	0.3844	0.16443	0.1680 ± 12	1.963 ± 33	0.0847 ± 13	1001	1103	1308	*25.2*
Z10 Med. colourless NOAB	21	43	12	2	216	0.4761	0.15717	0.21898 ± 93	2.814 ± 20	0.09319 ± 72	1276	1359	1492	*15.9*
Z12 Med. colourless NOAB	23	611	176	7.2	1287	0.0588	0.16856	0.2809 ± 10	6.144 ± 23	0.15861 ± 63	1596	1997	2441	*39.0*
Z15 Med. pink NOAB	17	359	132	2.7	1987	0.1598	0.13521	0.3370 ± 12	5.973 ± 22	0.12853 ± 51	1872	1972	2078	*11.4*
Z16 Med. pink NOAB	21	93	35	0.3	1774	0.1290	0.13462	0.3501 ± 16	6.137 ± 30	0.12714 ± 57	1935	1995	2059	*7.0*
Z19 Med. dark pink NOAB	12	367	179	2.5	2219	0.0700	0.18331	0.4607 ± 21	11.288 ± 52	0.17769 ± 71	2443	2547	2631	*8.6*

Table 1 (*continued*)

Sample	Weight	Concentration			IC measurements[a]			Corrected atomic ratios[b]			Ages (Ma)			% *Discordia*
	(μg)	U (ppm)	Pbr (ppm)	Pbi (ppm)	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{207}Pb}{^{206}Pb}$	$\frac{^{206}Pb}{^{238}U}$ ± 2σ	$\frac{^{207}Pb}{^{235}U}$ ± 2σ	$\frac{^{207}Pb}{^{206}Pb}$ ± 2σ	$\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$	
Lysogory Unit: Cambrian sandstone														
Z2 Lrg. clr. colourless AB	18	227	24	0.4	1078	0.2390	0.07343	0.09480 ± 47	0.7861 ± 51	0.06014 ± 37	584	589	608	*4.1*
Z5 Med. clr. colourless AB	> 10	308	37	2.6	325	0.3948	0.10792	0.10117 ± 66	0.8923 ± 88	0.06397 ± 57	621	648	740	*16.8*
Z8 Lrg. withish rd. AB	17	475	88	5	832	0.1221	0.12302	0.18151 ± 80	2.673 ± 13	0.10678 ± 54	1073	1321	1745	*41.6*
Z9 Lrg. pink AB	12	335	81	19.2	226	0.2937	0.15533	0.2251 ± 13	2.932 ± 23	0.09443 ± 65	1309	1390	1516	*15.0*
Z10 Med. dark AB	> 10	1877	423	67.4	371	0.1205	0.15417	0.22921 ± 95	3.733 ± 17	0.11812 ± 57	1330	1579	1928	*34.2*
Z11 Med. dark AB	> 10	3485	1089	30.8	1736	0.0906	0.13238	0.3039 ± 13	5.230 ± 23	0.12482 ± 56	1711	1858	2026	*17.7*
Z12 Med. pink-purple AB	> 10	136	46	0.9	952	0.1524	0.12405	0.3187 ± 26	4.830 ± 42	0.10993 ± 63	1783	1790	1798	*0.9*
Z17 Med. clr. colourless AB	> 10	344	197	11.8	638	0.1886	0.20093	0.5059 ± 33	12.672 ± 85	0.18167 ± 83	2639	2656	2668	*1.3*
Z18 Med. pink AB	11	151	87	0.1	3470	0.1124	0.19853	0.5167 ± 27	13.909 ± 73	0.19522 ± 90	2685	2744	2786	*4.4*

All crystals are from the 5°, 1.6 Å non-magnetic (Frantz) fraction. Lrg., large (> 160 μm); med., medium (160–120 μm); clr., clear; AB, air abrasion [39]; NOAB, no air abrasion.

[a] Isotope composition measurements corrected for fractionation.

[b] Atomic ratios corrected for fractionation, spike (^{208}Pb–^{235}U spike), laboratory blanks (5–10 pg Pb and 1 pg U) and initial common Pb [41].

not exposed, it has been drilled by more than 100 boreholes. This basement is a southern continuation of the Svecofennian crust of the Baltic Shield (Figs. 1A, 3A; [29]). This crystalline basement is overlain by a flat-lying sedimentary cover, which ranges in age from the Late Riphean to the Quaternary with numerous stratigraphic gaps. The thickness of the cover sequence ranges from 360 m in northeastern Poland to more than 5600 m along the Teysseire–Tornquist Line (Fig. 1B). These rocks are unmetamorphosed and only display a substantial diagenetic overprint in deeply buried levels.

The oldest rocks of the EEP cover are Late Precambrian (Late Riphean–Vendian) siliclastic rocks with volcanic intercalations (551 ± 4 Ma; U–Pb zircon ^{206}Pb/^{238}U SHRIMP age [19]). These volcanic rocks are present in southeastern Poland and are correlated with the widely distributed volcanic rocks associated to the Vendian aulacogens of Ukraine, Belarus and Moldavia [19]. Cambrian rocks locally overlay the Vendian clastic rocks, but in most cases rest directly on the crystalline basement. The Cambrian rocks contain Cambrian trilobites and brachiopod faunas with phosphate shells typical of the Baltic realm [20,30,31]. Well constrained Cambrian biostratigraphy [30,32,33] reveals the presence of three major basins separated by basement highs: the Peri-Baltic Depression in the north, the Podlasie Depression in the center, and the Lublin Slope in southeastern Poland (Fig. 3B). The Lower and Middle Cambrian sequence is formed by siliciclastic rocks. Tidal sands in the east and a shelf mud zone in the west indicate the presence of an open sea west of the TT Line. While the widely distributed Lower and Middle Cambrian rocks locally attain a thickness of several hundred meters, Upper Cambrian rocks are represented by a thin sequence only in the Peri-Baltic Depression. A detrital muscovite provenance study of Middle Cambrian sandstones (K–Ar ages of mica populations [11]) shows the presence of 1.8–1.9 Ga white micas which are interpreted to be derived from exposed parts of the Mazury High (Fig. 3B; 1.9–2.1 Ga, U–Pb Zr data [34]).

2.3. The Okuniew borehole IG-1

The Okuniew borehole IG-1 is located in the axial zone of the Podlasie Depression, approximately 15 km east of Warsaw, at the southwestern margin of the EEP (Fig. 3). This borehole has drilled ca. 4000 m of the platform sequence and 57.4 m of the crystalline basement (Fig. 4). The basement consists of biotite and amphibole-bearing gneiss, amphibolite, and micaschist of the Jadow Series. Ryka et al. [35] correlate the Jadow Series with the Svecofenno-Karelian rocks and suggest an age older that 1.75 Ga. Depuich et al. [36] reported K/Ar biotite and amphibole ages ranging between 1.28 and 1.2 Ga from these rocks. In the Okuniew borehole, the Cambrian sediments directly overly the crystalline basement. This succession is ca. 600 m thick and consists of Lower Cambrian siltstone and Middle Cambrian sandstone. Absolute age dating of detrital zircon (this study) and muscovite [11], to unveil the provenance of the clastic material, were done with material from the medium- to coarse-grained Middle Cambrian sandstones. These sandstones represent storm sand layers and amalgamated sand tongues with tidal channel fills [37].

3. Samples

To compare the age spectra of the detrital zircons in the Cambrian of the Lysogory Unit with those of the EEP, we have collected two samples from the Middle Cambrian sandstones at 3779 m and 3695–3701 m depths in the Okuniew borehole (7 and 18 kg, respectively). In the same borehole, the crystalline basement (20 kg) was also sampled.

In the *Lysogory Unit*, a 50 kg sample (WYM-

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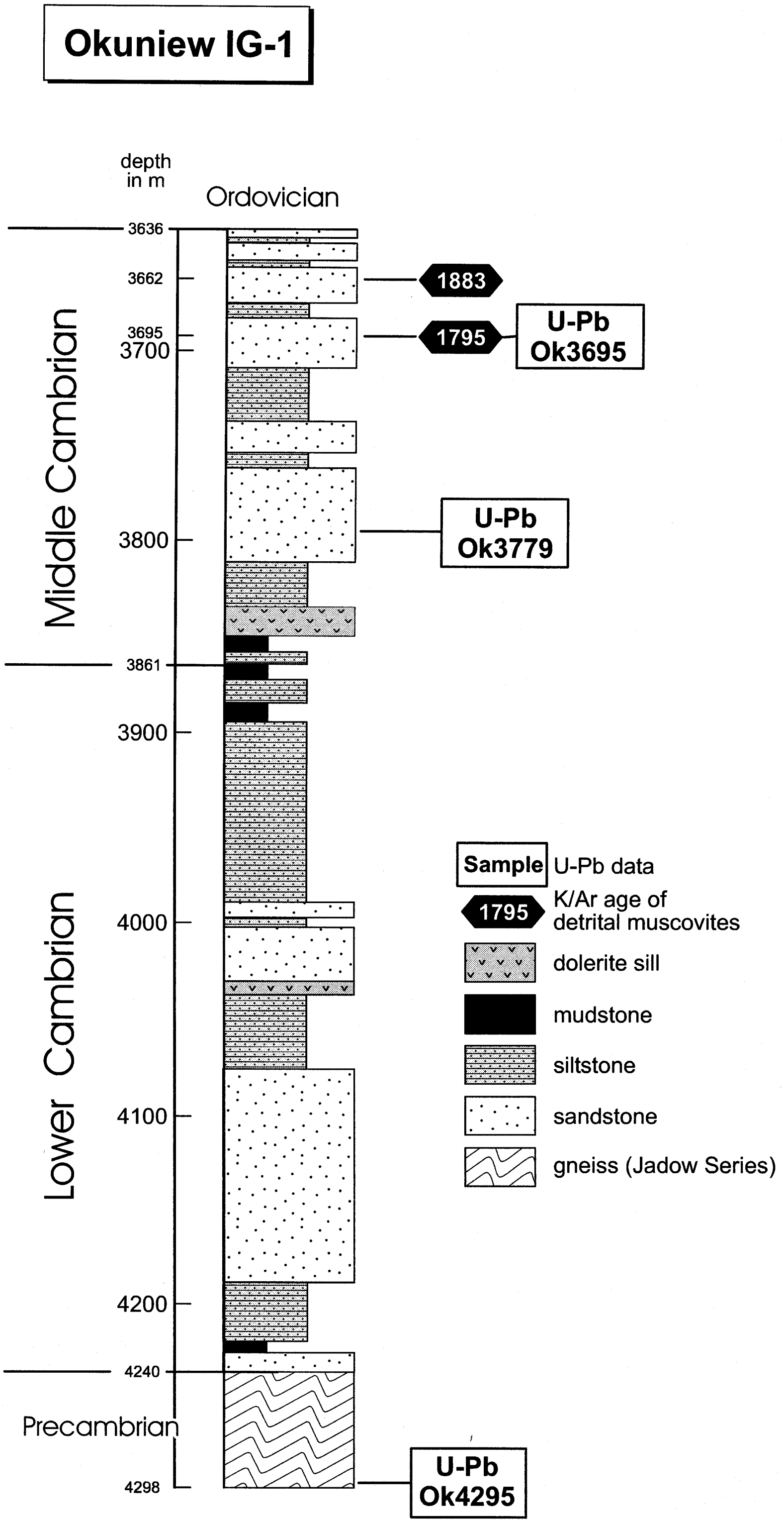
Fig. 4. Okuniew borehole: crystalline basement and simplified Cambrian stratigraphic column showing the sample location. K–Ar ages [11].


Okuniew IG-1
depth in m
Ordovician
Middle Cambrian
Lower Cambrian
Precambrian
3636
3662
3695
3700
3800
3861
3900
4000
4100
4200
4240
4298
1883
1795
U-Pb Ok3695
U-Pb Ok3779
U-Pb Ok4295
Sample U-Pb data
1795 K/Ar age of detrital muscovites
dolerite sill
mudstone
siltstone
sandstone
gneiss (Jadow Series)

01) was collected from the Wisniowka sandstone in an outcrop at the eastern end of the village Wymyslona (18 km east of Kielce; 20°51′25″E; 50°53′20″N; Fig. 1B), in which Upper Middle/Lower Upper Cambrian siliclastic rocks of the Wisniowka Formation are exposed (Fig. 2). The sample is a well sorted, grain-supported, fine- to very fine-grained quartz–arenite ($>90\%$ quartz) with accessory white mica, tourmaline, rutile and zircon. Grain boundaries are sutured, but the original quartz grains, when recognized, are well rounded. Most quartz grains are single crystals with undulose extinction. Only a few grains are lithic fragments, polycrystalline aggregates of small dynamically recrystallized quartz grains with textures suggesting subgrain rotation recrystallization (greenschist facies quartzite/mylonite?). All zircon and rutile crystals larger than 120 microns are well rounded and do not show crystallographic faces. These zircons range from purple and pink to clear colorless crystals. Smaller zircons ($=80$ μm) preserve some of their crystallographic faces.

3.1. *East European Platform (Okuniew: samples OK-3779 and OK-3695)*

These samples were collected from the Middle Cambrian succession of the Okuniew IG-1 borehole (Fig. 4). Both samples are well sorted, grain-supported, quartz–arenites/quartz–siltstones ($\varnothing \approx 0.06$ mm; $>90\%$ quartz) with minor glauconite and carbonate cement. The main accessory phases are rutile, tourmaline, zircon, and secondary titanite. Locally, glauconite ($\varnothing \approx 0.3$ mm) can make up to 20% of the rock. In most cases the quartz grains are sutured. Where the carbonate cement has filled the pore spaces, well rounded quartz grains are preserved, corroborating the mature character of the sandstone. All zircon grains bigger than 120 microns are well rounded and range in color from dark purple to colorless clear crystals. Smaller zircon grains are moderately to well rounded. Sample OK-3779 (depth 3779 m) was the first one to be processed, and the scarcity of zircon grains larger than 120 μm necessitated processing of sample OK-3695 (depth 3695–3701 m).

3.2. *East European Platform, crystalline basement (Okuniew: sample OK-4295)*

This sample was collected from a gneiss in the crystalline basement pierced by the Okuniew IG-1 borehole (depth 4295 m; Fig. 4). The gneiss has a migmatitic appearance with alternating leucocratic and melanocratic domains. These domains have identical mineralogy (plagioclase (An10–15), K-feldspar, quartz, and biotite) with biotite in different modal proportions. Grain size varies between 1 and 5 mm, the coarser grain size corresponds to the leucocratic, biotite-poor, domains. In all domains subparallel biotites define a continuous, coarse, schistosity. Quartz, K-feldspar, and plagioclase show textures indicative of grain boundary migration dynamic recrystallization (e.g. [38]), analogous to those observed in upper amphibolite facies rocks. Apatite, zircon, and opaques are accessory phases, while white mica, chlorite, and titanite are secondary phases. Chloritization of biotite can be quite extensive and associated with saussiritization of plagioclase; this secondary alteration took place under static conditions. The absence of any minerals indicative of anatectic reactions and the similar modal proportions of quartz, plagioclase, and K-feldspar between the leucocratic and melanocratic domains suggest that this gneiss represents a highly strained metaluminous granodioritic/granitic orthogneiss.

4. Analytical methods

The rock samples were processed and analyzed at the University of Giessen, Germany. Following crushing and pulverization, the sample was separated by flotation with water, bromoform, and diiodomethane into light and heavy mineral fractions. Further separation of the heavy mineral fraction was achieved by magnetic separation using a Frantz isodynamic separator. The non-magnetic, zircon-bearing, fraction was then sieved to recover the larger grains. Zircons with diameters larger than 120 μm were hand picked under a microscope for single-grain analysis. These grains were selected on the basis of color and crystal

Table 2
U–Pb data spiked with the $^{205}Pb–^{235}U$ isotopic tracer

Sample	Weight	Concentration			Measured[a]		Corrected atomic ratios[b]			Ages (Ma)			% *Discordia*
	(µg)	U (ppm)	Pbr (ppm)	Pbi (ppm)	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{206}Pb}{^{238}U}$ ±2σ	$\frac{^{207}Pb}{^{235}U}$ ±2σ	$\frac{^{207}Pb}{^{206}Pb}$ ±2σ	$\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$	
Okuniew borehole: cover, Cambrian sandstone (single grains)													
Bed at 3695–3701 m depth													
Z6 Med. clr. colourless AB	>10	86	15	1.4	622	0.1768	0.1668 ± 28	1.760 ± 41	0.0767 ± 12	993	1031	1113	*11.7*
Z7 Med. clr. colourless AB	>10	599	115	2.6	2531	0.1667	0.1803 ± 12	2.055 ± 16	0.08265 ± 33	1069	1134	1261	*16.5*
Z8 Med. clr. colourless AB	>10	480	93	8.3	669	0.1798	0.1854 ± 19	2.169 ± 27	0.08485 ± 57	1096	1171	1312	*17.9*
Z9 Med. clr. colourless AB	>10	186	39	0.8	2795	0.1396	0.1989 ± 22	2.253 ± 29	0.08214 ± 46	1169	1198	1249	*7.0*
Z11 Med. clr. colourless AB	10	115	35	2.4	756	0.3007	0.2571 ± 20	3.453 ± 31	0.09741 ± 43	1475	1516	1575	*7.1*
Z13 Med. pale pink AB	>10	166	60	1.9	1633	0.2074	0.3192 ± 20	5.173 ± 46	0.11755 ± 75	1786	1848	1919	*7.9*
Z17 Med. clr. colourless AB	10	230	86	0.6	7200	0.0910	0.3574 ± 11	6.101 ± 23	0.12379 ± 26	1970	1990	2011	*2.3*
Z18 Med. clr. colourless AB	15	63	29	1.5	998	0.2253	0.4029 ± 53	7.75 ± 11	0.13944 ± 99	2182	2202	2220	*2.0*
Lysogory Unit: Cambrian sandstone (single grains)													
Z1 Med. clr. colourless AB	20	118	11	0.3	2231	0.1794	0.09120 ± 67	0.7572 ± 79	0.06022 ± 43	563	572	612	*8.4*
Z3 Med. clr. colourless AB	>10	1073	111	4.7	1396	0.1820	0.0984 ± 16	0.877 ± 26	0.0646 ± 15	605	639	762	*21.6*
Z4 Med. pink AB	13	134	16	1.5	575	0.3985	0.10047 ± 33	0.886 ± 17	0.0640 ± 12	617	644	740	*17.4*
Z6 Med. clr. colourless AB	13	152	18	1.2	821	0.3097	0.1016 ± 10	0.894 ± 15	0.06382 ± 79	624	648	734	*15.7*
Z7 Med. clr. colourless AB	10	24	3	0.6	263	0.4553	0.1010 ± 42	0.909 ± 50	0.0653 ± 23	620	656	783	*21.8*
Z13 Med. clr. colourless AB	>10	329	125	5.8	1081	0.2779	0.3255 ± 11	4.979 ± 45	0.11096 ± 87	1819	1816	1815	*−0.1*
Z14 Med. pink AB	19	87	40	0.5	3711	0.3432	0.3676 ± 11	6.365 ± 22	0.12559 ± 19	2018	2027	2037	*1.1*
Z15 Med. clr. colourless AB	17	497	236	1.2	9495	0.3129	0.38408 ± 74	6.812 ± 14	0.12864 ± 11	2095	2087	2079	*−0.9*
Z16 Med. colourless pr. NOA	>10	86	38	0.8	2548	0.1191	0.3998 ± 30	10.199 ± 80	0.18503 ± 42	2168	2453	2698	*23.1*
Z19 Med. pink AB	10	153	96	0.7	6714	0.1642	0.5387 ± 10	14.662 ± 29	0.19738 ± 9	2778	2794	2805	*1.2*

All crystals are 5°, 1.6 Å non-magnetic (Frantz) fraction. Med, medium (160–120 µm); clr, clear; AB, air abrasion [39]; NOA, no air abrasion; pr., prism.

[a] Measured ratio corrected for blank and fractionation.

[b] Atomic ratios corrected for fractionation, spike ($^{205}Pb–^{235}U$ spike), laboratory blanks (5–10 pg Pb and 1 pg U) and initial common Pb [41].

quality. The selected grains were air abraded [39], except for some grains from the Okuniew borehole (Table 1). Each single grain was cleaned with 4 N HNO_3, double distilled H_2O, and ultrapure acetone, weighed, and dissolved in Krogh-type Teflon® dissolution bombs with HF. The first set of analyses was spiked with a ^{208}Pb–^{235}U spike (Table 1). The dissolved sample was split for IC and ID measurements, and the spike was added to the ID split. The second set of samples was spiked with a mixed ^{205}Pb–^{235}U spike which was added directly to the sample prior to dissolution (Table 2). In both cases, Pb and U separation was done using a scale-down version of the ion exchange chemistry of Krogh [40]. The purified Pb and U were collected, separately, with H_3PO_4 and loaded on separate single Re filaments using a mixture of SiGel and H_3PO_4. Isotopic ratios were measured in static and peak-jumping mode using a Finnigan MAT 261 mass spectrometer equipped with a Spectromat ion counting system. Beam intensities allowed, in all cases, static mode measurements; the ^{204}Pb was measured with the calibrated ion counter. All isotopic ratios are corrected for mass fractionation (1.12 ± 0.18‰/a.m.u.), blank (3–10 pg Pb, 1 pg U) and initial common Pb estimated after the model of Stacey and Kramers [41]. The isotopic ages were calculated using the decay constants of Jaffey et al. [42].

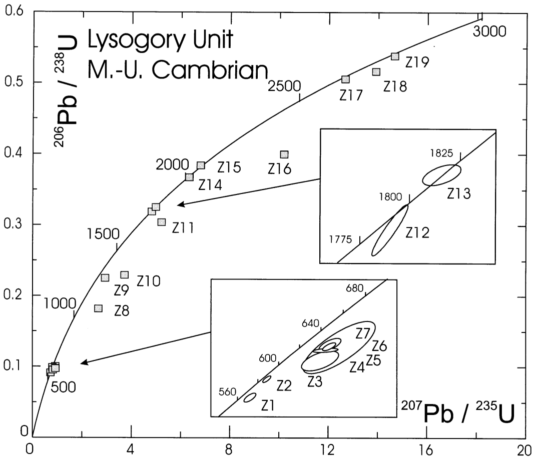


Fig. 5. U–Pb concordia diagram for the detrital zircon from the Wymyslona sandstone (Middle/Upper Cambrian; Lysogory Unit, Holy Cross Mountains).

Ages and uncertainties for the analyses spiked with ^{208}Pb (Table 1) were calculated after Ludwig [43] using an internal program of the University of Giessen. The analyses spiked with ^{205}Pb (Table 2) were calculated using PBDAT [44]. In all cases uncertainties are reported at the 2σ level. Total uncertainties on individual points are represented by 2σ uncertainty ellipses. Regression lines were calculated according to the least-squares method [45] with age and uncertainties reported at the 95% confidence interval.

5. Results

5.1. Middle/Upper Cambrian sandstone of Wymyslona (Lysogory Unit)

A total of 19 single detrital zircons were analyzed (Fig. 5). All the grains ranged between 160 and 120 microns. The data show one major cluster at ca. 600 Ma formed by analyses Z1–Z7. Analysis Z2 (608 Ma, $^{207}Pb/^{206}Pb$ apparent age) provides a solid constraint on the age of this Late Proterozoic component. Analyses Z8, Z9, Z10, and Z11 are discordant (15–40%), roughly indicating the presence of 1.5–2.2 Ga zircon component. The presence of Early Proterozoic component is well demonstrated by the concordant/subconcordant analyses of zircons Z12 (1798 Ma), Z13 (1816 Ma), and Z15 (2079 Ma). Analysis Z16 is 26% discordant suggesting an Archean component. The subconcordant analysis Z17 has a $^{207}Pb/^{206}Pb$ apparent age of 2668 Ma indicating the presence of Late Archean zircon. The analysis Z19 shows the presence of a Late Archean component of ca. 2.8 Ga.

5.2. Middle Cambrian sandstone at Okuniew (Eastern European Platform)

The zircon data set consists of 19 single-grain analyses (Fig. 6) with two clusters at ca. 600 Ma and ca. 1.0 Ga. The presence of ca. 600 Ma zircon in earlier analysis (Z3; sample OK-3771), and the scarcity of large zircon grains, led to sampling a second bed (OK-3695) where the ca. 600 Ma component was also found. Analyses Z3 and Z14 are from the first bed (OK-3771; Fig. 4), whereas the rest of the analyses where performed on zircons from the second bed (OK-3695; Fig. 4).

The ca. 600 Ma group is formed by analyses Z1, Z2, Z3, and Z4. Analyses Z1 and Z3 plot relatively close to the concordia curve with ^{206}Pb/^{238}U ages of 533 and 587 Ma, and ^{207}Pb/^{206}Pb ages of 607 and 668 Ma, respectively. Although these analyses are ca. 12% discordant, they bracket the age of the zircon component roughly at ca. 600 Ma. The second cluster of ages is defined by analyses Z4, Z6, Z7, Z8, and Z9 (6–17% discordant) with ^{206}Pb/^{238}U ages between 993 and 1249 Ma and ^{207}Pb/^{206}Pb ages between 1113 and 1312 Ma. Analyses Z10 and Z11 have ^{207}Pb/^{206}Pb apparent ages of ca. 1575 Ma, the relatively close position of Z11 to concordia suggests the presence of a 1500–1600 Ma old zircon component. Analyses Z13, Z15, Z16, and Z17 point towards the presence of Early Proterozoic 1800–2000 Ma zircons; analyses Z12 (39%) and Z14 (40%) are too discordant to provide any significant information. The presence of a ca. 2200 Ma zircon component is indicated by analysis Z18. Finally, analysis Z19 suggests the presence of an Archean zircon component older than 2.5 Ga.

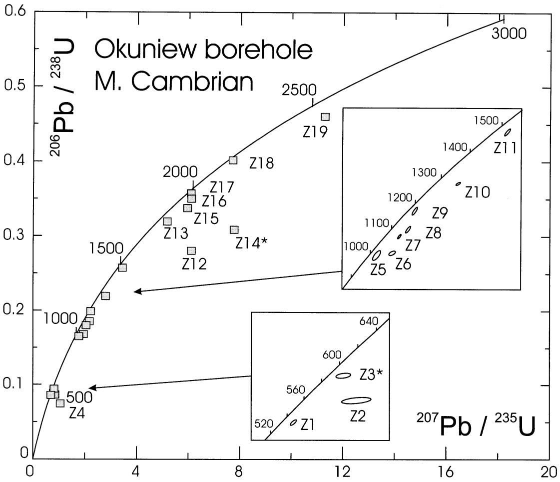


Fig. 6. U–Pb concordia diagram for the detrital zircon from the Middle Cambrian of the Okuniew borehole (Podlasie Depression; East European Platform). *: zircons from sample OK-3771.

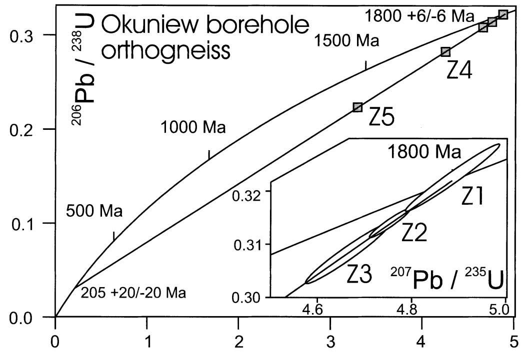


Fig. 7. U–Pb concordia diagram for the crystalline basement of the Okuniew borehole (OK-4295), granodioritic orthogneiss, Jadow Series.

5.3. *Crystalline basement at Okuniew (EEP)*

One concordant and four discordant analyses of euhedral zircon prisms define a collinear discordancy pattern (Fig. 7). The resultant discordia line has an upper intercept of 1800 ± 6 Ma and a lower intercept of ca. 205 Ma. The upper intercept at 1800 ± 6 Ma, coincident with a concordant analysis (Z1), reflects the age of zircon crystallization, and it is interpreted as the age of the magmatic protolith.

6. Discussion

The new data from the Okuniew IG-1 borehole demonstrate the presence of 1.8 Ga Svecofennian rocks in the crystalline basement of this part of the East European Craton (Fig. 3A), as suggested by Ryka et al. [35]. The absence of an inherited zircon component in all five analyses and the petrographic character of the gneiss suggest that this is a 1800 ± 6 Ma granodiorite. The timing of the deformational and metamorphic overprint is bracketed between the protolith age of the gneiss, 1.8 Ga, and the 1.2–1.28 Ga, K–Ar, biotite and amphibole cooling ages of Depciuch et al. [36] for the Jadow Series. Such K–Ar ages, however, are not found in the detrital micas of the overlying

Cambrian siliciclastic rocks (Fig. 4). Multigrain muscovite fractions from the Middle Cambrian sandstones yielded ages of 1883 ± 43 Ma and 1795 ± 41 Ma [11]. These document exclusive input from Svecofennian sources. Contrary to that, the age spectra of the single zircon grains extracted from these sandstones show a complexity of sources and/or recycled components (Fig. 6). The older, 2.2 Ga and >2.5 Ga grains probably represent recycled zircon, rather than components derived directly from the Early Proterozoic or Archean rocks of the East European Craton. The 1.8–2.0 Ga zircon ages are coincident with the white mica ages and suggest direct derivation from an exposed Svecofennian basement. It should be noted that in the Middle Cambrian the marginal parts of the EEP, including the area of Okuniew, were blanketed by Lower Cambrian sediments [37]. Additionally, the absence of 1.2 Ga micas suggests that recycling of zircon derived from the crystalline basement at Okuniew is an unlikely process. The most likely provenance for these zircons is the Svecofennian basement exposed further east in the Mazury High (Fig. 3B). Such derivation is consistent with facies trends and paleocurrents [37]. The ca. 1.5 Ga and 1.0–1.3 Ga zircon components reflect input from sources with Gothian and Sveconorwegian (Grenvillian) signatures [3]. Gothian rocks (1.5 Ga) are known from northern Poland (Fig. 3A) and southern Scandinavia. Sveconorwegian rocks are only known from southern Scandinavia, and their presence has so far not been demonstrated in Poland. This would imply southeastward transport (in modern coordinates) of the 1.0–1.3 Ga zircons, parallel to the coastline, along the margin of the Eastern European Platform (Fig. 1A). The most remarkable feature of the zircon age spectra is the presence of ca. 600 Ma zircons. These zircons represent 20% of the analyzed population. Furthermore, they were found in two independent samples (OK-3779 and OK-3695), indicating an unmistakable input of Vendian zircons in this part of the EEP. This material is probably derived from the Vendian tuffs, which are widely distributed in the southwestern part of the EEP [19]. Compston et al. (U–Pb SHRIMP; [19]) dated one of these tuffs on the Lublin slope (Fig. 3B) at ca. 551 Ma (^{206}Pb/^{238}U age) and found detrital or inherited components with ca. 588 and 635 Ma ^{206}Pb/^{238}U ages which match those of fractions Z1, Z2, and Z3.

The zircons from the Middle Upper Cambrian sandstones of the Lysogory Unit (Wymyslona; Fig. 1B) show a wide age spectrum with well defined Archean (>2.5 Ga), Early Proterozoic (1.8–2.1 Ga) and Late Precambrian (ca. 600 Ma) ages. Such age pattern (Fig. 5) is similar to that of Gondwanan-derived sources (e.g. [46]). Despite matching coincidence between the concordant zircon Z10 (1798 Ma) from the Lysogory and the age of the crystalline basement at Okuniew (1800 ± 6 Ma) and other similarities with the zircon age spectra from the Middle Cambrian at Okuniew, including the ca. 600 Ma component, the significant absence of ca. 1.0–1.2 Ga (Sveconorwegian) component questions the derivation of the zircon detritus from a zone adjacent to the Polish East European Platform. It is important to note that Belka et al. [11] obtained K–Ar ages ranging from 539 Ma to 1745 Ma from multigrain analysis of white micas from the Lysogory area and suggested derivation of clastic material from two different sources. The Svecofennian basement of Baltica (EEP) was envisaged as the source for the Early Proterozoic (1.7–1.8 Ga) old muscovites and a Cadomian basement as a source for ca. 600 Ma old grains. The derivation of 1.7–1.8 Ga old muscovites from the basement and/or sedimentary cover of Baltica would imply the accretion of Lysogory already during Middle/Upper Cambrian times. This scenario, however, is not compatible with the biogeographic data; the Cambrian fauna of Lysogory shows Gondwanan rather than Baltic affinities [11]. Another possibility is that Lysogory was still separated from Baltica during the Late Cambrian and was supplied with clastic material exclusively from Gondwanan sources.

The fact that significant amounts of ca. 600 Ma detrital zircons are present in the Cambrian of certain areas of the East European Platform, as we have shown at Okuniew, highlights the problem inherent in drawing paleogeographic correlations based on detrital zircons alone. From this study we can conclude that the single occurrence of Late Proterozoic (Vendian) zircons, alone, precludes a distinction between Gondwanan, Cadomian/Pan-African sediments and Baltic-derived clastic material. The same problem is likely to be found in other locations bordering areas of Baltica where Riphean–Vendian aulacogens (aborted rifts) with significant volcanism are located [47]. To avoid confusion we suggest that the term 'Cadomian' should only be used to refer to a ca. 600 Ma zircon detrital component in areas where there is unequivocal evidence of derivation from true Cadomian sources (i.e. a Late Proterozoic to Earliest Cambrian Andean-type orogen at the northern margin of Gondwana [48]).

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