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Recycling of Paleoproterozoic and Neoproterozoic crust recorded in Lower Paleozoic metasandstones of the Northern Gemericum (Western Carpathians, Slovakia): Evidence from detrital zircons

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Abstract: U–Pb (SHRIMP) detrital zircon ages from the Early Paleozoic meta-sedimentary rocks of the Northern Gemericum Unit (the Smrečinka Formation) were used to characterize their provenance. The aim was to compare and reconcile new analyses with previously published data. The detrital zircon age spectrum demonstrates two prominent populations, the first, Late Neoproterozoic (545–640 Ma) and the second, Paleoproterozoic (1.8–2.1 Ga), with a minor Archean population (2.5–3.4 Ga). The documented zircon ages reflect derivation of the studied metasedimentary rocks from the Cadomian arc, which was located along the West African Craton. The acquired data supports close relations of the Northern Gemericum basement with the Armorican terranes during Neoproterozoic and Ordovician times and also a close palinspastic relation with the other crystalline basements of the Central Western Carpathians. In comparison, the detrital zircons from the Southern Gemericum basement and its Permian envelope indicate derivation from the Pan-African Belt–Saharan Metacraton provenance.

Keywords: SHRIMP dating, detrital zircon ages, provenance, palinspastic constraints.

Introduction

Detrital zircon age dating is a powerful tool in deciphering the sedimentary provenance and tectonic evolution of continental realms, and constraining the paleogeography (e.g., Gehrels et al. 1995, 2000; McLennan et al. 2001; Stewart et al. 2001; Dickinson & Gehrels 2003, 2008; Hervé et al. 2003; Allen et al. 2006; Kolodner et al. 2006; Mueller et al. 2007; Lorenz et al 2008; Balintoni et al. 2010; Drost et al. 2011; Ustaömer et al. 2011; Zajzon et al. 2011; Avigad et al. 2012). In general, the study of clastic sediments is crucial for paleotectonic reconstructions as they can provide information about potential lithologies in ancient source areas. Particularly, the study of detrital zircons is important in terranes with the occurrence of siliciclastic sediments or metasedimentary rocks, lacking any bio-stratigraphic evidence of their age. Furthermore, in the absence of fossils and other stratigraphic data, the youngest zircon grains in a sedimentary rock can indicate the maximum depositional age (e.g., Fedo et al., 2003; Meinhold & Frei, 2008; Spencer et al. 2016).

In this paper, detrital zircon U–Pb ages for the Smrečinka metasandstones are presented, which belong to the basal part of the Rakovec Group and, which have been assigned to the pre-Carboniferous basement complexes of the Northern Gemeric Unit (NGU) (Fig. 1). From a tectonic point of view, the NGU represents the relic of the Variscan collision suture, consisting of two distinct crystalline complexes and the remnants of the Mississippian syn-orogenic basin-fill. Understanding the age and origin of the Smrečinka sedimentary sequence may give innovative approaches to test a current plate tectonic model, with implications for understanding the evolution of the Northern Gemericum basement during Paleozoic times.

The new zircon ages are interpreted in conjunctions with one previously published sample from Vozárová et al. (2013). We were able to put together a set of 93 analyses that provided a more solid set of data than the previously published 44 analyses. In both studies an equally sensitive high-resolution ion microprobe (SHRIMP) was applied to determine (Williams 1998; Larionov et al. 2004) the U–Pb ages of detrital zircon grains. The U–Pb detrital zircon ages reported here have significant implications that may inspire further work and discussion of the role of the NGU zone during the Variscan orogeny and for the structure of the Western Carpathians.

Geological background

In the sense of the latest syntheses on the geological structure of the Western Carpathians (Plašienka in Froitzheim et al. 2008; Plašienka 2018), the triple regional tectonic zonation is generally accepted. This division includes the Inner Western

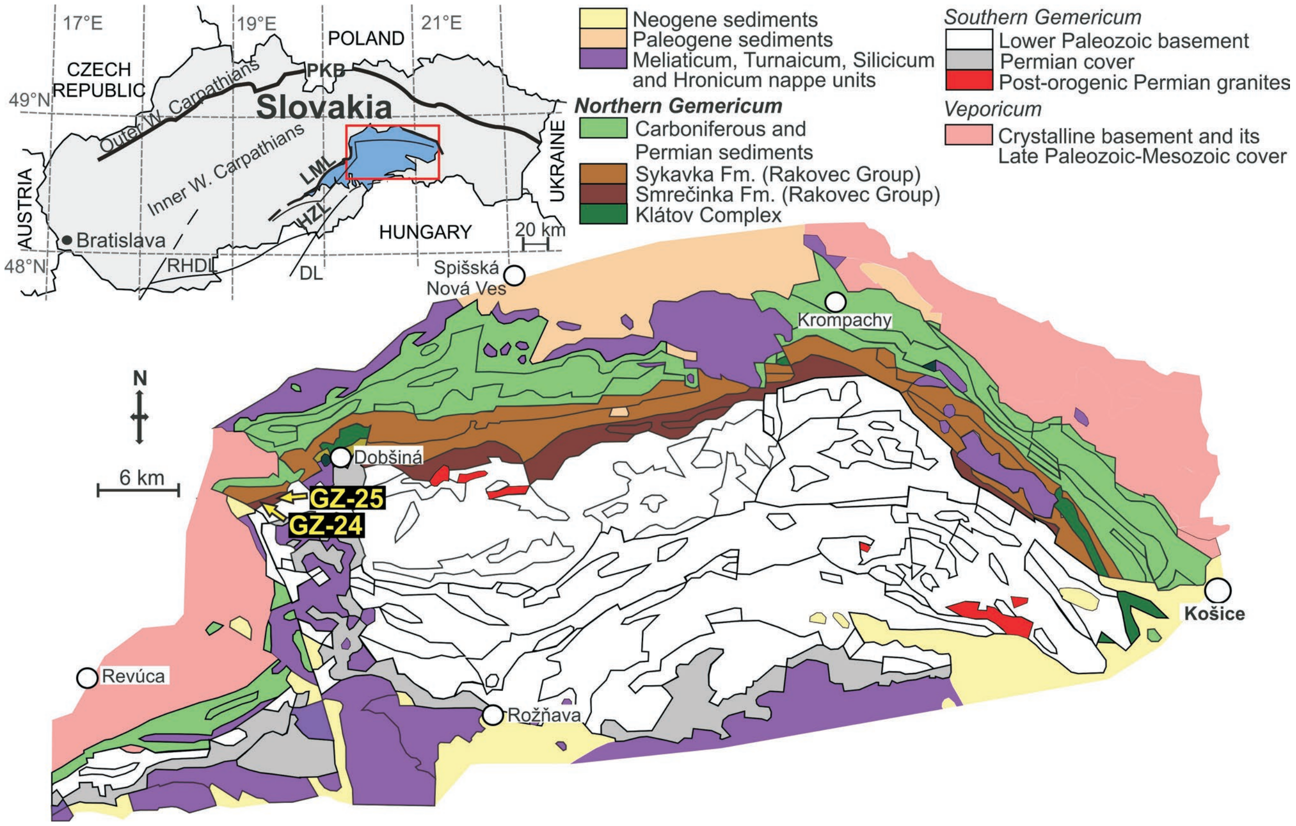


Fig. 1. Geological sketch of the Northern Gemeric Unit (modified according to the Geological map of Slovakia, 1:500,000, after Biely et al. 1996 and the Geological map of the Slovenské Rudohorie Mts. — eastern part, 1:50,000, after Bajaník et al. 1984), showing localities of the studied detrital zircon samples. *Abbreviations:* LML — Lubenik–Margecany Line; HZL — Hrádok–Železník Line.

Carpathians (IWC) in the south, the Central Western Carpathians (CWC) in the middle, and Outer Western Carpathians in the north. Each of these three major regional zones include their own principal tectonic units, which were incorporated into the growing orogenic wedge in particular time periods, spanning in time from late Jurassic/early Cretaceous to early Miocene, generally progressing from south toward north (Plašienka 2018 and references therein).

Fragments of the Variscan crust with their post-Variscan sedimentary cover were incorporated into the early and middle Cretaceous tectonic units of the Central and Inner Western Carpathians orogenic system.

The Northern Gemeric Unit (NGU) belongs to the innermost part of the CWC, and, as a whole, clearly overrides the Veporicum along the Early Alpine thrust contact recognized as the Lubeník–Margecany Line (LML; Andrusov 1959). Similarly, the tectonic contact of the NGU with the adjacent Southern Gemeric Unit (SGU), which belongs to the IWC zone, is represented by the Hrádok–Železník Line (HZL) (defined by Abonyi 1971), that continues into a system of thrust faults to the east (Fig. 1). The NGU is generally correlated with the Upper Austroalpine units, such as the eastern Greywacke Zone in the Eastern Alps (Andrusov 1968; Maheľ 1986; Neubauer & von Raumer 1993; Schmid et al 2008, and references therein).

The NGU contains relics of the Variscan collision suture, from which thrust wedges of two pre-Carboniferous complexes, the high-grade gneissic-amphibolites of the Klátov complex and the low-grade Rakovec complex, are preserved as well as relics of a Mississippian syn-orogenic turbidite sequence (Vozárová & Vozár 1996). Each of these units is lithologically distinct (Bajaník et al. 1983; Spišiak et al. 1985; Hovorka et al. 1988; Vozárová & Vozár 1988; Ivan 1994, 1997, and references therein). The mutual contact of both pre-Carboniferous crystalline basement complexes is tectonic, followed by lenses of antigoritic serpentinites at the base of the thrust plane. Deformational and metamorphic events recorded by both pre-Carboniferous terranes occurred in the Late Devonian/Mississippian but experienced later Alpine reworking (Dallmayer et al. 1996, 2005; Vozárová et al. 2005; Putiš et al. 2009). The Late Devonian/Mississippian deformation and metamorphism are documented by reworked rock fragments from both NGU crystalline complexes within the overstepping Pennsylvanian conglomerates (Vozárová 1973). These events were also proved by geochronological data: (i) 372±3 Ma by Ar/Ar ages of muscovite from orthogneiss pebble and 386±3 Ma of detrital white mica from the overlying Pennsylvanian sandstones (Vozárová et al. 2005); (ii) 386–372 Ma U–Pb ages from metamorphic rims of orthogneiss pebble zircons from Pennsylvanian conglomerates

(Putiš et al. 2008). Correspondingly, the climax of the Variscan orogeny in the NGU is indicated by the 355 Ma peak of the detrital-zircon ages from the post-Tournaisian basin fill (Vozárová et al. 2013).

The Mississippian (Tournaisian–Visean) turbidite wedges, supposedly derived from the Variscan suture, represent the fill of an intrasuture remnant ocean basin. Turbidite deposition was followed by deposition of latest Visean–Serpukhovian shallow-water clastics and carbonates. The Mississippian (Tournaisian–Visean) foredeep and remnant basins have been correlated across the whole Alpine–Carpathian realm (Nötsch–Veitsch–Northgemeric Zone, Neubauer & Vozárová 1990; Veitsch–Nötsch–Szabadbattyan–Ochtiná Zone, Ebner et al. 2008). Although partly syn-orogenic, they also postdate the Late Devonian/Mississippian climax of the Variscan orogeny. Post-Variscan deposition includes Upper Bashkirian–Moscovian fan-delta-shallow-marine to proximal delta and continental Permian sequences (Rakusz 1932; Rozlozsnik 1935; Rozložník 1963; Bajaník et al. 1981, 1983; Vozárová & Vozár 1988, and references therein).

Characteristics of the Rakovec Group

The Rakovec Group sequence, which is characterized by the prevalence of basalts and their pyroclastic rocks, is mainly associated with fine-grained sediments. Biostratigraphic age data are not available. The pre-Carboniferous low-grade Rakovec Group consists of two lithostratigraphic units (Fig. 1), (i) the lower Smrečinka Formation and (ii) the upper Sykavka Formation (Bajaník et al. 1981). The Sykavka Formation is composed mainly of metabasalts and associated volcaniclastics with rare intercalations of fine-grained metasediments. Thus, sampling for the zircon selection was focused on the basal Smrečinka Formation (Fig. 1). This formation is made up mainly of distal turbiditic metasandstones and metapelites. Thin slices of metabasalts and related volcaniclastics are present near the top of the formation. The Rakovec Group volcanic rocks show the geochemical affinity with E-MORB/OIT basalts (enriched mid-oceanic ridge basalts/oceanic island basalts) (Ivan 1994, 1997, 2009). In some areas, rhyolite/dacite bodies occur near the base of the Smrečinka Formation. U–Pb magmatic zircon from these metadacites yielded an age of 476±7 Ma (Putiš et al. 2008).

As a result of the lithological differences between the Sykavka and Smrečinka formations, Ivan (2009) considered the Smrečinka Formation as a separate lithostratigraphic unit. Németh (2002) also assigned the Smrečinka Formation to the upper part of the Gelnica Group (the Hnilec Formation according to the lithostratigraphy by Németh 2002). But the mineral composition of the Gelnica Group metasandstones is distinctly different from the Smrečinka Formation metasandstones, which are characterized, in particular, by the lack of detrital feldspars and the high degree of mineral maturity metasandstones of the Gelnica Group (Vozárová 1993). However, the U–Pb analysis of detrital zircons from the overstepping Carboniferous–Permian clastic sequences (Vozárová et al. 2013) confirmed the validity of the original division of Bajanik et al. (1981) and the legitimacy for incorporation of the Smrečinka Fm. within the pre-Carboniferous basement of the NGU zone.

Sample characteristics

One sample has been collected from the Smrečinka Formation for zircon dating (Fig. 1). The sample *GZ-25* was located NNW of Rejdová Village, along a forest road, 550 m above sea level (GPS coordinates: 48°47.812’ N, 20°17.162’ E).

The Smrečinka Formation metasandstone is composed of quartz, plagioclase, and relics of deformed and recrystallized lithic fragments, detrital mica, and rare detrital alkali feldspar grains. Among quartz grains (~75 % of total) the monocrystalline types are dominant, whereas the polycrystalline varieties are present in a minority. Feldspar grains are relatively common (~20 % of the total), of these, the plagioclases predominate. Since the sediments were affected by deformation and recrystallization reaching greenschist facies metamorphic conditions, the original lithic fragments are more difficult to distinguish. Only metasedimentary fragments and fine-grained detrital white mica were identified (Fig. 2).

The studied metasandstone is characterized by massive, partly foliated structure. A blastopsammitic texture is characteristic, with clastic grains displaying a variable degree of pressure solution deformation and a relatively high content of fine-grained recrystallized matrix (on average 30–40 %), consisting of fine-grained muscovite, chlorite, quartz and secondary albite. According to Dickinson’s criteria (1970) a considerable part of the matrix is represented by “pseudomatrix”. The process of low-grade recrystallization and deformation of former clay matrix and sedimentary/metasedimentary rock fragments is responsible for “graywackization” of metasandstones and relative increase of matrix and stable components in their texture.

Analytical method

Zircons were extracted from the rocks by the standard technique applying grinding, heavy liquid separation, magnetic separation and hand-picking. The internal zoning structures and shapes of the half-sectioned zircon crystals, mounted in an epoxy resin puck with chips of the TEMORA 1 (zircon standards derived from the Middledale Gabbroic Diorite; Black et al. 2003) and 91500 (Wiedenbeck et al. 1995) reference zircon, were imaged by optical microscopy, back-scattered electrons (BSE) and cathodoluminescence, to guide analytical spots positioning.

In situ U–Pb analyses were performed using Sensitive High-Resolution Ion Microprobe (SHRIMP-II) in the Centre of Isotopic Research (CIR), A.P. Karpinsky Russian Geological Research Institute at VSEGEI (Vserossijskij naučno-sledovateľskij geologičeskij institut), applying a secondary electron

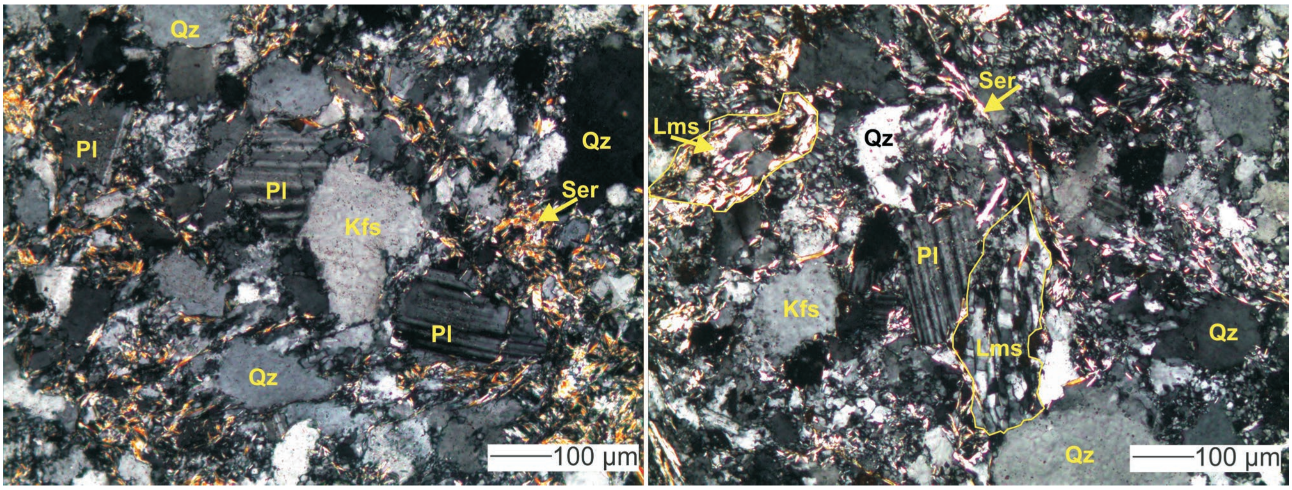


Fig. 2. Microtexture and mineral composition of the Smrečinka metasandstones. *Abbreviations:* Pl — plagioclase; Kfs — feldspar; Qz — quartz; Lms — lithic fragment; Ser — sericite (fine-grained muscovite in matrix).

multiplier in peak-jumping mode following the procedure described by Williams (1998) and Larionov et al. (2004). Primary beam size allowed the analysis of ca. 27×20 µm area. The 80 µm wide ion source slit, in combination with a 100 µm multiplier slit, allowed mass-resolution $M/\Delta M \geq 5{,}000$ (1 % valley); hence, all the possible isobaric interferences were resolved. The following ion species were measured in the sequence: $^{196}(Zr_2O)$–^{204}Pb–background (ca. 204.5 AMU) –^{206}Pb–^{207}Pb–^{208}Pb–^{238}U–^{248}ThO–^{254}UO. Four to five mass-spectra for each analysis were acquired. Each fifth measurement was carried out on the TEMORA-1 Pb/U standard (Black et al. 2003). The 91500 zircon (Wiedenbeck et al. 1995) was applied as the "U-concentration" standard. The obtained results have been processed by the SQUID v1.12 (Ludwig 2005a) and ISOPLOT/Ex 3.22 (Ludwig 2005b) softwares, with decay constants of Steiger & Jäger (1977). Common lead correction was done using the measured ^{204}Pb/^{206}Pb ratio. The ages given in the text, if not additionally specified, are ^{207}Pb/^{206}Pb ages for zircons older than 1.0 Ga, and ^{206}Pb/^{238}U, for those younger than 1.0 Ga. The errors are quoted at 1σ level for individual points and at 2σ level in the Concordia diagram, for the Concordia ages or any previously published ages discussed in the text. Age distributions of detrital zircons are displayed as Kernel Density Estimates (Vermeesch 2012). Only analyses that produced concordant ages within 10 % were used. For interpretation purposes, the Probability Density Plot (ISOPLOT/Ex 3.75, Ludwig 2012) was constructed using ^{206}Pb/^{238}U ages for zircon younger than 1.0 Ga and ^{207}Pb/^{206}Pb ages for zircons older than 1.0 Ga. The Probability Density Plots include analyses with discordance from 0 % to 15 %. The Kolmogorov–Smirnov statistical test (K–S) was adopted from Guynn & Gehrels (2010) and was used for the comparison of detrital zircon age distributions.

In this study, we follow the time-scale calibration of the International Chronostratigraphic Chart (2018-8) (http://www.stratigraphy.org/ICSchart/ChronostratChart 2018-08.pdf) in order to compare geochronological data from detrital zircons with paleontological ages of fossil-bearing sedimentary units and tectono–thermal events.

Results of zircon dating

49 detrital zircon grains have been analysed from sample *GZ-25*. The results of the U–Pb detrital zircon analyses are provided in the Table 1 and in the Figure 3. The age spectrum of the detrital zircons is dominated by Neoproterozoic ages (~56 %). Most of them are Ediacaran in age (~33 %), ranging between 545 and 635 Ma with major peaks at 547, 598 and 640 Ma on the Probability Density Plot (Fig. 3). Approximately 20 % of analysed zircons yielded Cryogenian ages with a peak at 640 Ma. Only two grains show late Tonian ages 757 and 774 Ma, whereas the 757 Ma age is related to a xenocrystic core. Two other grains revealed 0.9–1.0 Ga ages, just straddling the boundary between Tonian and Stenian. Analyses indicated U contents of 94–575 ppm and Th contents of 74–536 ppm. ^{232}Th/^{238}U ratios range between 0.30–1.49 for all Neoproterozoic zircons (Table 1). They are most likely to be results of crystallization from felsic melt composition with minor mafic influences (Wang et al. 2011). The only exception is spot 24 of the 633±7 Ma age (Table 1; Fig. 4) with a very low Th/U ratio of 0.01, indicating a strong post-magmatic or metamorphic recrystallization process.

A typical feature of the studied Neoproterozoic zircons is the presence of well-developed growth oscillatory zoning (Fig. 4). In others, resorption intervals with textural discontinuities have been quite regularly observed, along which the original zoning is resorbed and succeeded by newly-grown-zoned zircon. According to Corfu et al. (2003), these resorption intervals reflect intermediate periods of Zr saturation in the magma, owing to a large-scale mixing singularity, or to local kinetic phenomena. A special type of zoning is the rare irregular and patchy texture in solitary zircon grains. This type of texture may reflect strain experienced by zircons during the final magmatic emplacement or by texture modification during late- and post-magmatic processes (Corfu et al. 2003 and references therein). Scarce zircon grains with convolute texture or irregular domains of homogeneous enclaves that cut the original oscillatory growth zoned texture, also document the local post-magmatic recrystallization (Fig. 4).

The second major detrital zircon assemblage (17 grains of the total; 35 %) is represented by Paleoproterozoic ages, ranging from 1885 to 2132 Ma, whereas 9 concordant grains yielded a Concordia age of 1892±9 Ma (Fig. 3) corresponding to the Orosirian. In general, recrystallization features have been observed in the all studied Paleoproterozoic detrital zircon grains. Their internal textures are either homogenous and patchy or convolute. Some of them appear in the form of xenocrystic cores. The zircon analyses yielded U contents of 28–964 ppm and Th contents of 18–415 ppm. ^{232}Th/^{238}U ratios

Table 1: U–Pb (SHRIMP) detrital zircon age data from the sample *GZ-25*. Errors are 1 sigma; Pb$_c$ and Pb* indicate the common and radiogenic portion, respectively. Error in standard calibration was 0.52 % (not included in above errors but required when comparing data from different mounts); (1) Common Pb corrected using measured ^{204}Pb. (2) Common Pb corrected by assuming ^{206}Pb/^{238}U–^{207}Pb/^{235}U age concordance.

spot	^{206}Pb$_c$ %	U ppm	Th ppm	^{232}Th/^{238}U	^{206}Pb* ppm	1(Age) ^{206}Pb/^{238}U	±	1(Age) ^{207}Pb/^{206}Pb	±	Disc. %	1 ^{238}U/^{206}Pb*	± %	1 ^{207}Pb*/^{206}Pb*	± %	1 ^{207}Pb*/^{235}U	± %	1 ^{206}Pb*/^{238}U	± %	err corr
1	0.02	537	236	0.45	48.3	642.3	5.6	617	21	−4	9.544	0.92	0.0604	0.99	0.872	1.4	0.1048	0.92	.681
2	0.12	235	179	0.79	23.5	708.7	7	683	32	−4	8.605	1.0	0.0623	1.5	0.997	1.8	0.1162	1.0	.571
3	0.04	274	134	0.50	22.7	592.3	5.8	570	30	−4	10.39	1.0	0.05901	1.4	0.784	1.7	0.0962	1.0	.599
4	0.05	203	74	0.38	17.0	599.2	6.1	570	34	−5	10.27	1.1	0.0591	1.6	0.794	1.9	0.0974	1.1	.565
5	0.03	313	360	1.19	45.0	996	11	997	18	0	5.987	1.1	0.0724	0.89	1.667	1.5	0.1670	1.1	.788
6	0.23	115	47	0.42	9.29	578.3	6.8	526	69	−9	10.65	1.2	0.0579	3.2	0.749	3.4	0.0939	1.2	.364
7	0.03	94	59	0.65	29.1	1988	18	1956	15	−2	2.768	1.1	0.1200	0.84	5.976	1.4	0.3613	1.1	.786
8	0.20	28	18	0.67	9.04	2071	26	2046	32	−1	2.638	1.4	0.1262	1.8	6.59	2.3	0.3788	1.4	.617
9	0.21	138	72	0.54	12.1	622	12	555	66	−11	9.87	2.0	0.0587	3.0	0.820	3.6	0.1013	2.0	.549
10	0.41	110	159	1.49	9.19	597.2	6.7	534	68	−11	10.3	1.2	0.0581	3.1	0.778	3.3	0.0971	1.2	.358
11	0.29	264	177	0.69	23.0	619.7	6	599	59	−3	9.91	1.0	0.0599	2.7	0.833	2.9	0.1009	1.0	.350
12	0.04	362	165	0.47	31.6	622.4	5.9	614	25	−1	9.865	0.99	0.0603	1.2	0.843	1.5	0.1014	0.99	.647
13	0.10	109	72	0.68	32.0	1900	17	1921	15	1	2.917	1.0	0.1177	0.85	5.560	1.3	0.3427	1.0	.777
14	0.14	415	388	0.97	34.7	598.1	5.6	583	34	−3	10.28	0.99	0.0594	1.6	0.797	1.8	0.0972	0.99	.535
15	0.22	138	107	0.80	40.5	1889	17	1894	16	0	2.936	1.0	0.1159	0.91	5.440	1.4	0.3404	1.0	.743
16	1.46	118	103	0.90	10.8	643.7	9.8	568	91	−12	9.52	1.6	0.0590	4.2	0.854	4.5	0.1050	1.6	.360
17	0.29	153	81	0.54	14.8	684.7	8.3	637	46	−7	8.92	1.3	0.0609	2.1	0.941	2.5	0.1121	1.3	.515
18	0.02	1815	1337	0.76	518.0	1850	14	1886.7	3.8	2	3.008	0.88	0.1154	0.21	5.291	0.91	0.3324	0.88	.972
19	0.05	487	239	0.51	36.9	544.6	4.9	563	23	3	11.34	0.94	0.0589	1.1	0.716	1.4	0.0882	0.94	.658
20	0.14	1700	749	0.46	391.0	1525	14	2060.8	4.3	35	3.745	1.1	0.1273	0.24	4.685	1.1	0.2670	1.1	.975
21	0.01	107	96	0.92	65.8	3468	27	3444.6	6.2	−1	1.404	1.0	0.2951	0.4	28.99	1.1	0.7125	1.0	.930
22	0.04	912	415	0.47	290	2028	18	2033.4	8.6	0	2.705	1.1	0.1253	0.48	6.388	1.2	0.3697	1.1	.909
23	0.01	547	179	0.34	58.6	757.4	7.3	728	17	−4	8.021	1.0	0.0636	0.79	1.093	1.3	0.1247	1.0	.793
24	0.10	494	3	0.01	43.9	633.4	7.5	625	25	−1	9.69	1.2	0.0606	1.2	0.863	1.7	0.1032	1.2	.728
25	0.17	206	77	0.38	22.6	773.6	7.6	750	35	−3	7.842	1.0	0.0642	1.6	1.129	1.9	0.1275	1.0	.537
26	0.18	248	210	0.88	22.4	645.1	6.3	599	38	−7	9.5	1.0	0.0599	1.7	0.869	2.0	0.1053	1.0	.511
27	0.07	964	286	0.31	261.0	1768	14	2132.3	5.4	21	3.169	0.9	0.1326	0.31	5.767	0.95	0.3155	0.9	.945
28	0.02	105	45	0.44	63.1	3411	27	3413.5	9.2	0	1.434	1.0	0.2892	0.59	27.81	1.2	0.6974	1.0	.866
29	0.11	137	143	1.08	20.9	1056	10	1010	30	−4	5.619	1.0	0.0729	1.5	1.787	1.8	0.1779	1.0	.584
30	0.20	75	48	0.66	21.9	1880	18	1896	19	1	2.952	1.1	0.1160	1.1	5.418	1.5	0.3386	1.1	.724
31	0.01	404	400	1.02	36.0	634.8	5.9	642	22	1	9.664	0.97	0.0611	1.0	0.871	1.4	0.1035	0.97	.690
32	0.05	471	126	0.28	117.0	1640	17	2021	15	23	3.452	1.2	0.1244	0.86	4.969	1.4	0.2896	1.2	.803
33	0.17	50	28	0.57	4.80	675.5	8.9	699	70	3	9.05	1.4	0.0627	3.3	0.955	3.6	0.1105	1.4	.391
34	0.08	88	61	0.73	26.2	1927	19	1899	17	−1	2.87	1.1	0.1162	0.96	5.583	1.5	0.3483	1.1	.760
35	0.06	191	175	0.95	17.0	635.4	6.3	619	38	−3	9.65	1	0.0604	1.7	0.863	2.0	0.1036	1.0	.514
36	0.01	646	358	0.57	193.0	1924	15	1897.1	6	−1	2.875	0.9	0.1161	0.33	5.567	0.96	0.3478	0.9	.937
37	0.35	2078	536	0.27	159	549.5	5.9	525	15	−4	11.24	1.1	0.0579	0.69	0.7101	1.3	0.0890	1.1	.852
38	0.06	337	436	1.33	28.5	604.9	6	601	31	−1	10.16	1.0	0.0599	1.4	0.813	1.8	0.0984	1.0	.583
39	0.21	99	94	0.99	9.23	665.3	7.9	614	56	−8	9.2	1.2	0.0603	2.6	0.904	2.9	0.1087	1.2	.434
40	0.07	413	397	0.99	38.3	660.2	6.1	631	24	−4	9.272	0.97	0.0608	1.1	0.904	1.5	0.1078	0.97	.649
41	0.28	75	32	0.44	17.9	1573	16	2002	21	27	3.616	1.1	0.1231	1.2	4.693	1.6	0.2764	1.1	.692
42	0.10	94	69	0.76	28.1	1929	18	1893	17	−2	2.867	1.1	0.1159	0.94	5.571	1.4	0.3487	1.1	.750
43	0.09	159	105	0.68	46.5	1892	17	1885	15	0	2.931	1.0	0.1153	0.84	5.422	1.3	0.3411	1.0	.775
44	0.06	357	327	0.95	32.7	652.6	6.1	634	25	−3	9.386	0.99	0.0608	1.2	0.894	1.5	0.1065	0.99	.649
45	0.08	133	107	0.83	38.7	1875	17	1909	14	2	2.962	1.0	0.1169	0.79	5.441	1.3	0.3376	1.0	.792
46	0.25	94	128	1.40	8.55	648.1	7.4	652	61	1	9.45	1.2	0.0614	2.8	0.895	3.1	0.1058	1.2	.391
47	0.10	138	109	0.82	41.9	1952	17	1922	15	−2	2.827	1.0	0.1177	0.85	5.740	1.3	0.3536	1.0	.767
48	0.12	575	168	0.30	46.4	578.1	5.4	608	26	5	10.66	0.98	0.0601	1.2	0.778	1.5	0.0938	0.98	.635
49	0.01	740	495	0.69	316.0	2602	19	2596.4	3.8	0	2.011	0.9	0.1740	0.23	11.93	0.93	0.4973	0.9	.969

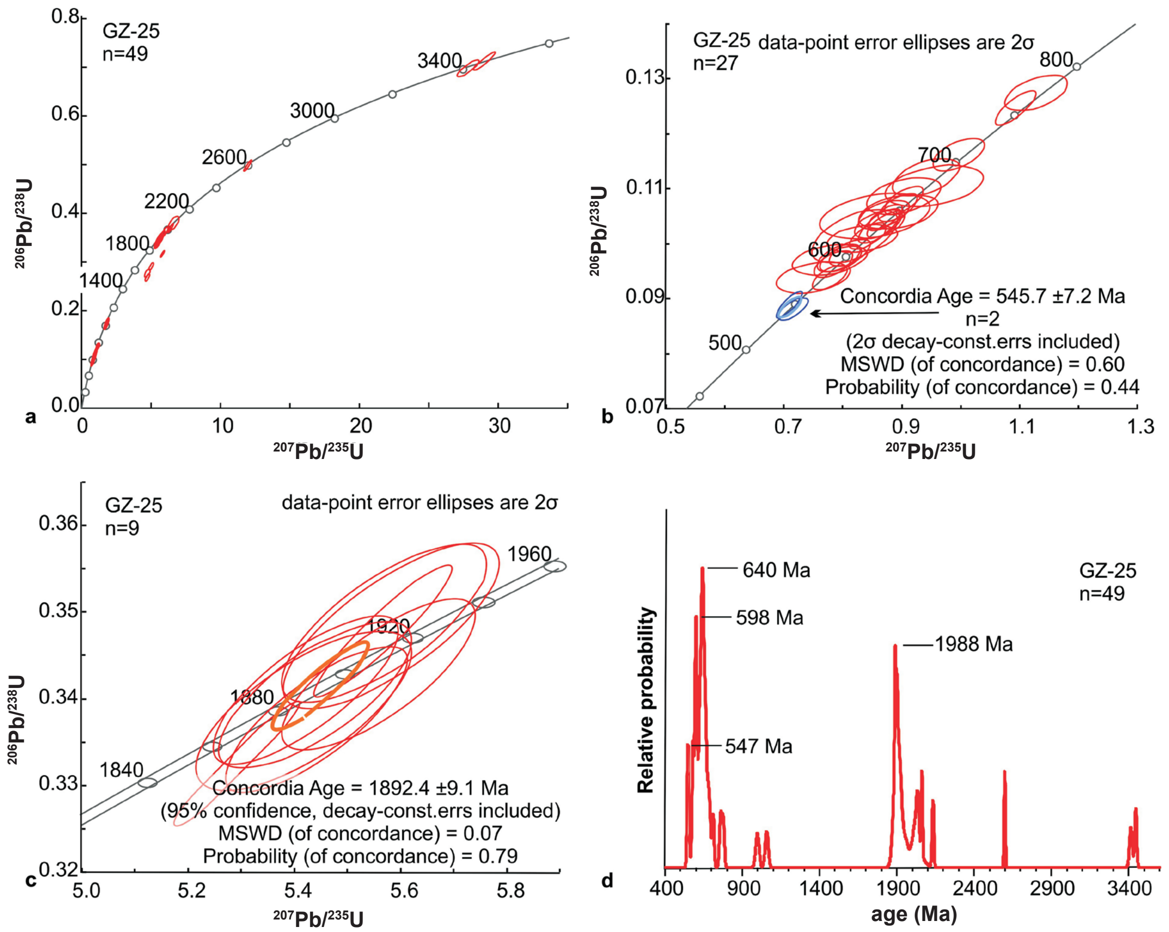


Fig. 3. a — Concordia plot of detrital zircons from the sample *GZ-25*. **b** — Selected sector of the Concordia relevant to the most prominent clusters for the age spectrum from 500 to 800 Ma, with indication of the youngest Concordia age. **c** — Concordia diagram depicting the Eburnian detrital zircon population. **d** — Corresponding Probability Density Plot of detrital zircon ages (according to ISOPLOT/Ex 3.75, Ludwig 2012).

of the Paleoproterozoic detrital zircons vary from 0.28 to 0.83, indicating crystallization from a felsic igneous melt (Table. 1).

Only a few zircon grains yielded Neoarchean (2596±6 Ma) and Paleoarchean (3445±6 and 3413±9 Ma) ages (Table 1).

Discussion

Age data and provenance

The detrital zircon assemblage analysed from the sample *GZ-25* shows a distinct bipolar age distribution (Fig. 3). A prevailing part of the detrital zircons in the *GZ-25*, metasandstone sample, displays Neoproterozoic ages spanning between 545 and 709 Ma with a major peak at 547, 598 and 640 Ma, while Ediacaran zircons are dominant (~33 % of all concordant grains). Additionally, the *GZ-25* sample contains negligible amounts of Tonian and Tonian/Stenian detritus (only 4 grains), ranging from 0.75 to 1.0 Ga. The second major detrital zircon age population is connected with Late Paleoproterozoic ages, ranging from 1.8 to 2.1 Ga.

The previously published zircon age data from the sample *GZ-24* (Vozárová et al. 2013), also coming from the Smrečinka Formation, and proved completely identical clusters of the detrital zircon ages as from the sample *GZ-25* (Fig. 5a). The K–S statistic test confirms that the samples *GZ-24* and *GZ-25* demonstrate the statistically significant similarity (at the 95 % confidence level), with the *P* value higher then 0.05, so that they correspond to 0.179 (Table 2).

Taking into account the detrital zircon ages from both samples (93 spots together), zircon grains show the Neoproterozoic, with dominance of Ediacaran ages (~60 % of all concordant grains), which highlights significant peaks at 586 and 629 Ma at KDE plot (Fig. 5b). The second most represented detrital zircon ages correspond to Paleoproterozoic (~31 % of all concordant grains) with a distinct peak at 1.90 Ga (Fig. 5b).

This detrital zircon age cluster indicates a significant input from a Cadomian arc that resides at the periphery of the West African Craton (WAC) of North Gondwana (Linnemann et al. 2008). The Early Ordovician breakup of the Cadomian crust and formation of the Rakovec Group sedimentary trough (back-arc basin) are interpreted as coincident with the crustal-derived

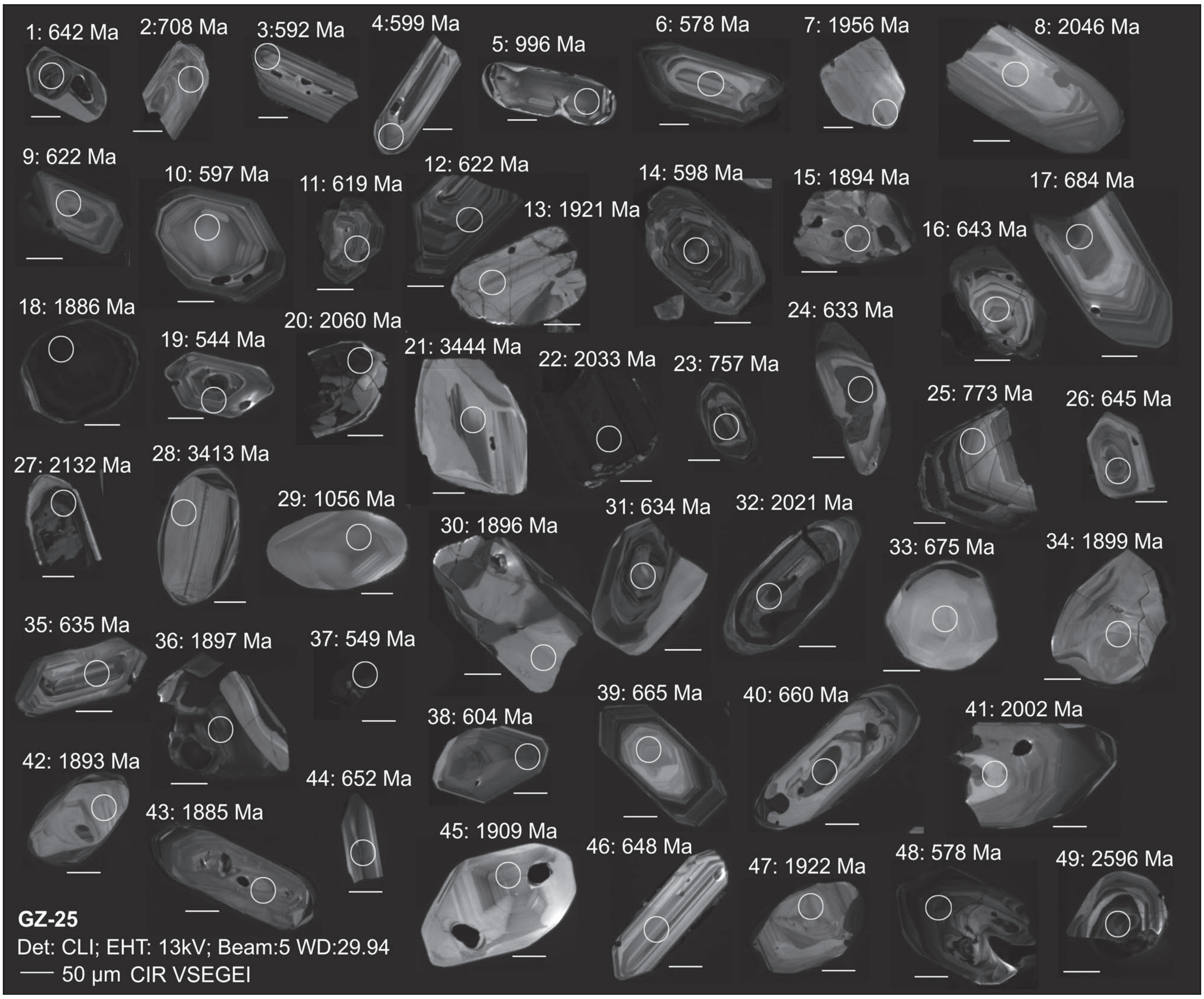
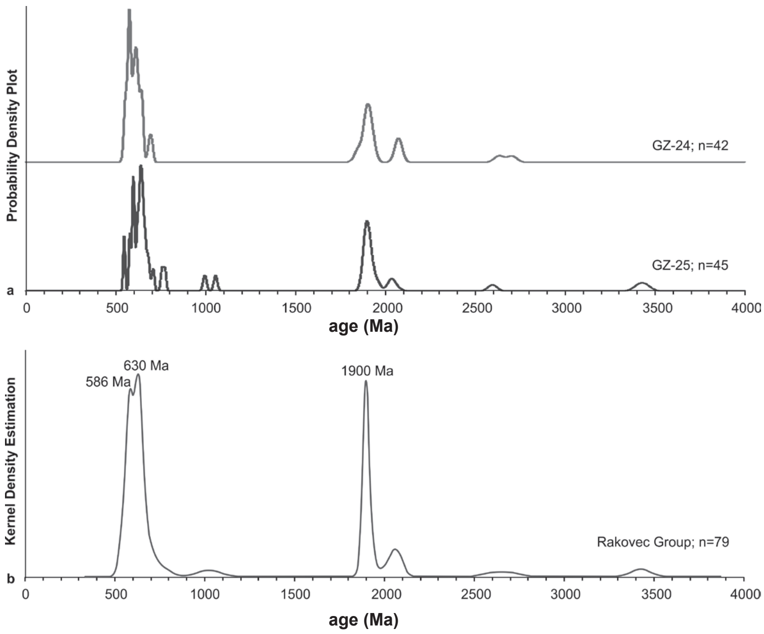


Fig. 4. Cathodoluminescence images of detrital zircons from the sample *GZ-25.*

Fig. 5. a — Normalized Probability Density Plot (according to ISOPLOT/Ex 3.75, Ludwig 2012) of detrital zircon ages from the Smrečinka metasandstones; samples *GZ-24* and *GZ-25,* with discordant filter from 0 % to 15 %. **b** — Kernel Density Estimation for the entire detrital zircon populations, with discordant filter of 10 % (in accordance Vermeesch 2012).



felsic volcanism that was identified by Bajaník et al. (1984) within the Smrečinka Formation, which were subsequently determined on the basis of U–Pb zircon data with an age of 476±7 Ma old (Putiš et al. 2008). A relatively high number of detrital zircons yielded 1.8–2.1 Ga (Paleoproterozoic, Eburnian) ages. The presence of Eburnian detrital zircons is usually taken to indicate the WAC provenance (e.g., Linnemann et al. 2007; Abati et al. 2012; Gärtner et al. 2013, 2016; Henderson et al. 2016). The discordant ages from the samples *GZ-24* and *GZ-25* appear to define two clusters, each of which can be roughly coordinated with a Discordia line with upper intercepts that lie at approximately 1.8 and 2.1 Ga, (Fig. 6). The presence of concordant grains of similar ages supports the reliability of the upper intercept ages and suggests that these discordant grains were derived from Paleoproterozoic (1.8–2.2 Ga) terranes. It may be suggested that these zircons could have been affected by lead loss during Early Paleozoic events (lower intercepts at 440 Ma and 480 Ma, respectively, Fig. 6), which were the most probably connected with thermal relaxation during crustal extension and the origin of the Rakovec Group sedimentary trough.

The Smrečinka detrital zircon age spectrum that is dominated by Ediacaran (545–625 Ma) and Paleoproterozoic (1.8–2.1 Ga) ages, with a minor Archean population (2.5–3.4 Ga), suggests a linkage with Armorican terranes. Generally, the Armorican age spectrum contains more Ediacaran ages than Cryogenian ones, with typical latest age peaks from 540 Ma to 570 Ma of the Cadomian active margin and with a distinctive Mesoproterozoic age gap (e.g. Fernández-Suárez et al. 2002, 2014; Friedl et al. 2004; Linnemann et al. 2004, 2008; Drost et al. 2011; Shaw et al. 2014; Dörr et al. 2015; Henderson et al. 2016; Avigad et al. 2018).

Table 2: K–S statistical test of the Smrečinka detrital zircon populations (samples *GZ-24* and *GZ-25*); table of P- and D-values for the comparison of studied samples.

using error in the Cumulative Distribution Function

K-S P-values			**D-values**	
	GZ 24	**GZ 25**	**GZ 24**	**GZ 25**
GZ 24	–	0.179	–	0.237
GZ 25	0.179	–	0.237	–
K-S P-values for no error			**D-values for no error**	
	GZ 24	**GZ 25**	**GZ 24**	**GZ 25**
GZ 24	–	0.102	–	0.264
GZ 25	0.102	–	0.264	–

using Monte-Carlo

Average K-S P-values			**Two std devs. of P-values**	
	GZ 24	**GZ 25**	**GZ 24**	**GZ 25**
GZ 24	–	0.088	–	0.090
GZ 25	0.088	–	0.090	–

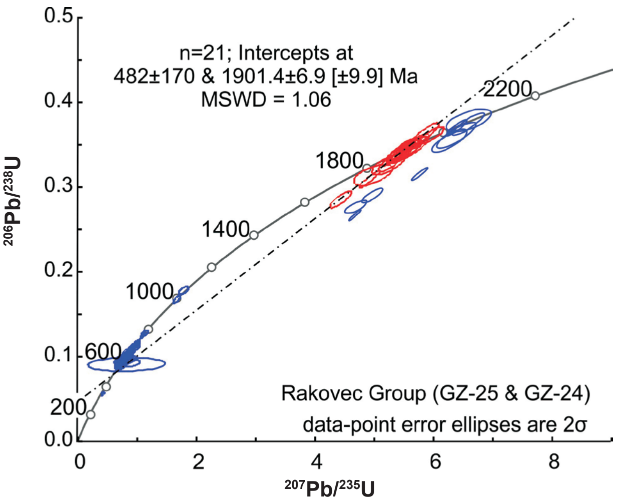


Fig. 6. Discordia diagram of the all dated detrital zircons from the Smrečinka Formation.

Similar detrital zircon assemblages have been found in the Saxo–Thuringian Zone (Linnemann et al. 2007, 2008), whereas the zircons overlap with the age and hafnium isotopic array of the West African Craton (Linnemann et al. 2014). Such ages, however, are also known from SW Iberia and Brittany (Fernández-Suárez et al. 2002, 2014), from the Ediacaran sedimentary rocks of the Teplá–Barrandian Complex in the Bohemian Massif (Drost et al. 2011) and in the Armorican Massif where Cadomian arc sequences are preserved directly with their Eburnian basement (Icartian gneisses, ~2 Ga) (e.g., D'Lemos et al. 1990; Chantraine et al. 2001). The observed spectrum of zircon ages from the Smrečinka Formation metasandstones correspond to the second event of the Cadomian orogeny, according to the interpretation of Linnemann et al. (2008). This was related to the assumed transition of juvenile to continental magmatic arc at ~620 Ma, crustal thickening and contamination by Eburnian basement aged at around 2.0 Ga. This is proven by the abundance of Paleoproterozoic zircons, as well as the dominance of Ediacaran ages (average mean at 610±11 Ma) within the Smrečinka Formation detrital zircons.

Correlation of the detrital zircon age spectra with published data

The record of Neoproterozoic and Archean zircon ages, is above all, in the xenocrystic cores of magmatic zircons, mainly in the Variscan granitoid rocks or in the Cambrian/Ordovician orthogneisses, coming from the Tatricum and Veporicum crystalline basements. Generally, they show two age maxima, either the Neoproterozoic ages ranging from 550 to 660 Ma or the Paleoproterozoic–Archean set, ranging from ~2.0 Ga to 3.4 Ga (Poller & Todt 2000; Poller et al 2000, 2001, 2005; Gaab et al. 2005; Putiš et al. 2008, 2009; Kohút et al. 2009; Broska et al. 2013; Burda et al. 2013). Rarely, 1.1–1.2 Ga inherited zircon grains were also described (Broska et al. 2013). An isolated detrital zircon study from mica-schists of the Western Tatra Mts. was performed by Kohút et al. (2008). The obtained detrital zircon data yielded mostly Cambrian/Neoproterozoic ages, in the range of 515–666 Ma. Several of the oldest cores yielded 1800 and 1980 Ma. Detrital zircon assemblages from the Late Paleozoic sediments of the Hronicum Nappe system determined the age and nature of their unknown basement and source area (Vozárová et al. 2018). Among the pre-Cambrian detrital zircon grains Ediacaran ages in the range of 545–612 Ma and Paleoproterozoic–Neoarchean ages ranging from 1.8 to 2.9 Ga are dominating. All these published zircon age data indicate a distinct proximity of the source areas and precursor rocks to the crystalline basements of the Central Western Carpathian tectonic units, namely the Tatricum, Veporicum and misplaced Hronicum basements. However, the Smrečinka detrital zircon age spectrum clearly shows a similarity with the above-mentioned zircon distributions and reinforcement of the provenance linkage to the Cadomian orogenic belt and West African Craton (Fig. 7).

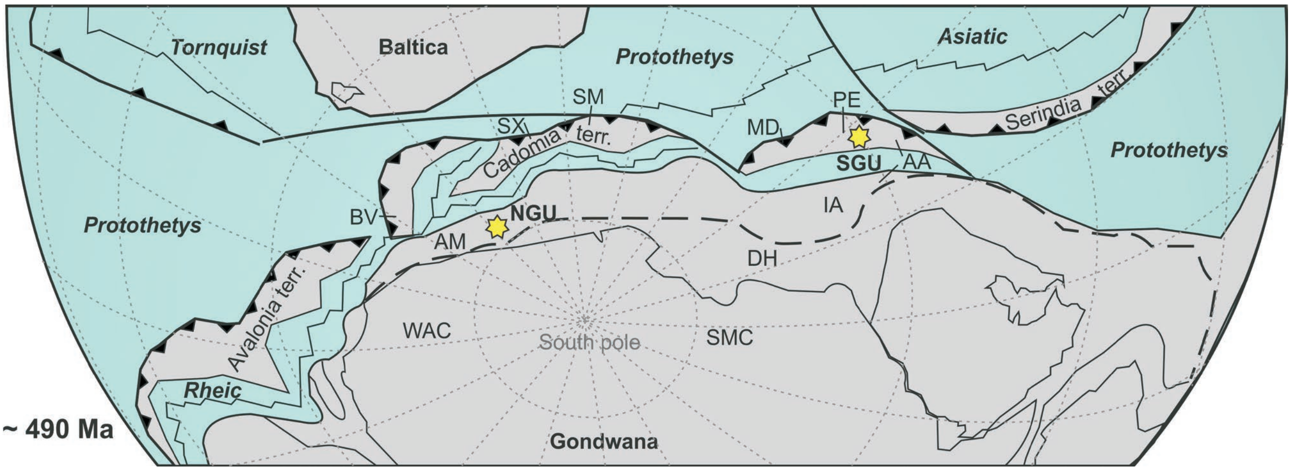


Fig. 7. Early Ordovician plate-tectonic reconstruction showing presumed location of the NGU and SGU terranes (yellow stars) in the peri-Gondwana realm (modified from von Raumer et al. 2003). *Abbreviations*: BV – Bruno-Vistulikum; SX – Saxothuringia; SM – Serbo-Macedonian; MD – Moldanubia; Am – Armorica; PE – Penninic; AA – Austro-Alpine; IA – Intra-Alpine; DH – Dinarides-Hellenides. Approximate position of the West African Craton (WAC) and the Sahara Metacraton (SMC) according to Meert & Lieberman (2008). Dashed line – future opening of Palaeotethys.

Further detrital zircon populations have been studied from the metasandstones of the Southern Gemericum (Vozárová et al. 2012), which borders with the NGU basement. The major part of the Southern Gemeric Unit (SGU) is formed by the low-grade Early Paleozoic volcanic–sedimentary sequence of the Gelnica Group and a pre-Permian low-grade complex of the Štós Formation. The mutual contact of these rock complexes is tectonic, along a shallow north-verging thrust plane, which is documented by deep seismic profile data (Vozár et al. 1995). Both these pre-Permian low-grade crystalline complexes are unconformably overstepped by the Permian continental sediments of the Gočaltovo Group (Bajaník et al. 1983, 1984). The dataset of concordant 46 detrital zircon ages from the SGU basement, which were combined with the 20 xenocrystic cores from the Early Paleozoic metavolcanics, yielded the three main zircon age populations. They are: (i) Neoproterozoic in the range of 560–870 Ma, with the main peaks at 630 and 700 Ma; (ii) Tonian–Stenian in the range of 0.9–1.1 Ga; (iii) Paleoproterozoic/Archean ranging from 1.75 to 3.2 Ga.

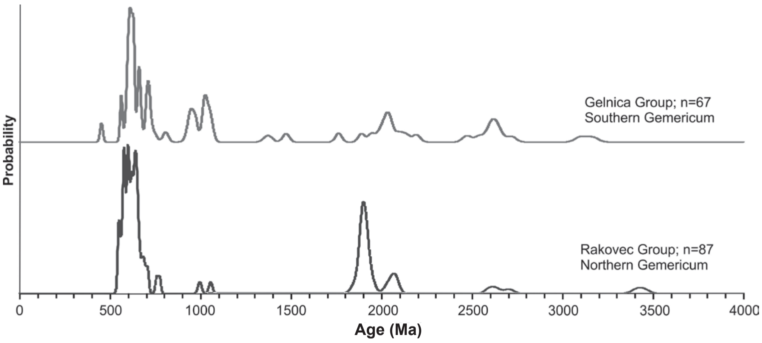


Fig. 8. Correlation plots of normalized Probability Density curves (according to ISOPLOT/Ex 3.75, Ludwig 2012) from Early Paleozoic detrital zircon assemblages of the Northern Gemericum and the Southern Gemericum units. The probability density curves include analyses with discordance between 0 % and 15 %. Detrital zircon age data are taken from the present paper and from Vozárová et al. (2012, 2013).

The main difference among the Smrečinka Fm. and the SGU zircon populations, are manifested by the presence of Tonian–Stenian ages in the range of 0.9 and 1.1 Ga, as well as by the shifting of the prevalent part of Neoproterozoic zircon ages to the Cryogenian, with peaks at 630 and 700 Ma in the SGU basement (Fig. 8). This zircon age span indicates derivation of Pan-African sources from within the Saharan Metacraton.

Thus, the main difference between the low-grade NGU and SGU Lower Paleozoic basements resulted from their different provenances, as well as from their diverse position along the North Gondwana margin, which was induced by the Cadomian arc and West African Craton provenance for the NGU basement and the Pan-African Belt–Saharan Metacraton provenance for the SGU basement (Fig. 7).

Conclusions

Forty-nine new U–Pb detrital zircon data from the Smrečinka Fm. metasandstones are presented. The Smrečinka Fm. metasandstones belong to the basal part of the Rakovec Group that is a part of the Northern Gemericum basement. These zircon age data were combined with forty-four previously published detrital zircon ages, assuring the provenance of this region from the N-Gondwanan realm, as well as to compare the Smrečinka zircon population to the zircon ages from the other parts of the Western Carpathian crystalline basements. The results can be summarized as follows:

- The studied assemblages of U–Pb detrital zircon ages show a significant bimodal distribution, which is dominated by Ediacaran (545–625 Ma) and Paleoproterozoic (1.8–2.1 Ga) ages, with a smaller Archean population (2.5–3.4 Ga).
- In general, this dispersal of detrital zircon ages suggests a linkage with Armorican terranes, which are characterized by derivation from the Cadomian arc which lay on the periphery of the West African Craton of North Gondwana. Reworking of the Eburnian crust is characteristic as is documented by the presence of the 1.8–2.1 Ga detrital zircons.
- The acquired detrital zircon assemblages enable us to correlate the source area of the Rakovec Group, including the Smrečinka Fm. metasedimentary rocks with the equivalent provenances for the Tatricum and Veporicum, as well as the displaced Hronicum basement rocks.
- The discordant ages can be roughly coordinated with a Discordia line with the upper intercept lying at 1.8 and 2.1 Ga, and the lower intercept at 440 Ma and 480 Ma, respectively. The presence of concordant grains of similar age supports the reliability of the upper intercept ages and suggests that these discordant grains were derived from Paleoproterozoic (1.8–2.2 Ga) terranes. It may be suggested that these zircons could have been affected by lead loss during Ordovician events. These were most probably connected with thermal relaxation during crustal extension and the origin of the Rakovec Group sedimentary trough.

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