

Precambrian crustal contribution to the Variscan accretionary prism of the Kaczawa Mountains (Sudetes, SW Poland): evidence from SHRIMP dating of detrital zircons

Ryszard Kryza · Jan Zalasiewicz · Stanisław Mazur · Paweł Aleksandrowski ·
Sergey Sergeev · Alexander Larionov

Received: 22 March 2006 / Accepted: 17 November 2006 / Published online: 12 December 2006
© Springer-Verlag 2006

Abstract SHRIMP dating of detrital zircons from sandstones of the Gackowa Formation (Kaczawa Complex, Sudetes, SW Poland) indicates input from late (550–750 Ma) and early Proterozoic to Archaean sources (~2.0–3.4 Ga, the latter being the oldest recorded age from the Sudetic region). These dates preclude within-terrane derivation from seemingly correlatory acid volcanic rocks of early Palaeozoic age. Rather, they indicate provenance from Cadomian and older rocks that currently form part of other, geographically distant terranes; the most likely source identified to date is the Lusatian Block in the Saxothuringian Zone. Hence, the Gackowa Formation may be late Proterozoic rather than early Palaeozoic in depositional age, possibly coeval with the late Proterozoic (pre-Cadomian) greywackes of Lusatia, being subsequently tectonically interleaved with early Palaeozoic volcanic rocks into the Kaczawa accretionary prism during the Variscan orogeny. However, correlation with the lithologically similar early Ordovician Dubrau Quartzite of Saxothuringia, and so assignation

to the early Paleozoic (post-Cadomian) rift succession deposited at the northern margin of Gondwana, cannot yet be precluded.

Keywords SHRIMP · Zircon · Precambrian · Sudetes · Variscides

Introduction

The extensive Palaeozoic volcano-sedimentary successions accreted within the Variscan belt were deposited in pre-orogenic, mostly extensional basins, initiated due to the break-up of the northern Gondwana margin (e.g., Pin and Marini 1993; Furnes et al. 1994; Floyd et al. 2000; Pin et al. 2007). The onset of sedimentation is currently thought to have taken place in late Cambrian to early Ordovician times and to be closely related to the incipient continental rifting of the Precambrian basement previously consolidated during the Cadomian orogeny (Linnemann et al. 2000, 2004). Shallow marine sedimentary and volcanic successions were deposited during the Ordovician on rifted continental margins of the early Palaeozoic terranes freshly separated from the Gondwana margin. These terranes, subsequently accreted within the European Variscides, included segments of Precambrian crust capable of supplying detritus to the Palaeozoic sedimentary basins. Although such Precambrian crustal components are known from many localities across the Variscan belt (e.g., Edel and Weber 1995), the provenance of material supplied to early Palaeozoic sedimentary successions remains poorly constrained. This is because the Palaeozoic pre-orogenic successions of the Variscides are usually detached from their original basement, having been

R. Kryza (✉) · S. Mazur · P. Aleksandrowski
Institute of Geological Sciences, Wrocław University,
ul. Cybulskiego 30, 50-205 Wrocław, Poland
e-mail: rkryza@ing.uni.wroc.pl

J. Zalasiewicz
Department of Geology, University of Leicester,
University Road, Leicester LE1 7RH, UK

S. Sergeev · A. Larionov
Center of Isotopic Research, A.P. Karpinsky All Russian
Geological Research Institute (VSEGEI),
74 Sredny Pr, St Petersburg 199 106, Russia

tectonically included into accretionary prisms and intensely deformed and metamorphosed during subduction and subsequent continental collision (Kryza et al. 2004 and references therein).

We have carried out U–Pb SHRIMP in situ analysis of detrital zircons from of the Gackowa Formation sandstones, previously considered to be Ordovician in depositional age (Kryza et al. 1994), to constrain the provenance of material supplied to the volcano-sedimentary succession of the Kaczawa Mountains during an early stage of its development. The sedimentary protolith of the Gackowa Formation was originally deposited on a passive continental margin or in the incipient continental rift that split an unidentified Precambrian basement (Kryza et al. 1994). The source area of the detritus remains unknown since the Gackowa sandstones, together with the entire Kaczawa succession, were subsequently included in a Variscan nappe complex and occupy an allochthonous position with regard to the adjacent units (Collins et al. 2000; Seston et al. 2000). Our geochronological data contribute to unravelling the arrangement of terranes prior to the Variscan collision and constrain the role of Variscan tectonism in the reshuffling of crustal blocks. They also illuminate the complex age relationships within the Precambrian crust that sourced terranes assembled within the Variscan orogen.

Geological framework

The Kaczawa Complex in the West Sudetes (NE part of the Bohemian Massif) was defined (Baranowski et al. 1990) to comprise (a) fragments of volcanic and sedimentary sequences of Cambrian? to Early Carboniferous age, and (b) *mélange* bodies, mostly of assumed Late Devonian and Early Carboniferous age. Both constituent elements are exposed in several fault-bounded units grouped into the northern, southern and western part of the Kaczawa Mountains structural unit (Fig. 1). The metamorphic imprint in the Kaczawa Complex varies from anchizone to epizone, with widespread evidence of blueschist facies metamorphism overprinted by greenschist facies metamorphism (Kryza et al. 1990; Kryza and Muszyński 2003 and references therein).

The volcanic-sedimentary successions of the Kaczawa Complex can be subdivided into two parts: (a) a lower part, Cambrian?-Ordovician in age (but see below), composed of composite metavolcanic rocks (transitional tholeiitic/alkaline pillow lavas, rhyodacites, and an alkaline bimodal suite) and metasedimentary rocks: metavolcaniclastic deposits, sandstones

of the Gackowa Formation, the Wojcieszów Limestone and locally abundant metamudstone sequences (Fig. 1c), and (b) an upper part, mostly Silurian–Devonian in age, comprising thick MOR-type metabasalts (pillowed and massive), Silurian graptolitic black slates and cherts and, locally, conodont-bearing Devonian fine-grained clastic and siliceous deposits. The top of the lithostratigraphic succession comprises a poorly dated sedimentary and tectonic *mélange*. The Kaczawa Complex has been interpreted as comprising fragments of a Variscan accretionary prism containing coherent thrust sheets of different parts of the Kaczawa succession, together with *mélange* bodies. The early stage of the pre-orogenic evolution of the succession involved rifting within a continental crust environment (Cambrian?-Ordovician), producing a basin floored by oceanic crust (Silurian–Devonian), and this was followed by accretion in the Late Devonian and Early Carboniferous. The latter produced polygenetic *mélanges* showing evidence of overlapping sedimentary and tectonic processes at the early stages of the Variscan orogeny. Recent structural models (Kryza et al. 1998; Collins et al. 2000; Seston et al. 2000; Aleksandrowski and Mazur 2002; Cymerman 2002) mostly invoke NW-directed thrusting during the main deformation event and subsequent collapse to the SE in a transtensional regime.

The Gackowa Formation

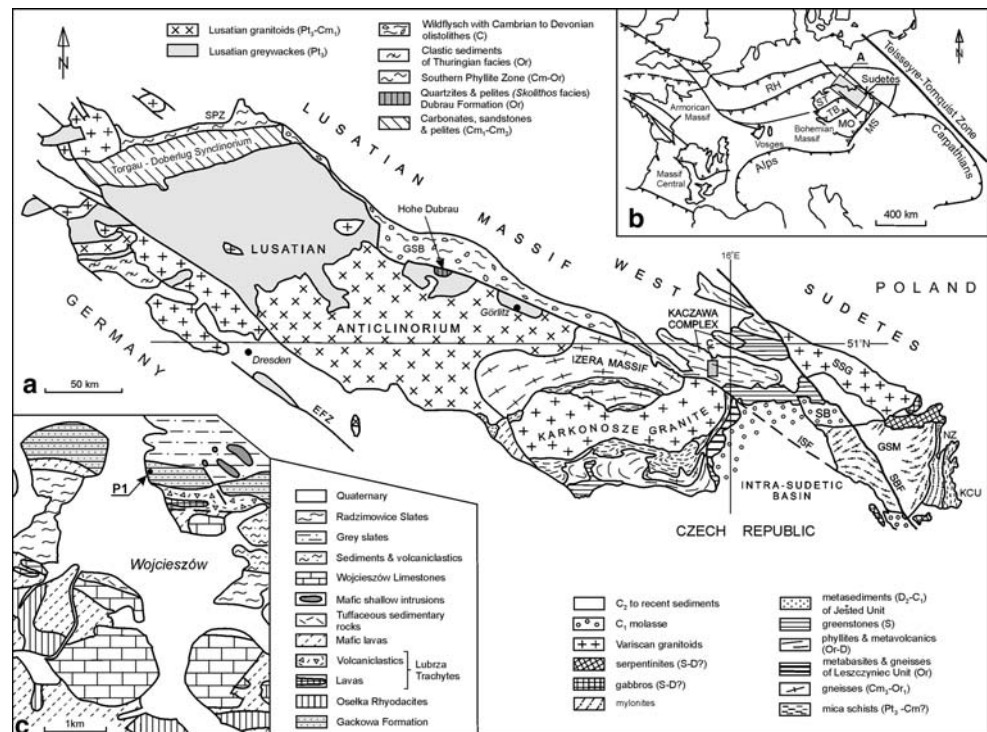
General characteristics and previous interpretations

The Gackowa Formation comprises a shallow-water immature sandstone unit, up to 200 m thick, that crops out for c. 15 km along the southern part of the Kaczawa Mountains in the West Sudetes (Fig. 1). These rocks were originally mapped as “keratophyres” (Zimmermann 1932; Teisseyre 1963), subsequently reinterpreted as sandstones (Pacholska 1975), and analysed in detail by Kryza et al. (1994).

The sandstones are thin- to thick-bedded, with subhorizontal to wavy bedding and hummocky cross-stratification predominant over cross-bedding, and with some beds being massive. The sandstones are sandwiched between underlying pillow lavas and overlying metabasalts and metatrachytes (the Lubrza Trachytes).

Four facies were distinguished in the Gackowa Formation (Kryza et al. 1994): facies A comprises interlaminated sandstones and mudstones; facies B is composed of well-sorted wavy-bedded and hummocky cross-stratified sandstones, interpreted to have been deposited on a storm-swept shelf, partly below storm

Fig. 1 **a** Geological sketch map of the Lusatian Massif and the West Sudetes with insets showing location within the Variscan belt **b** and sampling site P1 of the Gackowa Formation **c**. Map **a** GSB, Görlitz Slate Belt; GSM, Góry Sowie Massif; EFZ, Elbe Fault Zone; ISF, Intra-Sudetic Fault; KCU, Kamieniec-Niemcza Unit; NZ, Niemcza Shear Zone; SB, Świebodzice Basin; SBF, Sudetic Boundary Fault; SSG, Strzegom-Sobótka Granite; SPZ, Southern Phyllite Zone. Inset **b** MO, Moldanubian Zone; MS, Moravo-Silesian Zone; RH, Rhenohercynian Zone; ST, Saxothuringian Zone; TB, Teplá-Barrandian Zone. Inset **c** based on Kryza, Muszyński (1992)



wave base; facies C is characterized by increased bed thickness and grain size, and was interpreted as more proximal; the massive and structureless sandstones of facies D were considered as debris flows of volcanic material (Kryza et al. 1994). No body or trace fossils have been found.

The Gackowa sandstones have been interpreted, on the basis of a variety of petrographic and geochemical criteria, to have been derived from acid volcanic rocks of early Palaeozoic age that occupy the same stratigraphic position elsewhere in the Kaczawa Mountains (Kryza et al. 1994). Macroscopically, they resemble the shallow-water, storm-dominated sandstones of the Dubrau Quartzites of Tremadocian depositional age, in the flanks of the Lusatian Anticlinorium (Linne- mann et al. 2004; see also Fig. 1a).

Description of analysed sample P1

The sample selected for the SHRIMP study was collected from an exposure on the north side of the stadium in Wojcieszów (P1 in Fig. 1c). It is medium-grained, well-sorted sandstone, medium- to thick-bedded, with the original sedimentary structures overprinted by secondary cross-cutting iron oxide layers. The sandstone is composed of larger grains (typically 0.1–0.5 mm in diameter) of quartz and feldspars contained within a strongly recrystallized matrix of the same minerals accompanied by sericite, iron oxide and

accessory zircon and apatite. Locally, fragments of felsic volcanic rocks, feldspar phenocrysts and embayed quartz grains are present and indicate a significant contribution of volcanic material to the detritus. Distinctive microcline grains and large flakes of white mica are also common and suggest that a part of the sedimentary input could have been from a felsic plutonic or higher-grade metamorphic rock (Kryza et al. 1994).

Zircon study

Methods

The sample, c. 5 kg in weight, was crushed and the heavy mineral fraction (0.06–0.25 mm) separated using a standard procedure with heavy liquids and magnetic separation. Zircons were handpicked under a microscope, mounted in epoxy and polished. Transmitted and reflected light photomicrographs were made along with CL images in order to select grains and choose sites for analysis. The Sensitive High Resolution Ion Microprobe (SHRIMP II) at the All Russian Geological Research Institute (VSEGEI) in St Petersburg was used to determine zircon ages in 20 spots within 16 grains. We believe that the analytical coverage of the zircon population of the rock studied is statistically reasonable, despite the limited number of performed measurements; grains for analysis were carefully se-

lected to include all the main morphological and structural types (c.f. Fedo et al. 2003).

In situ U–Pb analyses were performed on a SHRIMP-II at the Center of Isotopic Research (CIR) at VSEGEI, applying a secondary electron multiplier in peak-jumping mode following the procedure described in Williams (1998) or Larionov et al. (2004). A primary beam of molecular oxygen was employed to bombard zircon in order to sputter secondary ions. The elliptical analytical spots had a size of c. $27 \times 20 \mu\text{m}$, and the corresponding ion current was c. 4 nA. The sputtered secondary ions were extracted at 10 kV. The $80 \mu\text{m}$ wide slit of the secondary ion source, in combination with a $100 \mu\text{m}$ multiplier slit, allowed mass-resolution of $M/\Delta M \geq 5,000$ (1% valley) so that all the possible isobaric interferences were resolved. One minute rastering over a rectangular area of c. $60 \times 50 \mu\text{m}$ was employed before each analysis in order to remove the gold coating and possible surface common Pb contamination.

The following ion species were measured in sequence: $^{196}(\text{Zr}_2\text{O})$ – ^{204}Pb –background (c. 204 AMU)– ^{206}Pb – ^{207}Pb – ^{208}Pb – ^{238}U – ^{248}ThO – ^{254}UO with integration time ranging from 2 to 20 s. Four cycles for each spot analyzed were acquired. Each fifth measurement was carried out on the zircon Pb/U standard TEMORA (Black et al. 2003) with an accepted $^{206}\text{Pb}/^{238}\text{U}$ age of 416.75 ± 0.24 Ma. The 91500 zircon with a U concentration of 81.2 ppm and a $^{206}\text{Pb}/^{238}\text{U}$ age of $1,062 \pm 0.4$ Ma (Wiedenbeck et al. 1995) was applied as a “U-concentration” standard.

The collected results were then processed with the SQUID v1.12 (Ludwig 2005a) and ISOPLOT/Ex 3.22 (Ludwig 2005b) software, using the decay constants of Steiger and Jäger (1977). The common lead correction was done using measured ^{204}Pb according to the model of Stacey and Kramers (1975). The results of the zircon analyses are shown in Table 1 and in Figs. 3 and 4.

General zircon characteristics

Antoniuk (1990) and Turniak (in Kryza et al. 1994) showed that the zircons of the Gackowa sandstones belong to various populations and that this heterogeneity is typical of samples throughout the entire outcrop. The zircons in our sample P1 are short- to normal-prismatic, some nearly spherical in shape, often with moderately to strongly rounded edges. In most crystals, the prism (100) dominates over (110) and both pyramids, (101) and (211), are well developed (barrel-shaped habit). Many of the crystals show distinct zoning, often asymmetrical and cut by the grain surface. Some grains contain distinct cores and domi-

nantly transparent inclusions. Many crystals are broken and their broken edges are rounded, this reflecting their detrital history. Details of the morphology and inner structure of the zircons studied as well as analytical spot locations can be found in Fig. 2.

SHRIMP data

All the isotope data were obtained during one analytical session. The corresponding results are presented in Table 1 and on Figs. 3 and 4. The ages given in the text are Concordia ages ± 2 sigma errors.

Group A: The oldest zircons, >2.4 Ga

Three zircon grains yielded nearly concordant Archean and early Proterozoic ages (point 5.1, 3411 ± 17 ; 8.1, 2971 ± 560 ; and 13.1, 2463 ± 350 Ma (errors at 95% confidence level). The oldest grain is a rounded, ellipsoidal fragment of a possibly long-prismatic crystal, transparent, the weak zoning of which is cut by the grain surface. The second oldest date (8.1) is from the rim of a rounded zircon with a distinct “euhedral” internal zoning pattern. The third zircon of that Archean group (13.1) is also rounded, oval in shape, and semi-transparent. All three crystals are moderately rich in Th (71, 127 and 308 ppm) and U (170, 237, 285 ppm). The Th/U ratios are high, above 0.42, which is normally considered to reflect magmatic origin (e.g., Rubatto and Gebauer 2000).

Group B: Early Proterozoic zircons (c. 2.0 Ga)

This group comprises four analyses from four zircon grains, with mostly good concordant ages: P1_11.1, 2094 ± 31 ; 16.1, 2067 ± 29 ; 14.1, 1995 ± 25 and 12.1, discordant $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1982 ± 18 Ma. They are spherical in shape and have a poorly developed internal structure. Grain 12.1 shows strong irregular zoning, whereas grains 14.1 and 16.1 show nearly structureless clear interiors. All four have generally constant U contents (205–301 ppm) but Th varies from 4 to 198 ppm. The Th/U ratios in three of the four analytical points are greater than 0.2, typical of magmatic origin.

Three points yielded strongly discordant values and their $^{207}\text{Pb}/^{206}\text{Pb}$ ages are interpreted as minimum estimates for the true ages: P1_1.1, c. 1.7 Ga; P1_4.2, c. 1.4 Ga; and P1_7.1, c. 875 ± 227 Ma (2σ error). The first analytical point is located in a distinct core of a subhedral, barrel-shaped zircon grain that has a strongly zoned mantle. The less obvious “core” P1_7.1 in a similarly

Table 1 Results of U–Pb SHRIMP dating of detrital zircons from the Gackowa sandstone, sample P1

Spot Name	$^{206}\text{Pb}_\text{C}$ (%)	U (ppm)	Th (ppm)	$\frac{^{232}\text{Th}}{^{238}\text{U}}$	Rad ^{206}Pb (ppm)	$\frac{^{206}\text{Pb}_\text{R}}{^{238}\text{U}}$	Error (%)	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$ Age	1 σ error	$\frac{^{207}\text{Pb}_\text{R}}{^{206}\text{Pb}_\text{R}}$	Error (%)	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$ Age	1 σ error	D (%)	Concordia age, Ma	$\pm 2\sigma$
4.2	2.65	953	2125	2.30	60.7	0.072	0.8	450	4	0.0905	3.8	1436	73	220	X	
9.2	0.00	621	228	0.38	47.4	0.089	0.8	548	4	0.0594	2.2	582	47	6	549	9
6.2	1.29	36	27	0.78	2.9	0.093	3.3	571	18	0.0591	14.5	571	316	0	571	36
2.1	0.14	278	183	0.68	22.2	0.093	1.4	572	8	0.0590	4.6	568	99	–1	572	15
7.2	0.41	237	56	0.24	19.1	0.094	1.3	577	7	0.0577	4.5	518	99	–10	577	14
4.1	0.55	47	47	1.03	3.8	0.094	2.9	579	16	0.0627	10.1	698	215	20	580	32
9.1	0.18	105	46	0.45	9.1	0.100	1.9	616	11	0.0603	4.9	614	107	0	616	22
15.1	0.00	909	174	0.20	78.8	0.101	0.6	620	4	0.0612	1.7	647	36	4	620	8
6.1	0.00	749	531	0.73	65.1	0.101	0.7	623	4	0.0606	1.8	625	38	0	623	9
10.1	0.39	91	57	0.65	8.0	0.102	2.0	626	12	0.0567	6.0	480	132	–23	625	24
3.1	0.64	147	76	0.53	13.3	0.104	1.7	639	10	0.0594	6.0	581	130	–9	639	20
7.1	0.00	87	20	0.24	9.0	0.121	2.2	736	15	0.0682	10.9	875	227	19	736	31
1.1	0.00	444	68	0.16	63.8	0.167	0.9	996	8	0.1036	1.4	1689	25	69	X	
12.1	0.09	205	4	0.02	63.0	0.358	1.1	1973	19	0.1285	1.3	2078	22	5	X	
14.1	0.00	301	198	0.68	94.3	0.365	1.0	2006	17	0.1218	1.0	1982	18	–1	1995	25
16.1	0.04	206	197	0.99	66.7	0.376	1.1	2058	20	0.1285	1.2	2078	21	1	2067	29
11.1	0.00	214	49	0.24	70.2	0.383	1.2	2089	21	0.1302	1.3	2100	22	1	2094	31
13.1	0.09	237	127	0.55	93.1	0.457	1.1	2425	22	0.1626	1.0	2483	16	2	2463	350 ^a
8.1	0.03	170	71	0.43	83.8	0.572	1.3	2917	30	0.2235	1.5	3006	23	3	2971	560 ^a
5.1	0.05	285	308	1.11	168.3	0.686	1.0	3368	25	0.2899	0.5	3417	8	1	3411	17

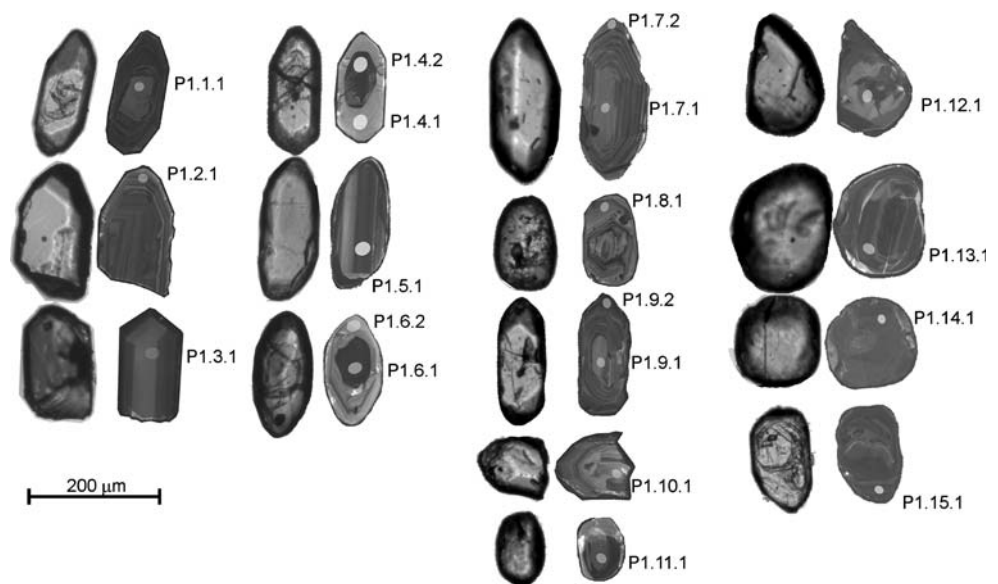
Pb_C and Pb_R are common and radiogenic lead, respectively. Errors are 1 σ unless otherwise specified. Error of standards mean $\pm 1\sigma$ – 0.28%. Given ages are corrected for measured ^{204}Pb

D%, discordancy D = $100 \times [(\text{age}^{207\text{Pb}/^{206}\text{Pb}})/(\text{age}^{206\text{Pb}/^{238}\text{U}}) - 1]$

X, discordant

^a Error at 95% confidence level

Fig. 2 Microphotographs (transmitted, non-polarized light–left columns) and CL images (right columns) of zircons analyzed from the Gackowa sandstone, sample P1. Various morphological types and various internal structures are represented (see text for further explanation). Analytical points indicated by brighter ellipses in CL images (note that magnification is slightly different from grain to grain; an approximate scale bar is given)



shaped zircon crystal has a zoned rim, 7.2, that belong to the dominant group D showing a Concordia age of 577 ± 14 Ma. Point 4.2 is within a dark internal part of a zircon crystal, conformably surrounded by an outer bright rim, the latter dated at 580 ± 32 Ma. This point (4.2) is extremely discordant which, together with its

chemical features (common $^{206}\text{Pb} = 2.65\%$, unusually high Th = 2125, and U = 953 ppm, and very high Th/U = 2.23), suggest a high-metamict state, implying easy Pb-loss. The true ages of all these three grains are, apparently, Precambrian, but cannot be more precisely assessed.

Fig. 3 Concordia diagram showing results of SHRIMP II zircon analyses from the Gackowa sandstone, sample P1 (symbols of analytical points correspond to those in Fig. 2 and Table 1)

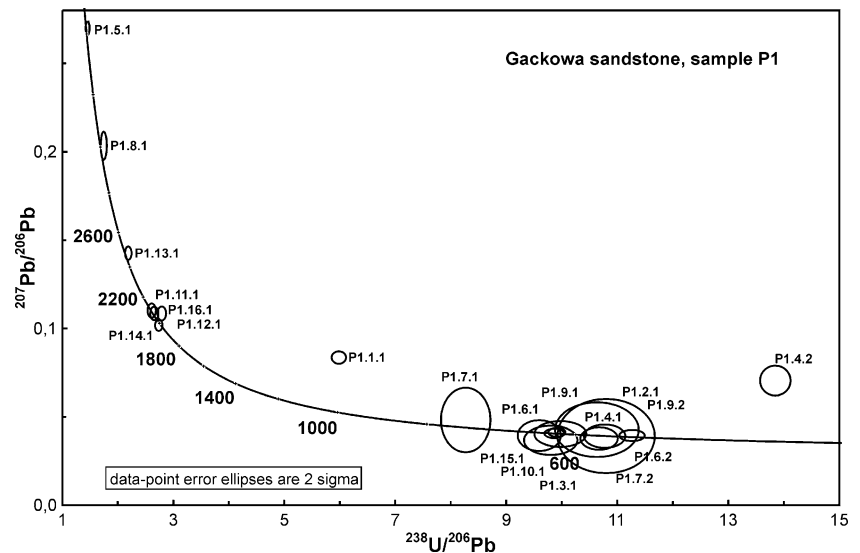
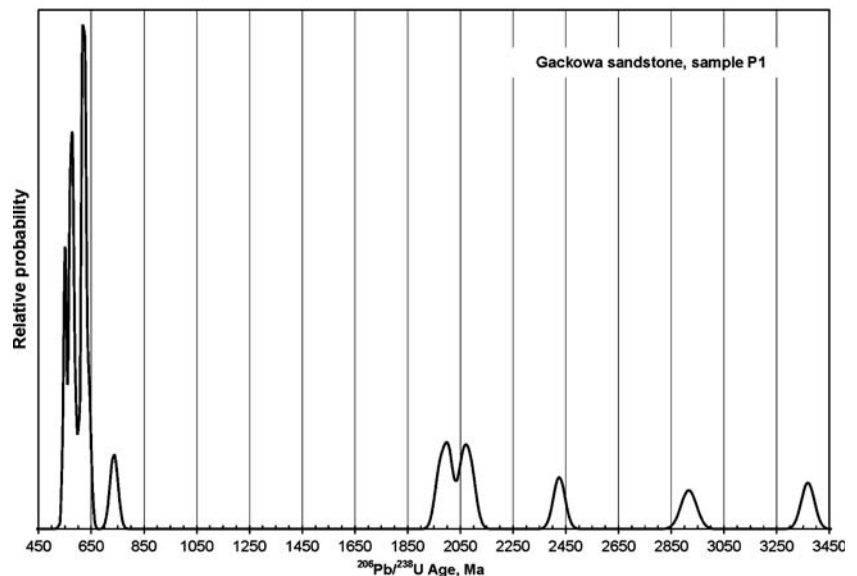


Fig. 4 Probability density plot of $^{206}\text{Pb}/^{238}\text{U}$ ages of zircons from the Gackowa sandstone, sample P1 ($n = 20$)



Group C: Zircons of 622 ± 10 Ma (mean age)

Five analytical points gave mostly (except for two spots) concordant ages around 622 Ma. Three of these (P1_6.1, 9.1, and 10.1) are in cores and the remaining two (3.1 and 15.1) are in the more external parts of roughly euhedral crystals with a characteristic barrel-shaped outline (due to significant development of two pyramids: (211) and (101)). The analyses showed variable Th (46–531 ppm) and U (91–909 ppm) concentrations. The Th/U ratios are fairly constant, between 0.19 and 0.71, typical of magmatic zircon. The rims of these four zircons appear to belong to the younger generation D of c. 575 Ma.

Group D: Zircons of 575 ± 20 Ma (mean age)

Most of the five points of this group display generally concordant ages. The corresponding analytical spots are located in rims of euhedral to subhedral, characteristically barrel-shaped crystals (see above and Fig. 2). The dominant parts of these crystals (mantles and rims) show intense zoning of oscillatory “magmatic” type. In two cases, the rims are CL-bright (6.2 and 4.1) which corresponds to their low U (36 and 47 ppm, respectively) and Th (27 and 47 ppm) contents. In the other analytical spots, the concentrations of these elements are higher: Th 56–228 ppm, U 237–621 ppm. The Th/U ratios are similar to those within

Group C (0.24–0.99), characteristic of magmatic zircons.

Discussion and conclusion

Twenty analyses from 16 zircon grains reveal a wide spectrum of ages (Fig. 4), all but one (considerably disturbed) grain being Precambrian. The oldest zircons (Group A) include Archaean grains of c. 2.5, 2.9, and 3.4 Ga, the latter being among the oldest dated zircons in this part of the Variscan belt.

Three groups of younger zircon ages are coherent and comprise four to five analytical points each:

- Group B: c. 2.0 Ga
- Group C: 622 ± 10 Ma
- Group D: 575 ± 20 Ma

Three individual, strongly discordant ages obtained, apparently, also represent various Proterozoic sources, however, only their minimum ages, between c. 875 Ma and 1.7 Ga, can be estimated.

Group B, c. 2.0 Ga in age, is well defined and represented by very rounded grains, derived from a Palaeoproterozoic source, that must have gone through prolonged sedimentary abrasion. Zircons of similar age are very common inherited components in the Variscan crust elsewhere (Zeh et al. 2001) and, thus, provide evidence for intense crust-forming processes in Early Proterozoic times (Gebauer et al. 1989; Friedl et al. 2000, 2004).

Group C with ages of 622 ± 10 Ma is also clearly defined: three of five ages are from zircon cores, while the other two obtained from outer parts of barrel-shaped crystals which are morphologically distinct due to the presence of two pyramids: (211) and (101). The majority of the outer parts and rims display distinct zoning typical of magmatic growth (e.g., Rubatto and Gebauer 2000; Kempe et al. 2000 and references therein) and these were found to belong to the younger Group D with ages of 575 ± 20 Ma. It seems likely that zircons of the C and D age groups come from the same source, e.g., granitoids intruded at c. 575 Ma but containing a vestige of an older magmatic/high-grade metamorphic or anatexic event represented by inherited zircons of c. 622 Ma. Zircons of similar ages have been found elsewhere across the Cadomian basement blocks incorporated into the Variscan belt (Friedl et al. 2000, 2004; Zeh et al. 2001).

Importantly, no detrital zircons younger than c. 550 Ma have yet been found in the Gackowa Formation sandstone. This runs counter to the previous interpretation (Kryza et al. 1994) in which, based largely on similarities in zircon morphology, the seemingly

contemporaneous felsic volcanics of the neighbouring area (the Osełka Rhyodacites recently dated at 501 ± 2.7 Ma, Kryza et al. 2007, in press) were thought to be the main source of detritus supplied to the sandstones. Our new data comprehensively falsifies this hypothesis, and indicates that the source area for these sandstones was a terrain containing dominant Precambrian granitoids or products of their reworking, such as the Lusatian Massif to the west.

However, we emphasize that the absence of zircon grains younger than c. 550 Ma, at the present state of investigations, cannot yet rule out an early Palaeozoic depositional age. Firstly, because the sample set analysed is insufficiently large to ensure that no zircon younger than 550 Ma was omitted at the sample selection stage; conceivably, there may have been rare zircons of that age that escaped recognition. Secondly, potential source rocks younger than c. 550 Ma might simply have not been exposed and hence did not supply any detrital material at the time of deposition of the Gackowa sandstones.

Thus, the new data do not preclude a Cambrian–Early Ordovician depositional age of the Gackowa sandstones, earlier assigned to them on grounds of assumed superposition and association (Kryza and Muszyński 1992; Fig. 5, alternative correlation 1; Fig. 6). However, it now seems equally likely that sedimentation took place in the late Neoproterozoic (though not earlier than 575 Ma). For comparison, the sedimentation of the nearby located Lusatian graywackes and mudstones commenced at 575 Ma (Linnemann et al. 2000, 2004; Linnemann and Romer 2002), i.e., exactly at the time constrained as the maximum depositional age of the Gackowa Formation sandstones. Qualified support for a Precambrian depositional age is given by the lack, to date, of any trace fossils or body fossils within the Gackowa Formation (Kryza et al. 1994). If the Gackowa sandstones were Neoproterozoic in age, then their deposition would not be related to the Cambro-Ordovician rifting of Gondwana, but would relate to an earlier phase of the evolution of this region (and be broadly equivalent to the Lusatian greywackes; Fig. 5, alternative correlation 2; Fig. 7). Subsequent tectonic interleaving of lithologies, characterized by contrasting ages and provenance, would have taken place during the Variscan orogeny, within the Kaczawa accretionary prism.

The time span between 622 and 575 Ma, constrained by zircons of groups C and D, corresponds to the period of Cadomian magmatic activity in the type area of the Armorican Massif (Samson et al. 2005; Inglis et al. 2005). Two distinct thermal events at c. 615–600 and 585–575 Ma, documented in that area, fit perfectly

Fig. 5 Two alternative correlations of the Gackowa sandstones: 1 with the Early Ordovician Dubrau quartzites (normal stratigraphic succession), and 2 with the Neoproterozoic Lusatian greywackes (tectonic incorporation into Early Palaeozoic succession)

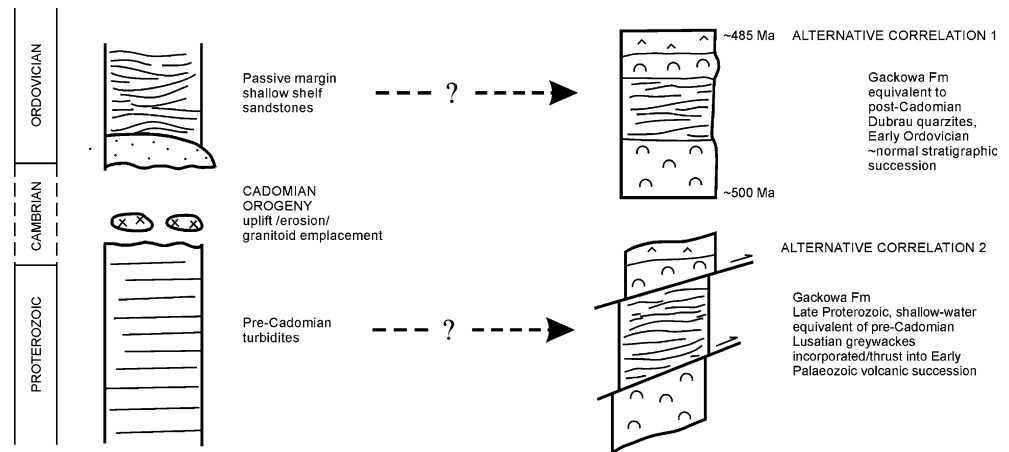


Fig. 6 Scenario 1: the Gackowa Formation developed as passive margin shallow-water sandstones within an early Palaeozoic extensional basin

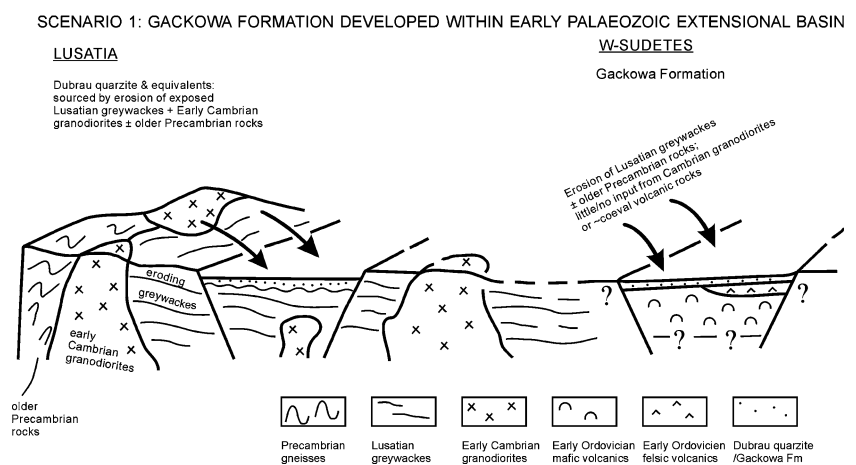
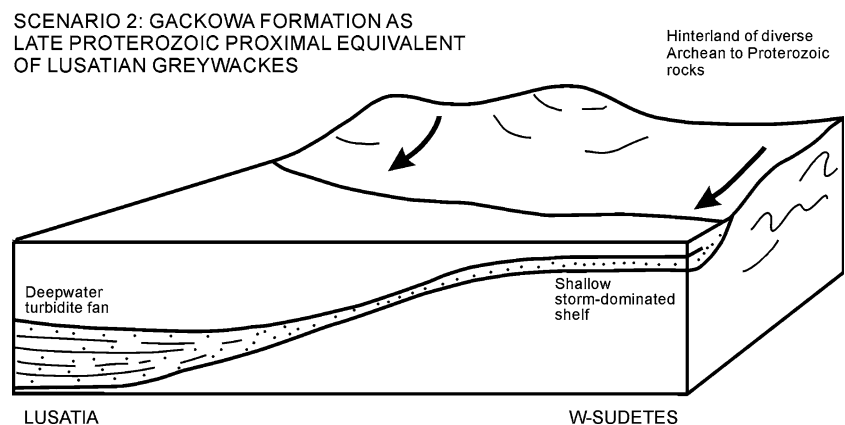


Fig. 7 Scenario 2: the Gackowa Formation as a possible shallow-water equivalent of the pre-Cadomian Lusatian greywackes



to those revealed by the zircons analysed from the Gackowa sandstones. By contrast, the lack of Mesoproterozoic zircons seems to preclude the derivation of detritus from crust characteristic of Avalonia or Baltica. Consequently, the source supplying the material to the Gackowa sandstones must have comprised Cadomian granites, which are widespread within the Neoproterozoic crust belonging to the Armorican

Terrane Assemblage. The nearest present-day exposure of Neoproterozoic granitoids extends over the Saxothuringian Zone of East Germany, starting c. 70 km to the west of the sandstone locality sampled. However, the emplacement age of many granitoids currently cropping out in that area is dated by zircons at c. 540 Ma (Linnemann et al. 2000), i.e., 35 Ma later than the age of magmatic zircons found in the Gack-

owa Formation. Thus, the Neoproterozoic granitoids of Saxothuringia cannot represent the source for detritus of the Gackowa sandstones, either because they were not exposed at the time of their deposition, or because they were intruded after the Gackowa Formation was deposited. On the other hand, the granitic pebbles and detrital zircons extracted from the Lusatian graywackes and associated deposits yielded an age spectrum of 630–575 Ma (Linnemann et al. 2000, 2004), closely comparable to the scatter of Neoproterozoic ages obtained from the Gackowa Formation. Consequently, the Gackowa sandstones and the Lusatian deposits may well have been supplied from the same or a similar source area currently buried beneath younger deposits or nappe units. This correlation supports (1) the Saxothuringian affinities of the Gackowa sandstones and, possibly, of the entire Kaczawa succession, and (2) the large-scale allochthonous nature of the Kaczawa accretionary complex as postulated in recent nappe models (Collins et al. 2000; Seston et al. 2000).

The diverse assemblage of the Palaeoproterozoic and Archean zircons indicates a polygenetic character of the Precambrian basement (sedimentary source). Their presence shows that a Cadomian thermal event overprinted older crust characterized by a complex evolution and structure, including Archean components that are relatively rare in the Armorican terranes (Zeh et al. 2001). The similarity of the Palaeoproterozoic-Archean age spectrum obtained in this study to that recently documented for the deposits of the Saxothuringian Zone of Germany additionally supports a Saxothuringian affinity for the Gackowa Formation and, furthermore, points to their West African provenance (see discussion in Linnemann et al. 2004).

Acknowledgments Wrocław University Internal Grant 2022/W/ING/05 provided funds for the SHRIMP study. Maciek Kryza helped in preparing computerized figures. The mounting and preparation of zircons was done by Anna Saltykova (CIR VSEGEI). Ulf Linnemann and an anonymous reviewer are thanked for their constructive comments.

References

- Aleksandrowski P, Mazur S (2002) Collage tectonics in the northeasternmost part of the Variscan belt: the Sudetes, Bohemian Massif. In: Winchester J, Pharaoh T, Verniers J (eds) Palaeozoic Amalgamation of Central Europe. *Geol Soc Lond Spec Publi* 201:237–277
- Antoniuk A (1990) Zircons from epimetamorphic rocks of the Świerżawa Unit in the Kaczawa Mts. Unpublished MSc Thesis, University of Wrocław, Wrocław, pp 1–80 (in Polish)
- Baranowski Z, Haydukiewicz A, Kryza R, Lorenc S, Muszyński A, Solecki A, Urbanek Z (1990) Outline of the geology of the Góry Kaczawskie (Sudetes, Poland). *N Jb Geol Paläont Abh* 179:223–257
- Black LP, Kamo SL, Allen CM, Aleinikoff JN, Davis DW, Korsch RJ, Foudoulis C (2003) TEMORA 1: a new zircon standard for Phanerozoic U–Pb geochronology. *Chem Geol* 200:155–170
- Collins AS, Kryza R, Zalasiewicz JA (2000) Macrofabric fingerprints of Late Devonian–Early Carboniferous subduction in the Polish Variscides, the Kaczawa complex, Sudetes. *J Geol Soc Lond* 157:283–288
- Cymerman Z (2002) Analiza strukturalno–kinematyczna i waryscyjska ewolucja tektoniczna kompleksu kaczawskiego. Variscan tectonic evolution of the Kaczawa complex revealed by structural and kinematic analysis. *Prace Państwowego Instytutu Geologicznego CLXXV*, pp 1–147 (in Polish, English summary)
- Edel JB, Weber K (1995) Cadomian terranes, wrench faulting and thrusting in the central Europe Variscides: geophysical and geological evidence. *Geol Rundsch* 84:412–432
- Fedo CM, Sircombe KN, Rainbird RH (2003) Detrital zircon analysis of the sedimentary record. *Rev Mineral Geochem* 53:277–303
- Floyd PA, Winchester JA, Seston R, Kryza R, Crowley QG (2000) Review of geochemical variation in Lower Palaeozoic metabasites from the NE Bohemian Massif: intracratonic rifting and plume–ridge interaction. In: Franke et al. (eds) Orogenic processes: quantification and modelling in the Variscan belt. *Geol Soc Lond Spec Publi* 179:155–174
- Friedl G, Finger F, McNaughton NJ, Fletcher IR (2000) Deducing the ancestry of terranes: SHRIMP evidence for South America-derived Gondwana fragments in central Europe. *Geology* 28:1035–1038
- Friedl G, Finger F, Paquette JL, von Quadt A, McNaughton NJ, Fletcher IR (2004) Pre-Variscan geological events in the Austrian part of the Bohemian Massif deduced from U–Pb zircon ages. *Int J Earth Sci (Geol Rundsch)* 93:802–823
- Furnes H, Kryza R, Muszyński A, Pin C, Garmann LB (1994) Geochemical evidence for progressive rift-related volcanism in the eastern Variscides. *J Geol Soc Lond* 151:91–109
- Gebauer D, Williams IS, Compston W, Grünenfelder M (1989) The development of the central European continental crust since the early Archean based on conventional and ion-microprobe dating of up to 3.84 by old detrital zircons. *Tectonophysics* 157:81–96
- Inglis JD, Samson SD, D’Lemos RS, Miller BV (2005) Timing of Cadomian deformation and magmatism within La Hague NW France. *J Geol Soc Lond* 162:389–400
- Kempe U, Gruner T, Nasdala L, Wolf D (2000) Relevance of cathodoluminescence for interpretation of U–Pb zircon ages, with an example of an application to a study of zircons from the Saxonian Granulite Complex, Germany. In: Pagel M, Barbin V, Blanc P, Ohnenstetter D (eds) Cathodoluminescence in geosciences. Springer, Berlin Heidelberg New York, pp 415–455
- Kryza R, Muszyński A (1992) Pre-Variscan volcanic-sedimentary succession of the central southern Góry Kaczawskie, SW Poland: Outline Geology. *Ann Soc Geol Pol* 62:117–140
- Kryza R, Muszyński A (2003) Kompleks metamorficzny Gór Kaczawskich—fragment waryscyjskiej pryzmy akrecyjnej. The metamorphic Kaczawa complex—fragment of Variscan accretionary prism. In: Ciężkowski W, Wojewoda J, Żelazniewicz A (eds) Sudety Zachodnie: od wendy do czwartorzędu. WIND, Wrocław, pp 95–104 (in Polish, English summary)
- Kryza R, Muszyński A, Vielzeuf D (1990) Glaucofane-bearing assemblage overprinted by greenschist-facies metamor-

- phism in the Variscan Kaczawa complex, Sudetes, Poland. *J Metamorph Geol* 8:345–355
- Kryza R, Muszyński A, Turniak K, Zalasiewicz JA (1994) A Lower Palaeozoic shallow-water sequence in the eastern European Variscides (SW Poland): provenance and depositional history. *Geol Rundsch* 83:5–19
- Kryza R, Aleksandrowski P, Mazur S (1998) The structural and metamorphic evolution of the Kaczawa Complex (West Sudetes): a tentative model. *EUROPROBE TESZ and PACE TMR network meetings Prague, 4–6 Oct 1998, Abstract volume*, pp 25
- Kryza R, Mazur S, Oberc-Dziedzic T (2004) The Sudetic geological mosaic: insights into the root of the Variscan orogen. *Przegl Geol* 52(8/2):761–773
- Kryza R, Mazur S, Aleksandrowski P, Zalasiewicz J, Sergeev S, Presnyakov S (2007) Ordovician initial-rift volcanism in the Central European Variscides (the Kaczawa Mountains, Sudetes, SW Poland): evidence from SHRIMP dating of zircons (in press)
- Larionov AN, Andreichev VA, Gee DG (2004) The Vendian alkaline igneous suite of northern Timan: ion microprobe U–Pb zircon ages of gabbros and syenite. In: Gee DG, Pease VL (eds). *The Neoproterozoic Timanide Orogen of Eastern Baltica*. *Geol Soc Lond Mem* 30:69–74
- Linnemann U, Romer RL (2002) The Cadomian orogeny in Saxo-Thuringia, Germany: geochemical and Nd–Sr–Pb isotopic characterization of marginal basins with constraints to geotectonic setting and provenance. *Tectonophysics* 352:33–64
- Linnemann U, Gehmlich M, Tichomirova M, Buschmann B, Nasdala L, Jonas P, Lützner H, Bombach K (2000) From Cadomian subduction to Early Palaeozoic rifting: the evolution of Saxo-Thuringia at the margin of Gondwana in the light of single zircon geochronology and basin development (Central European Variscides, Germany). In: Franke W, Haak V, Oncken O, Tanner D (eds). *Orogenic processes: quantification and modelling in the Variscan belt*. *Geol Soc Lond Spec Publ* 179:131–153
- Linnemann U, McNaughton NJ, Romer RL, Gehmlich M, Drost K, Tonk C (2004) West African provenance for Saxo-Thuringia (Bohemian Massif): did Armorica ever leave pre-Pangean Gondwana?—U/Pb-SHRIMP zircon evidence and the Nd-isotopic record. *Int J Earth Sci* 93:683–705
- Ludwig KR (2005a) SQUID 1.12 A User's Manual. A Geochronological Toolkit for Microsoft Excel. Berkeley Geochronology Center Special Publication, pp 1–22, <http://www.bgc.org/klprogrammmenu.html>
- Ludwig KR (2005b) User's Manual for ISOPLOT/Ex 3.22. A Geochronological Toolkit for Microsoft Excel. Berkeley Geochronology Center Special Publication, pp 1–71, <http://www.bgc.org/klprogrammmenu.html>
- Pacholska A (1975) Petrography of metasandstones of the Świerzawa Unit in the Kaczawa Mts (Góry Kaczawskie). *Geologia Sudetica* 10:105–116 (in Polish, English summary)
- Pin C, Marini F (1993) Early Ordovician continental break-up in Variscan Europe: Nd–Sr isotope and trace element evidence from bimodal igneous associations of Southern Massif Central, France. *Lithos* 29:177–196
- Pin C, Kryza R, Oberc-Dziedzic T, Mazur S, Turniak K, Waldhausová J (2007) The diversity and geodynamic significance of Late Cambrian (ca. 500 Ma) felsic anorogenic magmatism in the northern part of the Bohemian Massif: a review based on Sm–Nd isotope and geochemical data. In: Linnemann U, Kraft P, Nance D, Zulauf G (eds). *The Geology of Peri-Gondwana: Avalonian-Cadomian terranes, adjoining cratons, and the Rheic Ocean*. *Geol Soc Am Spec Publi* (in press)
- Rubatto D, Gebauer D (2000) Use of cathodoluminescence for U–Pb zircon dating by ion microprobe: some examples from the Western Alps. In: Pagel M, Barbin V, Blanc P, Ohnenstetter D (eds). *Cathodoluminescence in geosciences*. Springer, Berlin Heidelberg New York, pp 373–400
- Samson SD, D'Lemos RS, Miller BV, Hamilton MA (2005) Neoproterozoic paleogeography of the Cadomia and Avalon terranes: constraints from detrital zircon U–Pb ages. *J Geol Soc Lond* 162:65–71
- Seston R, Winchester JA, Piasecki MAJ, Crowley QG, Floyd PA (2000) A structural model for the western-central Sudetes: a deformed stack of Variscan thrust sheets. *J Geol Soc Lond* 157:1155–1167
- Stacey JS, Kramers JD (1975) Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth Planet Sci Lett* 26:207–221
- Steiger RH, Jäger E (1977) Subcommittee on geochronology: convention on the use of decay constants in geo- and cosmochemistry. *Earth Planet Sci Lett* 36:359–362
- Teisseyre H (1963) Siodło Bolków–Wojcieszów jako charakterystyczny przykład struktury kaledońskiej w Sudetach Zachodnich. The Bolków–Wojcieszów Anticline—a representative Caledonian structure in the Western Sudetes. *Prace Instytutu Geologicznego* 30:279–300 (in Polish, English summary)
- Wiedenbeck M, Allé P, Corfu F, Griffin WL, Meier M, Oberli F, Von Quadt A, Roddick JC, Spiegel W (1995) Three natural zircon standards for U–Th–Pb, Lu–Hf, trace element and REE analyses. *Geostand News* 19:1–23
- Williams IS (1998) U–Th–Pb Geochronology by ion microprobe. In: *Applications in microanalytical techniques to understanding mineralizing processes*. *Rev Econ Geol* 7, pp 1–35
- Zeh A, Braetz H, Millar IL, Williams IS (2001) A combined zircon SHRIMP and Sm–Nd isotope study of high-grade paragneisses from the Mid-German crystalline rise; evidence for northern Gondwanan and Grenvillian provenance. *J Geol Soc Lond* 158(6):983–994
- Zimmermann E (1932) *Geologische Karte von Preussen und benachbarten deutschen Ländern*, 1:25 000, Blatt Hirschberg. Preussische Geologische Landesanstalt, Berlin