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SHRIMP U-Pb ZIRCON CHRONOLOGY OF THE POLISH WESTERN OUTER CARPATHIANS SOURCE AREAS

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Abstract. The Western Outer Carpathians flysch of Poland comprises clasts of crystalline rocks representing source areas that supplied sedimentary basins with clastic material. Zircon from quartz syenite and granite cobbles representing the Silesian Ridge, the currently unexposed source area located at the southern margin of the Silesian Basin, yielded uniform U-Pb dates of 604±6 Ma and 599±6 Ma. These are interpreted as the age of igneous crystallization. Similarly, zircon from a gneiss cobble derived from the northern source terrain gave 610±6 Ma date, which is interpreted as the age of crystallization of the granitic protolith to the gneiss. The Neoproterozoic magmatism is interpreted to have occurred at the Gondwana active margin.

Key words: zircon, U-Pb geochronology, ion microprobe, provenance, Carpathians.

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INTRODUCTION

The study of accessory minerals provides a broad range of constraints on the igneous, metamorphic and sedimentary processes. In the latter, particularly in the field of provenance studies, information on multiple igneous and/or metamorphic processes related to sources of mineral detritus can be obtained (Weltje & von Eynatten, 2004, and references therein). The application of geochronology to questions of provenance requires selecting radioisotope-bearing minerals resistant to alteration and weathering, such as zircon (*e.g.*, Hoskin & Ireland, 2000; Belousova *et al.*, 2002; Fedo *et al.*, 2003; Andersen, 2005). Zircon preserves both isotopic signatures and internal textures characteristic of growth in igneous or metamorphic rocks (Corfu *et al.*, 2003), so that sub-grain zircon geochronology usually enables us to link sediments with recognised and dated crustal sources.

The Western Outer Carpathians (WOC) flysch of Poland includes clasts of crystalline and sedimentary rocks that provide links to source areas which supplied Carpathian basins with sediments (*e.g.*, Wieser, 1949, 1985; Książkiewicz, 1965; Oszczypko, 1975; Sikora, 1976). Igneous and metamorphic events recorded in clasts of crystalline rocks have been temporally constrained using K-Ar dating of micas (Poprawa *et al.*, 2004, 2005), LA-ICP-MS U-Pb dating of zircon (Michalik *et al.*, 2006), and total Th-U-Pb dating of monazite (*e.g.*, Poprawa *et al.*, 2004, 2005; Budzyń *et al.*, 2008). This study presents extension of geochronological constraints on the provenance of the WOC flysch. Zircon U-Pb dating by sensitive high resolution ion microprobe (SHRIMP) of three crystalline clasts from sediments derived from the Silesian Ridge and the northern source reveals new information about the relationships between these two provenances.

GEOLOGICAL BACKGROUND

The 1,300 km long Carpathian mountain chain stretches from the Vienna Forest in Austria to the Iron Gate on the

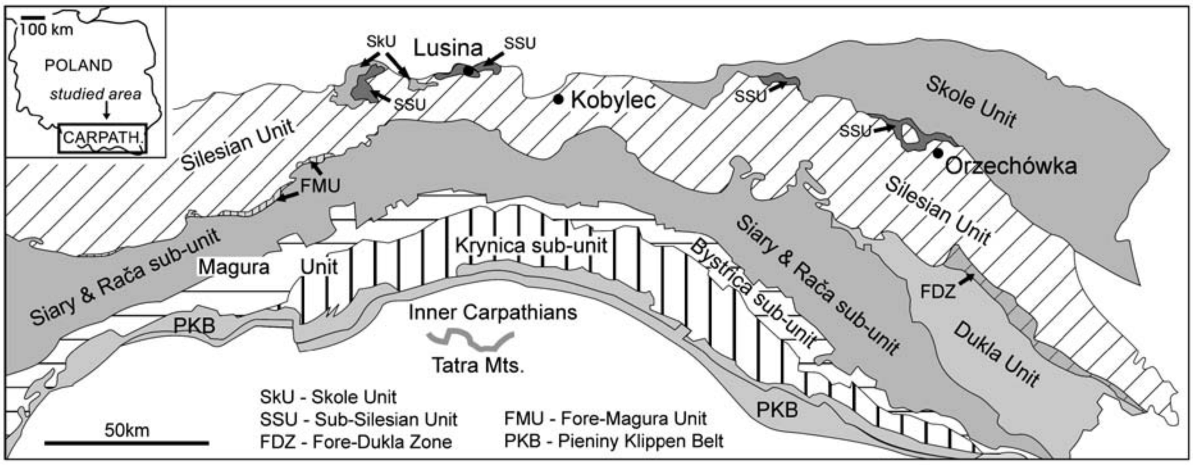

Fig. 1. Sketch of the Polish part of the Western Carpathians (modified from Żytko *et al.*, 1989) with sampling locations

Danube in Romania. In Poland (Fig. 1), it comprises the Inner (south) and Outer (north) Carpathians, separated by the Pieniny Klippen Belt (*e.g.*, Oszczypko 2004, 2006, and references therein). The WOC comprise folded and up-thrust flysch rocks deposited between the Late Jurassic and the Neogene, and currently exposed in several tectonic units representing sedimentary basins identified from lithostratigraphic sequences. These include, from the south to the north, the Magura, Silesian, and Skole Basins (*e.g.*, Książkiewicz, 1972, 1977). Clasts of crystalline and sedimentary rocks were supplied to Carpathian sedimentary basins from internal sources (ridges) separating subbasins (*e.g.*, Wieser, 1949; Książkiewicz, 1965; Unrug, 1968; Sikora, 1976; Wieser, 1985; Wójcik-Tabol & Ślączka, 2009 and references therein), and from the external source, the northern margin related to the Małopolska Terrane and/or Brno–Upper Silesia Terrane (Kotas, 1982, 1995) alias Brunovistulicum (*e.g.*, Pharaoh, 1999; Winchester, 2002). Internal detrital sources include the Silesian Ridge and the Magura Ridge that were uplifted, eroded, covered by upthrust rocks and, consequently, are not exposed in the modern land-surface (*e.g.*, Książkiewicz, 1931; Wieser, 1949, 1985). Therefore, investigation of clastic material provides insights into the reconstruction of the evolution of the basement of source areas.

The Silesian Ridge is interpreted as a thick-skinned fold-and-thrust belt rapidly elevated and eroded during the Late Cretaceous and Palaeocene syn-collisional compression, which proximally supplied the Carpathian sedimentary basins with clastic material (Poprawa & Malata, 2006). The wide spectrum of Neoarchaic to Mesoproterozoic (2740–1250 Ma) and Neoproterozoic to Early Cambrian (570–530 Ma) U-Pb ages of igneous zircons from gneiss clasts from Gródek at the Rożnów Lake were obtained using LA-ICP-MS (Michalik *et al.*, 2006). The monazite total Th-U-Pb age of 592±11 Ma from the same gneiss clasts population was also interpreted as related to the igneous protolith (Budzyń *et al.*, 2008). Monazite in a similar gneiss clast from the same flysch horizon in Krzesławice yielded a total Th-U-Pb igneous age of 628±6 Ma (Budzyń *et al.*, 2006). Monazite ages of *ca.* 420–390 Ma were interpreted as related to the protolith of the gneiss from Blizne (Poprawa *et al.*, 2005). Timing of metamorphism is constrained to *ca.* 340–330 Ma by total Th-U-Pb monazite chronology (Poprawa *et al.*, 2005; Budzyń *et al.*, 2008), while K-Ar dating of micas indicates *ca*. 330–250 Ma ages (Poprawa *et al.*, 2005) probably related to the cooling during initial uplift. Moreover, Hanžl *et al.* (2000) documented *ca.* 320–300 Ma monazite ages for granitic clasts from the Moravian part of the Carpathian flysch belt.

The geochronological data concerning the northern source are more limited compared to those from the Silesian Ridge. The K-Ar dating of muscovite and biotite from several clasts of metamorphic and magmatic rocks yielded *ca.* 550–500 Ma cooling ages interpreted as postdating metamorphism or magmatism in the crystalline basement of the northern source (Ślączka, 1998; Poprawa *et al.*, 2004, 2005). The monazite total Th-U-Pb geochronology from three clasts indicates individual grain ages in a broad range of *ca.* 600–520 Ma, with subordinate younger ages (*ca.* 500–300 Ma) interpreted as related to diagenetic overprints (Poprawa *et al.*, 2005). The northern source terrain has been considered as an uplifted massif at the southern margin of the European Platform and related to the Małopolska and Brunovistulian terranes, which are recognised north of the Outer Carpathians and beneath the Carpathian accretionary prism (*e.g.*, Oszczypko 2006; Poprawa & Malata, 2006).

ANALYTICAL METHODS

Observation and identification of minerals in polished thin sections was performed using an optical microscope and a HITACHI S-4700 field-emission scanning electron microscope, equipped with a NORAN Vantage energy dispersive spectrometer. Additionally, identification and quantification of minerals in the samples was performed using X-ray diffractometry (XRD). The samples for XRD analysis were prepared according to the procedure given by Środoń *et al.* (2001). The XRD patterns were recorded using Philips X'Pert diffractometer with vertical goniometer (PW3020) from 2° to 65° 2Θ. Quantitative Rietveld XRD analyses were performed using AUTOQUAN/BGMN (GE Inspection Technologies) program. Samples of igneous rocks were classified according to IUGS classification of

Table 1

Modal mineral composition calculated using quantitative XRD analysis

Quartz syenite from Kobylec sample KB2		
	%	[±]
Plagioclase Albite	47.54	6.24
Plagioclase Oligoclase An16	17.70	4.80
Microcline	12.02	1.92
Quartz	7.63	0.51
Chlorite IIb	7.28	0.84
Muscovite 2M1	3.48	0.63
Plagioclase Andesine An50	2.41	1.32
Anatase	0.79	0.17
other minerals	1.10	2.28
Total	99.95	

Granite from Orzechówka sample O1		
	%	[±]
Quartz	25.17	1.11
Plagioclase Albite	17.57	5.88
Plagioclase Oligoclase An16	15.10	4.20
Plagioclase Oligoclase An25	12.60	3.90
Microcline	12.25	4.92
Muscovite 1M	4.49	1.71
Chlorite IIb	3.09	1.41
Sanidine	2.74	1.83
Muscovite 2M1	2.27	1.38
Plagioclase Andesine An50	1.21	1.23
Pyrite	0.84	0.26
Calcite	0.54	0.33
other minerals	1.90	3.90
Total	99.77	

Gneiss from Lusina sample LS3		
	%	[±]
Quartz	40.37	0.93
Plagioclase Oligoclase An25	21.50	2.04
Plagioclase Albite	11.32	2.61
Biotite 1M	6.79	0.72
Microcline	5.83	0.63
Muscovite 2M1	5.71	0.66
Muscovite 1M	2.40	0.66
Chlorite IIb	2.21	0.60
Calcite	0.81	0.14
other minerals	2.94	2.28
Total	99.88	

felsic, phaneritic igneous rocks containing >10% of (quartz + feldspar + feldspathoids) using the results of quantitative XRD analyses (Table 1).

The rock samples for U-Pb dating were crushed, sieved, and rinsed in the water to obtain schlich followed by hand picking of zircons under a binocular microscope. Zircon grains were mounted in epoxy along with reference zircon FC1 (1099 Ma; Paces & Miller, 1993), polished to expose the grain centres, cleaned to eliminate surface contamination by common lead, and coated with 100 Å of high-purity gold. Grains were imaged by cathodoluminescence (CL) and electron backscattering (BSE) with a JEOL JSM– 5900 LV scanning electron microscope equipped with a Gatan MiniCL detector, at the National Institute of Polar Research (NIPR), Tokyo. Spots were analysed by SHRIMP-II at NIPR, using a primary O_2^- ion beam with a current of 6nA on the sample surface to produce a 30 µm long, flat-floored oval pit. Secondary ionisation was measured on a single electron multiplier on mass stations 196 (Zr_2O) through to 254 (UO), with a mass resolution of >5000 for $^{238}U^{16}O$ and a sensitivity on ^{206}Pb of 18cps per ppm per nA of primary current. Mass stations were measured through 7 cycles, including count times of 10s per cycle for ^{204}Pb, background (at 204.04 amu) and ^{206}Pb, and 20s for ^{207}Pb. Reduction of raw data for standards and samples was performed using the SQUID v.1.12a (Ludwig, 2001), and Isoplot v.3.6 (Ludwig, 2003) add-ins for Microsoft Excel 2003. Abundance of U was calibrated against zircon standard SL13 (238 ppm), provided by the Australian National University. U-Th-Pb isotopic ratios were calibrated against 16 measurements of FC1. Corrections for common Pb on U/Pb values and ages were done with common Pb estimated from ^{204}Pb counts and the Stacey and Kramers' (1975) common Pb model for the approximate U-Pb age for each analysis. However, it was found that in all samples the imprecision of ^{204}Pb measurements increased scatter in age estimates. Accordingly, data are also presented and plotted on Tera-Wasserburg concordia diagrams that were obtained using the ^{208}Pb correction method, which assumes concordance between $^{206}Pb/^{238}U$ and $^{208}Pb/^{232}Th$ ages. Spot-to-spot errors on the standard were added in quadrature to errors on pooled concordia ages, which take into account both equivalence of data and discordance of mean $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ages (Ludwig, 2003). Individual ratios and ages are quoted and plotted at one sigma, whereas pooled concordia ages are quoted at 95% confidence.

RESULTS

Sample description

Three samples of crystalline rocks collected from the Carpathian flysch were selected for U-Pb zircon dating. The quartz syenite cobble from Kobylec (KB2) and the granite cobble from Orzechówka (O1) (Fig. 1) were collected from conglomerates occurring within the Upper Istebna beds of Palaeocene age (*cf.* Unrug, 1963), representing the Silesian tectonic unit (Fig. 2). The samples are considered to have been derived from the Silesian Ridge (Fig. 3). The gneiss cobble from Lusina (LS3) was collected from the Lhota beds of Albian age. The palaeotransport directions indicate that the source area for this sample most probably was located on the northern margin of the Western Outer Carpathian sedimentary basin (Fig. 3).

Sample KB2 from Kobylec is a fine- to medium-grained quartz syenite, containing albite ($Ab_{96-98}An_{<1}Kfs_{<3}$), microcline, quartz, biotite and muscovite (Table 1). Albite grains are up to 4 mm across and commonly sericitized. Some grains are deformed, with cracks filled with calcite and K-feldspar. Microcline occurs as subhedral to anhedral crystals, <6 mm across, with subhedral inclusions of albite. Biotite is strongly altered, and most of the flakes are completely replaced by chlorite with inclusions of anatase. Muscovite is intergrown with chlorite. The accessory minerals include ap-

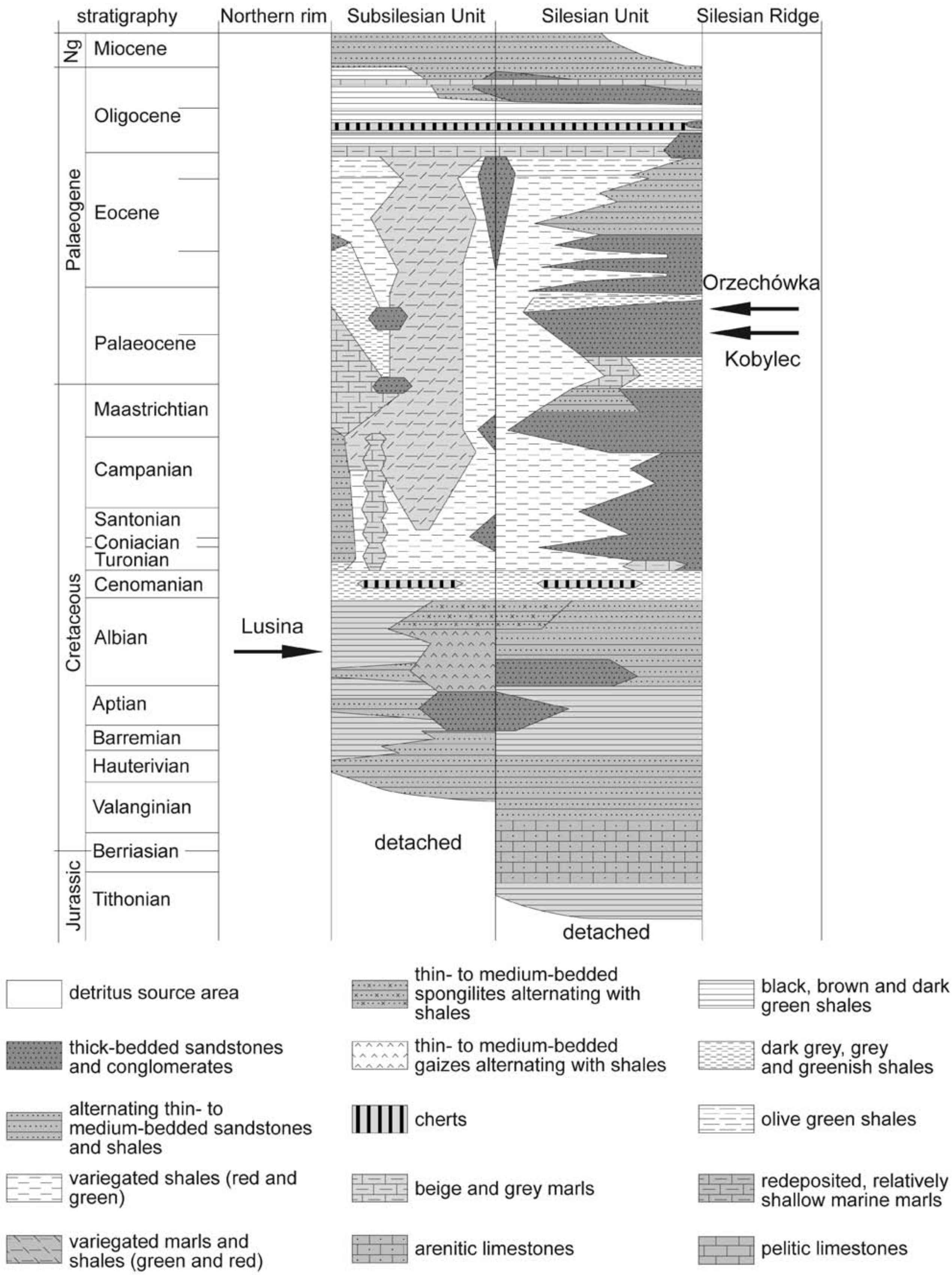

Fig. 2. Lithostratigraphic scheme of the Silesian and Subsilesian basin sedimentary fill with position of provenance areas (simplified from Koszarski, 1985; Leszczyński & Malik, 1996, Poprawa & Malata, 2006) and stratigraphic position of analysed cobbles. Figure not to scale

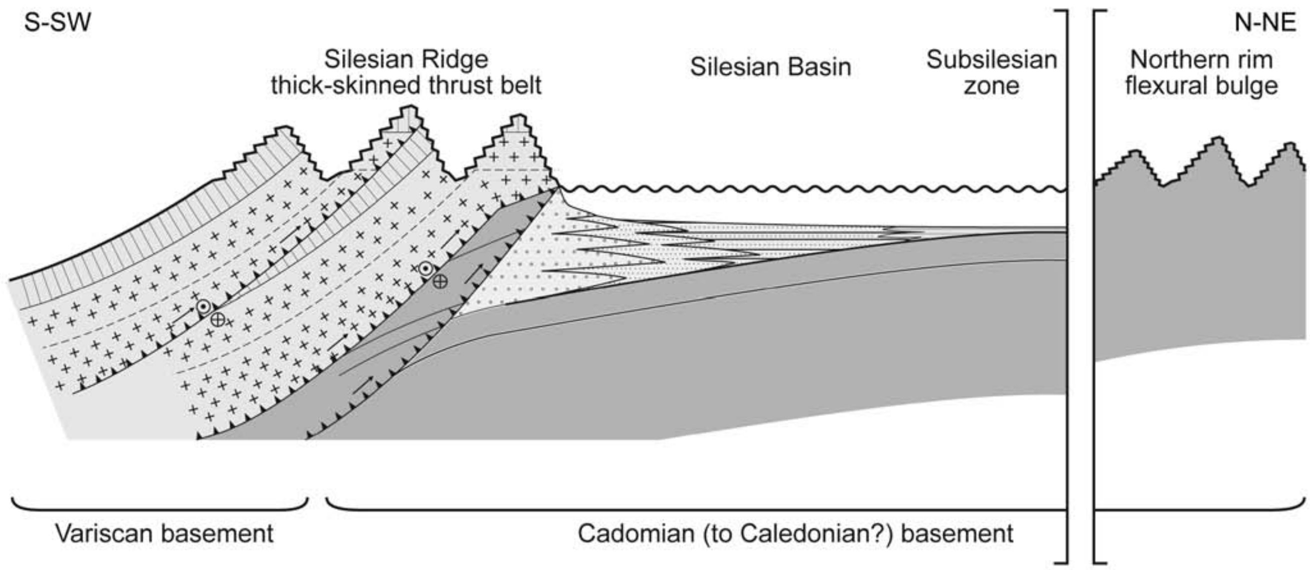

Fig. 3. Cartoon illustrating relation of the Western Outer Carpathian source areas to sedimentary basins and basement domains (modified from Poprawa & Malata, 2006). Figure not to scale

atite, zircon, anatase and not identified iron oxides. Apatite occurs as subhedral elongated grains, up to 120 µm long; larger are commonly cracked, and smaller grains are mostly enclosed in chlorite.

The granite from Orzechówka (sample O1) is medium grained with main mineral assemblage of quartz, plagioclase ($Ab_{76–82}An_{16–22}Kfs_{1–2}$), K-feldspar and biotite. The subhedral plagioclase (<7 mm across) shows well developed concentric oscillatory zoning with some zones sericitized. Some plagioclase grains form inclusions in the K-feldspar. Biotite flakes, up to 4 mm in size, are commonly chloritized and contain pyrite inclusions intercalating along the cleavage. The accessory minerals include apatite, and zircon. Apatite forms subhedral grains up to *ca.* 20×100 µm.

The gneiss from Lusina (sample LS3) is mostly composed of fine-grained quartz, plagioclase ($Ab_{63–77}An_{22–37}Kfs_{<1}$), biotite, and muscovite. Plagioclase (< 800 µm across) forms polygonal aggregates with quartz (< 700 µm across), and commonly is sericitized. Some biotite flakes are chloritized. Quartz ribbons and discrete flakes or aggregates of biotite (< 900 µm in length) define the foliation. None of the minerals forms porphyroclasts or porphyroblasts. Accessory minerals include galena, sphalerite and pyrite, the latter occurring as anhedral grains, up to 60 µm across. Grains of sphalerite, up to 100 µm across, contain rare 6 µm wide inclusions of galena. There is no specific evidence to determine the protolith of the gneiss. However, for the purpose of age interpretation, zircon is assumed to be igneous due to their internal textures reflecting oscillatory zoning (Fig. 4e, f; *vide* Corfu *et al.*, 2003).

Zircon U-Pb geochronology

Zircon in the quartz syenite from Kobylec (sample KB2) occurs as euhedral grains. Strong oscillatory zoning with distinctive small cores are visible in CL images (Fig. 4a, b). A total of 11 spots on 9 zircon grains were analysed, with U and Th contents of 68–252 ppm and 41–133 ppm, respectively (Table 2). Multiple spots on grains no. 3 and 6 have no significant variation in age. Excluding younger analysis no. 10.1, which may have lost Pb through alteration or weathering, ten ^{208}Pb-corrected data define a concordia age of 603.8±6.0 Ma (MSWD of equivalence = 1.2, probability of concordance = 0.23; Fig. 5). The age is interpreted as the time of crystallization of the quartz syenite.

Zircon grains in the granite from Orzechówka (sample O1) are euhedral to subhedral and show fine oscillatory zoning typical of igneous growth (Fig. 4c, d). Twelve analytical spots in 8 zircon grains were analysed, with U contents between 125 and 237 ppm, and Th contents of 47–124 ppm (Table 2). Together, all ^{208}Pb-corrected data define a concordia age of 598.6±5.7 Ma (MSWD of equivalence = 0.86, probability of concordance = 0.16; Fig. 5). The age is interpreted as that of granite crystallization.

The gneiss from Lusina (sample LS3) contains euhedral zircon grains exhibiting either sector (Fig. 4e) or oscillatory (Fig. 4f) zoning. A total of 14 spots were analysed on 12 grains. There are no significant differences in age or composition between sector and oscillatory-zoned zircon spots, which have U and Th contents of 68–252 ppm and 32–113 ppm, respectively (Table 2). Two analyses yielded younger age estimates, but also have elevated common Pb, and thus probably represent contaminated and/or altered zircon. The remaining 12 data from 10 grains define a concordia age of 609.7±6.3 Ma (MSWD of equivalence = 1.0, probability of concordance = 0.45; Fig. 5). From the consistency of ages and compositions between sector and oscillatory-zoned zircon, the concordia age is interpreted as that of the magmatic crystallization of the granitic protolith to the gneiss.

DISCUSSION AND CONCLUSIONS

The previous knowledge of the geological setting of the unexposed Silesian Ridge relied on geochronological data from sedimentary cover, including limited data from clasts

Isotopic data for zircon grains in quartz syenite clast from Kobylec (sample KB2)

Spot	% $^{206}Pb_c$	ppm U	ppm Th	$^{232}Th/^{238}U$	ppm $^{206}Pb^*$	(1) $^{206}Pb/^{238}U$ Age	1se	(2) $^{206}Pb/^{238}U$ Age	1se	(3) $^{206}Pb/^{238}U$ Age	1se	(1) $^{207}Pb/^{206}Pb$ Age	1se	(3) $^{207}Pb/^{206}Pb$ Age	1se	(1) $^{208}Pb/^{232}Th$ Age	1se
Quartz syenite KB2																	
1.1	-	162	65	0.41	13.2	585.7	7.0	586.7	7.2	587.5	7.5	532	34	630	47	556	12
2.1	-	207	91	0.45	17.6	608.9	7.2	608.9	7.3	610.0	7.7	608	26	665	45	592	10
3.1	-	191	87	0.47	16.0	597.7	7.1	597.8	7.2	599.2	7.6	593	32	668	49	577	11
3.2	-	170	82	0.50	14.1	592.1	7.1	592.2	7.3	594.9	7.7	587	46	726	55	555	11
4.1	0.17	182	133	0.75	15.5	611.5	7.3	612.0	7.5	610.5	8.3	587	24	534	82	620	9.4
6.1	-	95	41	0.45	7.85	591.7	8.9	590.8	7.8	591.7	8.2	638	237	640	59	591	74
6.2	-	165	74	0.46	14.1	610.7	7.4	610.3	7.5	610.3	7.9	630	28	613	51	616	11
7.1	0.30	231	130	0.58	19.8	614.0	7.2	613.1	7.4	612.2	7.9	657	22	566	64	634	10
8.1	0.01	197	84	0.44	16.6	603.5	7.2	603.2	7.3	602.9	7.7	614	27	585	48	612	11
9.1	0.20	127	57	0.46	10.8	612.6	7.8	612.0	7.8	610.9	8.1	641	101	551	59	638	33
10.1	-	111	50	0.47	8.79	569.7	7.3	569.9	7.5	570.4	7.9	557	39	597	61	559	12
Granite O1																	
1.1	-	221	98	0.46	18.5	599.5	7.2	598.6	7.3	599.1	7.7	646	36	624	49	606	13
2.1	-	237	102	0.44	20.0	603.2	7.2	603.7	7.4	603.8	7.7	578	24	609	54	594	10
3.1	-	236	124	0.55	19.2	584.5	7.0	584.4	7.2	584.8	7.7	590	27	608	63	580	11
4.1	-	167	63	0.39	13.8	594.4	8.0	593.0	8.2	593.3	8.5	665	42	612	50	612	17
5.1	0.04	210	73	0.36	17.4	595.8	7.2	596.2	7.3	596.0	7.6	573	28	586	43	591	11
5.2	0.18	143	59	0.43	11.8	593.3	7.7	593.7	7.8	592.8	8.2	573	39	544	62	602	13
5.3	0.01	180	95	0.55	15.3	606.9	9.9	607.5	10.1	607.1	10.7	575	32	587	77	604	13
6.1	-	230	73	0.33	19.6	609.4	7.2	608.9	7.4	609.4	7.6	632	29	636	38	608	13
6.2	0.02	160	47	0.31	13.7	612.4	9.9	611.6	7.7	611.8	7.9	651	314	618	42	627	151
7.1	0.00	183	106	0.60	15.3	598.8	7.3	597.9	7.5	599.1	8.0	643	28	660	62	595	10
7.2	0.01	125	75	0.62	10.3	589.8	7.6	588.5	7.7	589.2	8.3	651	61	622	75	596	16
8.1	-	212	80	0.39	17.3	586.3	7.2	584.0	7.3	585.9	7.6	703	37	684	45	593	14
Gneiss LS3																	
1.1	0.09	144	99	0.71	12.4	613.6	7.8	612.5	7.8	611.8	8.6	669	71	576	78	630	17
2.1	-	89	56	0.64	7.91	628.6	10.7	631.8	10.9	631.6	11.8	467	75	621	105	598	21
2.2	-	103	59	0.59	8.72	606.8	9.9	607.1	10.1	607.2	10.8	591	35	612	82	602	13
3.1	-	68	43	0.66	5.81	611.0	8.4	612.2	8.6	614.0	9.4	553	62	700	97	582	18
4.1	-	104	82	0.81	8.89	607.9	7.9	610.3	8.0	611.9	9.0	486	71	691	88	577	14
5.1	-	89	58	0.67	7.72	620.5	8.1	620.7	8.3	621.6	9.0	609	41	661	79	610	12
6.1	-	103	51	0.51	8.68	603.3	7.9	602.1	8.0	602.9	8.5	659	51	640	65	608	16
6.2	0.38	120	71	0.61	10.6	627.0	11.7	628.6	12.0	626.1	12.9	548	58	503	107	636	18
7.1	0.11	108	32	0.31	8.91	590.9	8.8	588.7	7.9	589.5	8.1	700	208	632	52	621	99
8.1	2.59	134	68	0.52	11.0	576.8	7.4	577.6	7.4	575.4	8.1	538	100	459	111	594	27
9.1	0.26	115	113	1.01	9.8	606.3	7.7	608.7	7.9	606.7	9.2	480	59	500	124	604	12
10.1	0.05	252	98	0.40	21.6	613.9	7.2	612.5	7.4	612.6	7.7	678	29	616	43	635	12
11.1	2.31	157	90	0.59	12.9	578.5	8.0	576.8	7.7	575.0	8.9	668	214	479	267	616	55
12.1	-	176	79	0.46	14.6	595.1	7.4	593.3	7.5	594.5	7.9	681	33	654	55	603	14

Errors are 1-sigma (1se); Pb_c and Pb* indicate the common and radiogenic portions, respectively.
Error in Standard calibration was 0.32% (not included in above errors but required when comparing data from different mounts).
(1) Common Pb estimated and corrected for using measured ^{204}Pb.
(2) Common Pb estimated and corrected for by assuming $^{206}Pb/^{238}U$-$^{207}Pb/^{235}U$ age-concordance
(3) Common Pb estimated and corrected for by assuming $^{206}Pb/^{238}U$-$^{208}Pb/^{232}Th$ age-concordance

of crystalline rocks (Poprawa *et al.*, 2005). The monazite and mica geochronology indicates three main age patterns recorded in clasts of granitoids, gneisses and granulites. The Cadomian monazite dates were interpreted as related to the magmatism (Michalik *et al.*, 2006; Budzyń *et al.*, 2008), while younger dates represented a magmatic and/or metamorphic event at *ca.* 380 Ma, followed by Variscan metamorphic overprint at *ca.* 330 Ma (Poprawa *et al.*, 2004, 2005; Budzyń *et al.*, 2008). The quartz syenite and granite samples selected in this study are not affected by metamorphism, except some signs of hydrothermal alterations interpreted as related to post-magmatic processes. It was expected, therefore, to obtain Variscan zircon ages. However, the U-Pb dating yielded only Cadomian ages (599±6 Ma and 604±6 Ma), which are within error of a previously reported monazite total Th-U-Pb age for the igneous protolith of gneiss clast (592±11 Ma; Budzyń *et al.*, 2008). The previous ages obtained from U-Pb dating of zircon in gneiss clasts with igneous protoliths range from *ca.* 2740 Ma to 1250, along with younger ages concentrated at 570–520 Ma (LA-ICP-MS; Michalik *et al.*, 2006). In contrast, there are no data in our study indicating the Archaic or Mesoprotero-

Table 2

granite clast from Orzechówka (sample O1) and gneiss clast from Lusina (sample LS3)

(1) % Discor-dant	(3) %Discor-dant	Total $^{238}U/^{206}Pb$	±%	Total $^{207}Pb/^{206}Pb$	±%	(1) $^{238}U/^{206}Pb^*$	±%	(1) $^{207}Pb^*/^{206}Pb^*$	±%	(3) $^{238}U/^{206}Pb^*$	±%	(3) $^{207}Pb^*/^{206}Pb^*$	±%
Quartz syenite KB2													
-9	7	10.49	1.3	0.06000	1.2	10.51	1.3	0.05805	1.6	10.48	1.3	0.0607	2.2
0	9	10.09	1.2	0.06063	1.0	10.10	1.2	0.06011	1.2	10.08	1.3	0.0617	2.1
-1	11	10.27	1.2	0.06115	1.2	10.29	1.2	0.05972	1.5	10.27	1.3	0.0618	2.3
-1	22	10.37	1.3	0.06170	1.7	10.39	1.3	0.05950	2.1	10.34	1.4	0.0635	2.6
-4	-12	10.05	1.3	0.05951	1.1	10.05	1.3	0.05955	1.1	10.07	1.4	0.0581	3.7
8	8	10.42	1.3	0.05985	1.6	10.40	1.6	0.06100	11.0	10.40	1.4	0.0610	2.7
3	0	10.07	1.3	0.05999	1.2	10.06	1.3	0.06075	1.3	10.07	1.4	0.0603	2.4
7	-8	10.01	1.2	0.06143	1.0	10.01	1.2	0.06151	1.0	10.04	1.4	0.0590	3.0
2	-3	10.20	1.2	0.05958	1.1	10.19	1.2	0.06030	1.2	10.20	1.3	0.0595	2.2
5	-10	10.04	1.3	0.06026	1.4	10.03	1.3	0.06100	4.7	10.06	1.4	0.0586	2.7
-2	5	10.81	1.3	0.05957	1.5	10.82	1.3	0.05870	1.8	10.81	1.4	0.0598	2.8
Granite O1													
8	4	10.27	1.3	0.06021	1.1	10.26	1.3	0.06120	1.7	10.27	1.3	0.0606	2.3
-4	1	10.20	1.3	0.05926	1.1	10.19	1.3	0.05929	1.1	10.18	1.3	0.0601	2.5
1	4	10.53	1.3	0.06008	1.2	10.54	1.3	0.05962	1.3	10.53	1.4	0.0601	2.9
12	3	10.38	1.4	0.05989	1.3	10.35	1.4	0.06170	1.9	10.37	1.5	0.0602	2.3
-4	-2	10.32	1.3	0.05981	1.2	10.33	1.3	0.05917	1.3	10.32	1.3	0.0595	2.0
-3	-8	10.36	1.4	0.05990	1.6	10.37	1.4	0.05920	1.8	10.38	1.4	0.0584	2.8
-5	-3	10.13	1.7	0.05961	1.4	10.13	1.7	0.05923	1.5	10.13	1.9	0.0595	3.5
4	4	10.09	1.2	0.06058	1.1	10.09	1.2	0.06080	1.4	10.09	1.3	0.0609	1.7
6	1	10.04	1.3	0.06059	1.3	10.03	1.7	0.06130	15.0	10.05	1.3	0.0604	2.0
7	10	10.27	1.3	0.06163	1.2	10.27	1.3	0.06112	1.3	10.27	1.4	0.0616	2.9
10	6	10.45	1.3	0.06061	1.5	10.44	1.4	0.06130	2.8	10.45	1.5	0.0605	3.5
20	17	10.52	1.3	0.06158	1.2	10.50	1.3	0.06280	1.7	10.51	1.4	0.0623	2.1
Gneiss LS3													
9	-6	10.04	1.3	0.06001	1.3	10.01	1.3	0.06180	3.3	10.04	1.5	0.0593	3.6
-26	-2	9.72	1.8	0.06034	1.6	9.76	1.8	0.05640	3.4	9.71	2.0	0.0605	4.9
-3	1	10.13	1.7	0.05977	1.6	10.13	1.7	0.05964	1.6	10.12	1.9	0.0602	3.8
-9	14	10.03	1.4	0.06120	1.9	10.06	1.4	0.05860	2.8	10.01	1.6	0.0628	4.5
-20	13	10.07	1.3	0.06058	1.6	10.11	1.4	0.05680	3.2	10.04	1.5	0.0625	4.1
-2	6	9.89	1.4	0.06070	1.7	9.90	1.4	0.06010	1.9	9.88	1.5	0.0616	3.7
9	6	10.20	1.4	0.06090	1.6	10.19	1.4	0.06160	2.4	10.20	1.5	0.0610	3.0
-13	-20	9.77	2.0	0.06040	1.7	9.79	2.0	0.05850	2.7	9.80	2.2	0.0573	4.9
19	7	10.43	1.4	0.06170	1.6	10.42	1.6	0.06280	9.8	10.44	1.4	0.0608	2.4
-7	-20	10.43	1.3	0.07740	1.5	10.68	1.3	0.05820	4.6	10.71	1.5	0.0562	5.0
-21	-18	10.11	1.3	0.05937	1.5	10.14	1.3	0.05670	2.7	10.13	1.6	0.0572	5.6
10	1	10.03	1.2	0.06075	1.0	10.01	1.2	0.06210	1.3	10.03	1.3	0.0603	2.0
15	-17	10.47	1.3	0.07550	4.6	10.65	1.4	0.06180	10.0	10.72	1.6	0.0567	12.0
14	10	10.36	1.3	0.06078	1.2	10.34	1.3	0.06219	1.6	10.35	1.4	0.0614	2.6

zoic events recorded by zircon. The new ages for clasts reveal that the Silesian Ridge included Cadomian granites not affected by later significant deformation or thermal events, as well as granites metamorphosed into gneisses during the Variscan orogeny (*cf.* Michalik *et al.*, 2006; Budzyń *et al.*, 2008).

The previous data on the northern source included total Th-U-Pb dating of monazite in a granite clast from Lusina that yielded various apparent (single analysis) dates of *ca.* 300 Ma, 360 Ma, 520–550 Ma, and 640 Ma (Poprawa *et al.*, 2005). These are difficult to compare with our zircon results. Although these dates are geologically meaningful, several factors can be considered as a cause of such scattered results, including methodological errors (*cf.* Jercinovic & Williams, 2005) or the effect of fluids (*cf.* Harlov & Hetherington, 2010; Budzyń *et al.*, 2011; Williams *et al.*, 2011). Furthermore, a 530±20 Ma K-Ar muscovite age for a granite clast from the same locality (Poprawa *et al.*, 2004) suggests that significant metamorphism probably did not occur after this time, assuming that both granitic clasts were derived from the same source. Currently, comparing our results with the previous ones is strongly limited, and continuation of the geochronological works is required to expand and verify previous data, possibly applying several methods, such as Sm-Nd and Lu-Hf dating of garnet, Th-U-Pb monazite dating, U-Pb zircon dating, and Ar-Ar dating of mica.

The Cadomian age (610±6 Ma) of igneous zircon in the gneiss clast from Lusina provides a date for magmatism in the northern source of clastic material supplied to the Carpa-

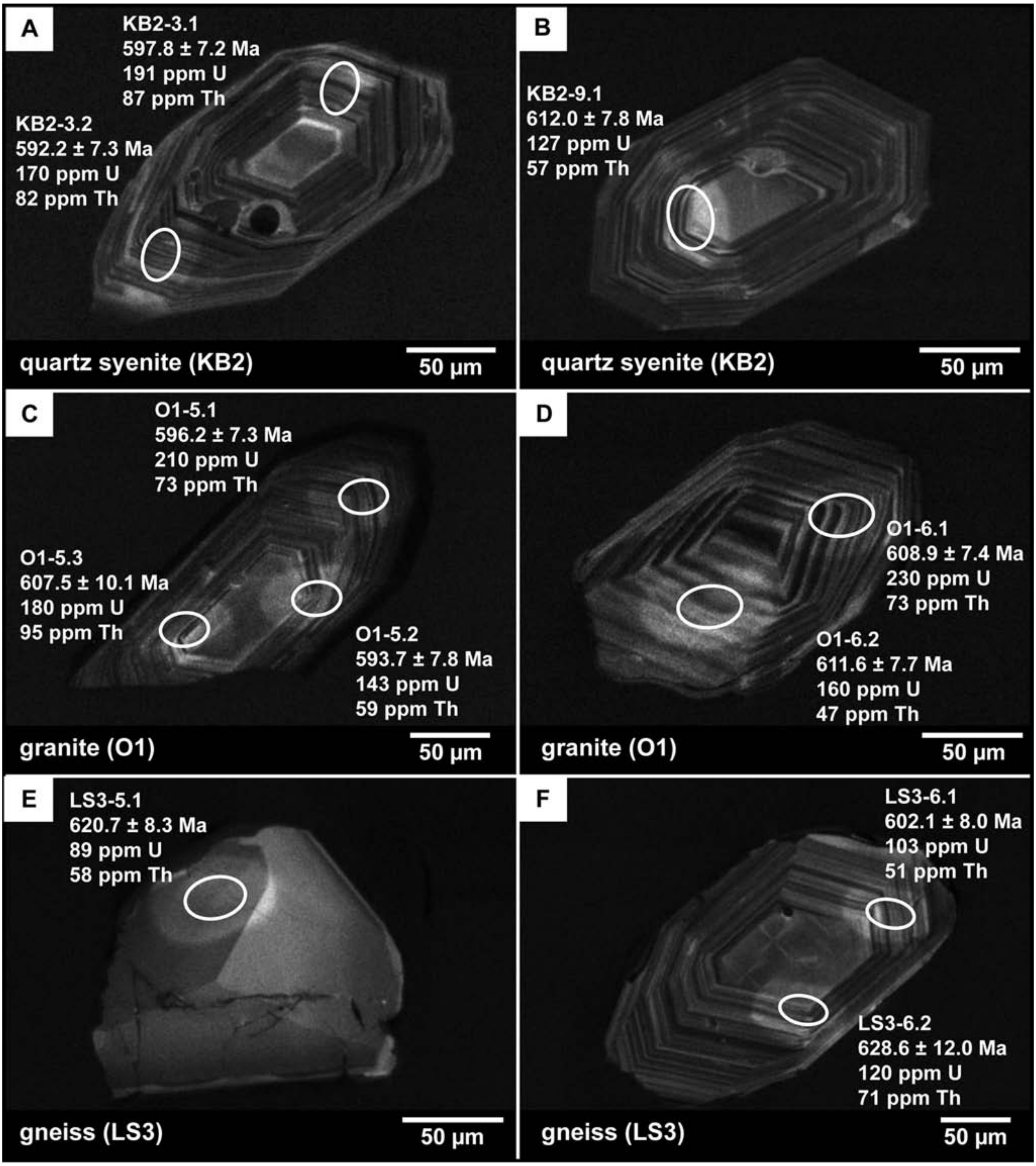

Fig. 4. Cathodoluminescence images of selected analysed zircon grains from (A, B) the quartz syenite clast from Kobylec (sample KB2); (C, D) the granite clast from Orzechówka (sample O1); and (E, F) the gneiss clast from Lusina (sample LS3). Analytical spot labels correspond with the labels in Table 2

thian sedimentary basins. The Cadomian basement is documented in the Brunovistulian and Małopolska terranes in the southern part of the European platform, over which the WOC were thrust (Dudek, 1980; Żelaźniewicz, 1998; Żelaźniewicz *et al.*, 2009; Kalvoda & Bábek, 2010). Zircon ages of Brunovistulian granitoids range from *ca.* 600 to 580 Ma (van Breemen *et al.*, 1982; Friedl *et al.*, 1998), and are equivalent to Ar-Ar ages (van Breemen *et al.*, 1982; Finger *et al.*, 2000a, b). Similarly, *ca.* 600 and 570 Ma SHRIMP zircon ages were recorded in gneisses from the Strzelin Massif in the eastern part of the Fore-Sudetic Block (NE margin of the Bohemian Massif) (Oberc-Dziedzic *et al.*, 2003, 2005; Klimas *et al.*, 2009). Recent chronology of detrital zircon grains in the flysch series from Małopolska terrane yielded 670–570 Ma ages (Żelaźniewicz *et al.*, 2009). Furthermore, gneissic granitoid clasts are known from a Carboniferous olistostrome on the western margin of the Małopolska terrane (Unrug *et al.*, 1999). Consequently, the zircon age from this study is consistent with previous geochronological results reported for the southern part of the European platform regions believed as linked to the northern source supplying Carpathian basins with clastic material.

The tectonic provenance can be concluded by correlation with previous studies discussing Neoproterozoic patterns in the Carpathians and adjacent regions (*e.g.*, Winchester, 2002; Munteanu & Tatu, 2003; Murphy *et al.*, 2004; Carrigan *et al.*, 2006; Rino *et al.*, 2008; Balintoni *et al.*, 2009, 2010, 2011; Meinhold *et al.*, 2009; Kalvoda & Bábek, 2010). The closest relation of our results can be compared to the volcanic arc granitoids of *ca.* 594 Ma age that were a protolith of the gneisses representing the Silesian Ridge (Budzyń *et al.*, 2008, 2010). In the Central-West Carpathian basement, the *ca.* 607 Ma age of zircon from orthogneisses was interpreted as a record of Cadomian fragments from the Gondwana active continental margin (Putiš *et al.*, 2008). To the south, zircon ages of 600–590 Ma related to the extensive granitoid plutonism were reported within the Lainici-Paiuş terrane (South Carpathians, Romania) and interpreted as a record of the active margin of peri-Gondwanan continental fragment (Balintoni *et al.*, 2011). This leads to a conclusion that the presented zircon ages of *ca.* 610–600 Ma provide a record on the emplacement of the granitoids within the Gondwana active margin.

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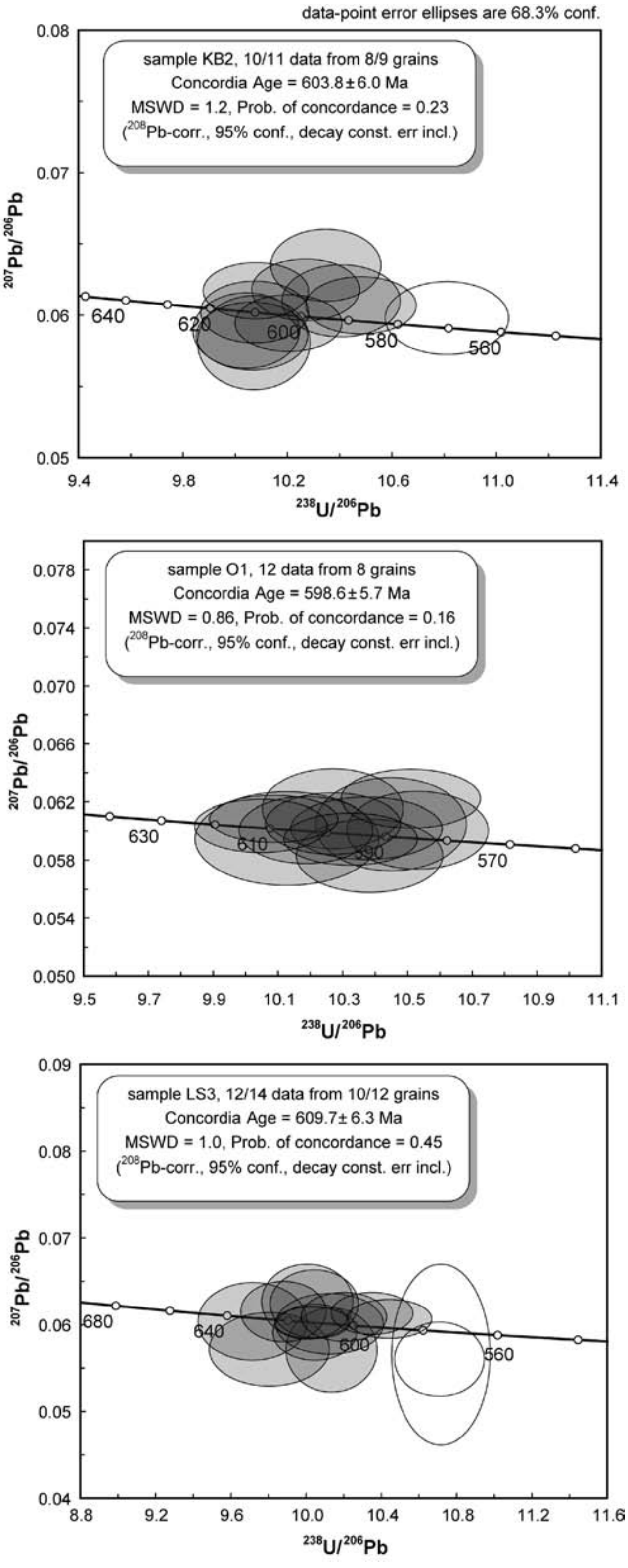

Fig. 5. Tera-Wasserburg concordia diagrams showing ^{208}Pb-corrected SHRIMP data from zircons of the following samples: the quartz syenite clast from Kobylec (sample KB2), the granite clast from Orzechówka (sample O1), and the gneiss clast from Lusina (sample LS3)

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