Geol. Mag. **145** (*1*), 2008, pp. 85–93. © 2007 Cambridge University Press
doi:10.1017/S0016756807003962 First published online 15 October 2007 *Printed in the United Kingdom*

Multiple Archaean to Early Palaeozoic events of the northern Gondwana margin witnessed by detrital zircons from the Radzimowice Slates, Kaczawa Complex (Central European Variscides)

RAFAŁ TYSZKA*, RYSZARD KRYZA*§, JAN A. ZALASIEWICZ† & ALEXANDER N. LARIONOV‡

*University of Wrocław, Institute of Geological Sciences, Department of Mineralogy and Petrology, ul. Cybulskiego 30, 50-205 Wrocław, Poland
†University of Leicester, Department of Geology, University Road, Leicester LE1 7RH, UK
‡Centre of Isotopic Research, A.P. Karpinsky All Russian Geological Research Institute (VSEGEI), 74 Sredny Pr, St Petersburg, 199 106, Russia

(*Received* 18 November 2006; *accepted* 16 March 2007)

Abstract – SIMS dating of detrital zircons from the stratigraphically enigmatic Radzimowice Slates of the Kaczawa Mountains (Sudetes, SW Poland), near the eastern termination of the European Variscides, has yielded age populations of: (1) 493–512 Ma, corresponding to late Cambrian to early Ordovician magmatism and constraining a maximum depositional age; (2) between 550 and 650 Ma, reflecting input from diverse Cadomian sources; and (3) older inherited components ranging to *c.* 3.3 Ga, with age spectra similar to those from Gondwanan North Africa. The new data show that the Radzimowice Slates cannot form a Proterozoic base to the Kaczawa Mountains succession, as suggested by earlier models, but was deposited, at the earliest, as an extensional basin-fill, during a relatively late stage of the break-up of this part of northern Gondwana.

Keywords: SIMS zircon dating, slates, Kaczawa Complex, Sudetes, Variscides, Gondwana.

1. Introduction

The eastern termination of the Variscan belt of central Europe exposed in the Sudetes of SW Poland remains largely enigmatic, despite nearly two centuries of close study (Zimmermann, 1932; Teisseyre, 1963; Baranowski *et al.* 1990; Kryza & Muszyński, 1992; Kryza, Mazur & Oberc-Dziedzic, 2004; Mazur *et al.* 2006; and references therein). The component rock masses are mostly poorly exposed, tectonically dismembered and variably metamorphosed up to granulite grade. Even the lower-grade, (anchi-/epizone) sedimentary successions are pervasively sheared, rendering most searches for macro- and microfossils futile and seriously hindering attempts to determine depositional age and to construct stratigraphic successions.

These difficulties have created sufficient uncertainty in geological interpretation to lead to serious debate, even in recent years, over whether this region is indeed Variscan in construction, or is Caledonian with a minor Variscan overprint (Oliver, Corfu & Krogh, 1993, Aleksandrowski *et al.* 2000). Its Variscan nature has recently been confirmed by combining detailed field studies with the application of modern geochronological techniques, including SIMS dating. This has allowed elucidation of a generalized history for the region of Cambro-Ordovician rifting and continental break-up, Silurian–early Devonian ocean opening, and ocean closure in late Devonian to early Carboniferous times culminating in continent–continent collision (e.g. Baranowski *et al.* 1990; Furnes *et al.* 1994; Collins, Kryza & Zalasiewicz, 2000; Seston *et al.* 2000; Kryza & Muszyński, 2003; Kryza, Mazur & Oberc-Dziedzic, 2004; Mazur *et al.* 2006).

While this broad regional framework now seems to be commonly accepted, there remain many substantial questions related to extensively outcropping rock units whose position within this framework, and hence whose contribution to the geological picture, is unknown.

One notable example has been the Radzimowice Slates of the Kaczawa Complex in the West Sudetes (Fig. 1), a northeastern part of the Bohemian Massif. The Radzimowice Slates have been attributed variously to the Neoproterozoic (Teisseyre, 1963) and early Palaeozoic, the latter assignation being based on sparse and low-resolution conodont evidence (Urbanek & Baranowski, 1986), while a sedimentological analysis (Baranowski, 1988) inferred a trench-fill setting, suggesting a further alternative of possible late Palaeozoic deposition during ocean closure.

§Author for correspondence: rkryza@ing.uni.wroc.pl

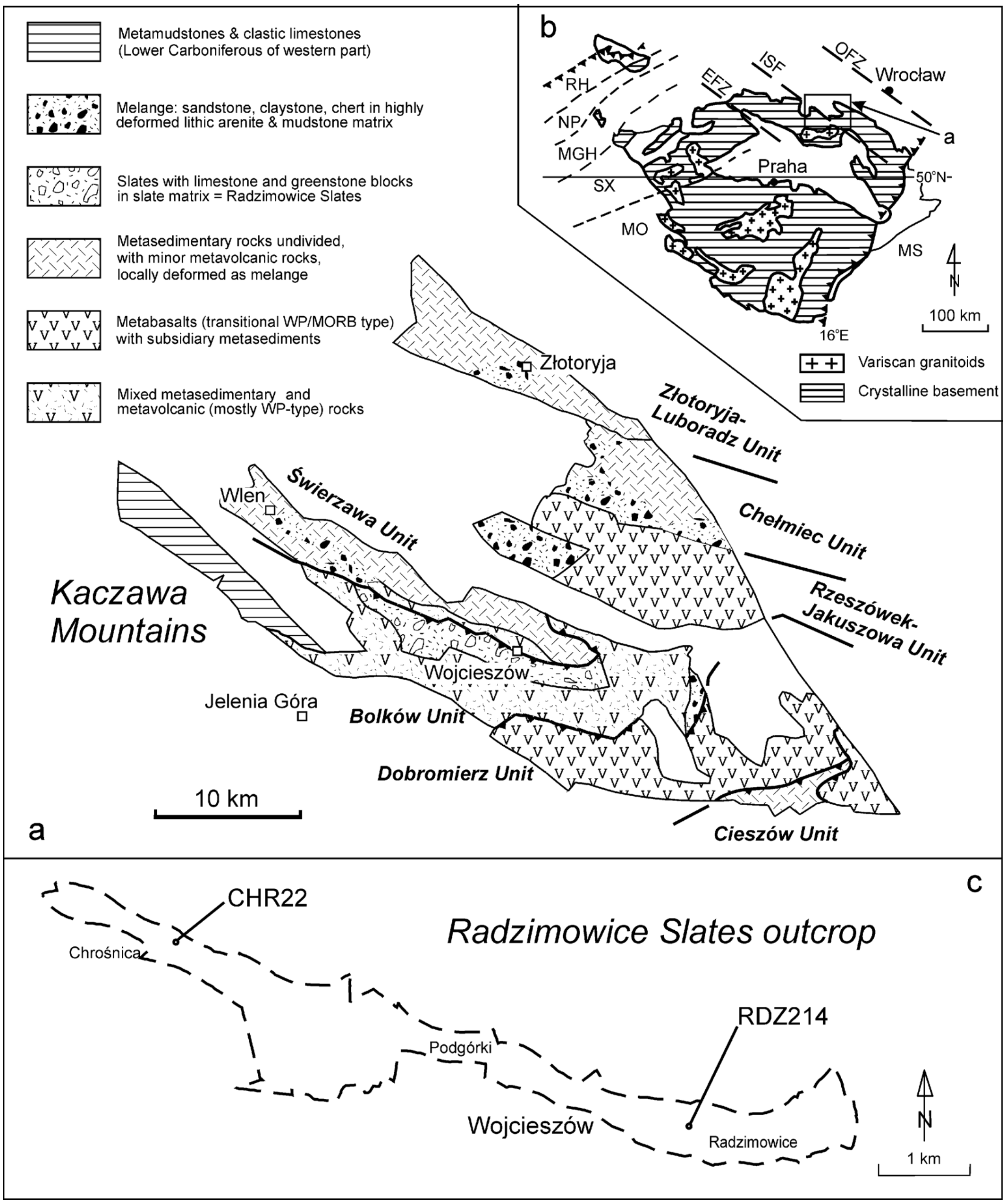

Figure 1. Geological sketch map of the Kaczawa Mountains (a) showing major lithological subdivisions, tectonic units and location of the study area and sampling sites (c). Inset map (b) shows the location of the area in the Bohemian Massif; EFZ – Elbe Fault Zone; ISF–Intra-Sudetic Fault; MGH – Mid-German Crystalline High; MO – Moldanubian Zone; MS – Moravo-Silesian Zone; NP – Northern Phyllite Zone; OFZ – Odra Fault Zone; RH – Rhenohercynian Zone; SX – Saxothuringian Zone. The Radzimowice Slates outcrop (c) based on Zimmermann (1932) and Baranowski (1988).

In this report we present new results of SHRIMP dating of detrital zircons from the Radzimowice Slates. These give useful constraints on approximate depositional age and local stratigraphic context, and additionally provide important insights into contemporaneous palaeogeography, helping place the Sudetan region into its global palaeogeographic context.

2. Geological setting

The Radzimowice Slates form an outcrop up to 3 km wide and 20 km long in the central southern Kaczawa Mountains (Fig. 1). Formerly, on the basis of regional lithological correlations, they were assigned to the latest Proterozoic and considered as the lowermost part of the Bolków Unit, thrust over the (para)autochthonous Świerzawa Unit (Teisseyre, 1963; Fig. 1). More recently their age was revised to not older than Ordovician, based on sparse and low-resolution conodont findings (Urbanek & Baranowski, 1986), and they were re-interpreted as a separate tectonic unit, the Radzimowice Unit (Kryza & Muszyński, 1992).

The Radzimowice Slates comprise a set of variably deformed rocks, locally mylonitic, but with low-strain

https://doi.org/10.1017/S0016756807003962 Published online by Cambridge University Press

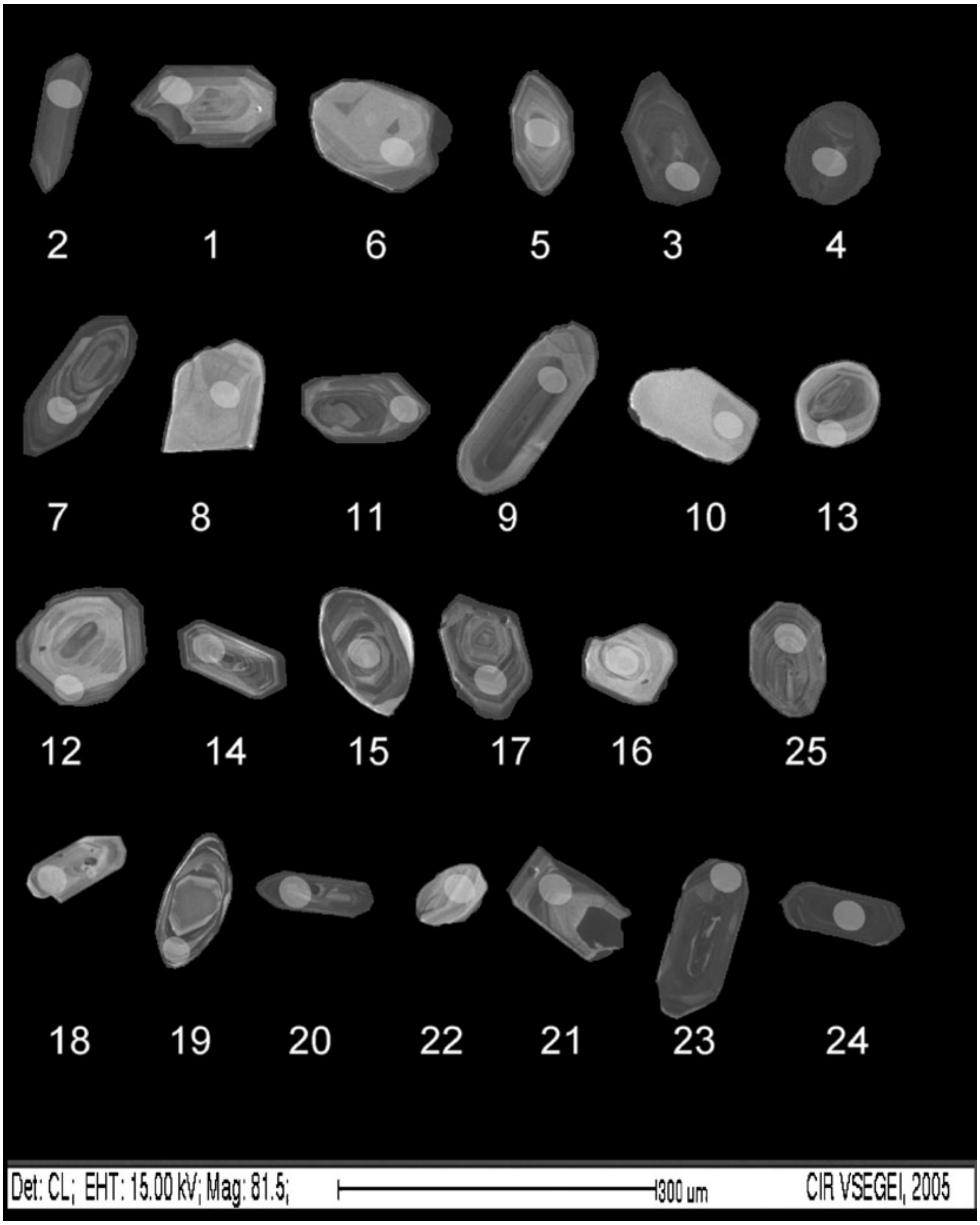

Figure 2. CL images of selected zircons of sample CHR22. Analytical points indicated by brighter ovals; their symbols correspond to those given in Table 1.

domains preserving primary sedimentary features. Strongly foliated, white-mica-rich varieties could be termed phyllites or even mylonites, but here we prefer to use the local traditional term 'slates' for this rock assemblage. The metamorphic grade corresponds to the epizone (greenschist facies) as shown by their fabric and mineral composition, as well as by the white mica characteristics (Baranowski, 1988, Kryza & Muszyński, 2003).

Baranowski (1988) recognized relict sedimentary structures and distinguished a range of lithofacies, including: mudstones that are variably siliceous, graphitic or silt-laminated; siltstones; fine-grained sandstones (quartz wackes); medium- and coarse-grained sandstones (lithic wackes with volcanic component); chaotic deposits (sedimentary breccias and olistoliths of mafic volcanics and limestones); and mafic tuffites. He interpreted this suite as representing turbidites and hemipelagites/pelagites with intercalated slide to debris flow deposits. The lithic wackes were interpreted as sourced from a magmatic arc, and the quartz wackes from a continental block. The facies association and the petrographic composition of the lithic wackes were ascribed to deposition in an oceanic trench or an immature slope basin.

Seston *et al.* (2000) suggested that the Radzimowice Slates represent a high-strain zone sandwiched between the low-strain Świerzawa Unit and the moderate-strain Bolków Unit (Fig. 1). In such a structural position, the slates could incorporate a range of rocks of various ages, including those seen in the neighbouring units. However, the lithological association of the Radzimowice Slates is distinct and represents an internally consistent sedimentary succession markedly different from those exposed in the neighbouring units. For instance, they include negligible volcanic rocks other than a few probable olistoliths.

Thus, the primary nature, age and tectonic position of the Radzimowice Slates have remained controversial, and their resolution is critical to constructing wider regional geological interpretations.

3. Methods

Two samples were selected for SIMS zircon dating (Fig. 1c):

(1) Sample CHR22 is a dark grey, fine-grained slate, composed of quartz, white K-mica, and minor albite, K-feldspar and black carbon-rich matrix; it comes from a small gorge, 300 m NW of the church at Chrośnica, in the western part of the Radzimowice Slates outcrop.

(2) Sample RDZ214 is a pale grey to greenish grey, fine-grained slate, composed of quartz, white K-mica, and subordinate K-feldspar and chlorite (± altered biotite); it was collected in a small exposure, 1.5 km east of Wojcieszów Górny (eastern part of the Radzimowice Slates outcrop).

Both the samples represent a facies of thinly laminated mudstones with silt laminae, as defined by Baranowski (1988); in the former exposure they are associated with siliceous and graphitic slates. The relative stratigraphic position of both the samples is unknown.

The samples, each about 3 kg in weight, were crushed, and heavy minerals separated by a conventional heavy liquid (sodium polytungstate, d 3.0 g cm^{-1}) method. Hand-picked zircon grains representing various morphological and structural types were studied by optical microscope and afterwards mounted in Buehler Epoquick® resin, ground and polished for CL imaging and *in situ* U–Pb dating. The analyses were performed on the SHRIMP II at VSEGEI, St Petersburg. The analytical conditions and data treatment procedures were as described in Larionov, Andreichev & Gee (2004). The results were processed using SQUID v1.12 (Ludwig, 2005*a*) and ISOPLOT/Ex 3.22 (Ludwig, 2005*b*).

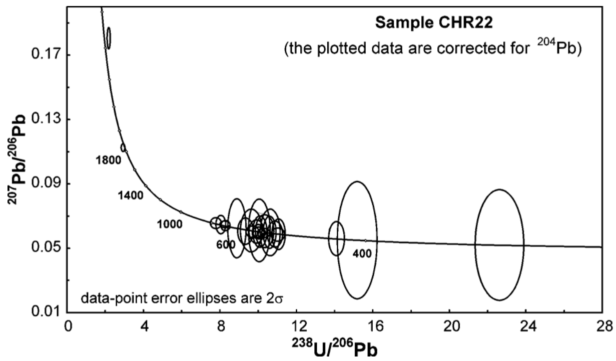

Figure 3. Terra-Wasserburg plot showing results of SHRIMP II zircon analyses from sample CHR22.

4. Results

4.a. Sample CHR22

The zircons in this sample have diverse morphology and internal features, most of the grains being prismatic to subrounded (Fig. 2). Most of the grains are colourless, but pale yellow and rose-coloured transparent crystals were found, as well as subordinate brownish semi-transparent grains. Distinct cores are moderately common and many grains display simple or complex and regular ('magmatic') zoning. They differ also in their brightness in CL, from very bright to dark.

The ^{206}Pb–^{238}U age spectrum is widely dispersed between 279 and 2427 Ma (Table 1, Fig. 3). Most of the ages are Precambrian, and older than 558 ± 7 Ma. Indistinct age clusters occur around 560 (see peak in Fig. 6), 580–600, 610–620 (another peak in Fig. 6), 630–656 and 734–780 Ma. The two oldest grains are 1889 ± 21 and 2427 ± 31 Ma.

The three youngest ^{206}Pb–^{238}U dates obtained are 279 ± 6 (grain 13.1), 411 ± 11 (grain 8.1) and 442 ± 5 Ma (grain 24.1) (Table 1, Fig. 3). These grains contain much common Pb (this roughly increasing with decreasing age) and possess tiny fractures, barely visible under gold coating. The youngest date of *c.* 279 Ma is less than the minimum age of the regional metamorphism in this area, which is constrained by a magmatic zircon age of 317 ± 1 Ma from a non-metamorphosed rhyolite cutting the Radzimowice Slates (Muszyński *et al.* 2002). On these grounds, we reject these three youngest ages as geologically unreliable (although they are shown in Table 1 and Fig. 3).

4.b. Sample RDZ214

The zircons in this sample also vary widely, from idiomorphic to rounded, mostly colourless and transparent grains; some contain more or less distinct cores, and most crystals display zoning (Fig. 4). A minor portion (about 5 %) is represented by brownish semi-transparent grains. In CL the zircons of this sample range from mostly dark to less common bright grains.

https://doi.org/10.1017/S0016756807003962 Published online by Cambridge University Press

Table 1. Results of *in situ* U–Pb analysis of the Radzimowice Slates detrital zircons

Spot	$^{206}Pb_c$ %	U (ppm)	Th (ppm)	$\frac{^{232}Th}{^{238}U}$	$^{206}Pb^*$ (ppm)	(1) $\frac{^{238}U^*}{^{206}Pb^*}$	±%	(1) $\frac{^{206}Pb}{^{238}U}$ age	±	(1) $\frac{^{207}Pb^*}{^{206}Pb^*}$	±%	(1) $\frac{^{207}Pb}{^{206}Pb}$ age	±	D%	(1) $\frac{^{207}Pb^*}{^{235}U}$	±%	(1) $\frac{^{206}Pb^*}{^{238}U}$	±%	Err. corr.
Sample CHR22																			
13.1	7.20	244	72	0.30	10	22.62	2.3	279	6	0.0520	27	282	610	1	0.316	27	0.0442	2.3	.085
8.1	3.41	47	139	3.06	2.76	15.18	2.8	411	11	0.0550	27	403	610	−2	0.500	27	0.0659	2.8	.103
24.1	5.38	1320	773	0.61	85	14.10	1.2	442	5	0.0560	7.7	450	170	2	0.547	7.8	0.0709	1.2	.157
19.1	1.99	310	196	0.65	24.6	11.07	1.3	558	7	0.0587	6.6	555	140	0	0.731	6.8	0.0903	1.3	.198
21.1	0.43	350	167	0.49	27.4	11.03	1.3	559	7	0.0585	2.9	547	64	−2	0.731	3.2	0.0906	1.3	.410
7.1	0.35	199	50	0.26	15.7	10.88	1.5	567	8	0.0588	5.6	560	120	−1	0.745	5.8	0.0919	1.5	.255
1.1	1.26	70	58	0.85	5.72	10.63	2	580	11	0.0598	9.9	597	210	3	0.776	10	0.0941	2.0	.202
23.1	3.78	777	268	0.36	65.4	10.60	1.3	581	7	0.0599	6.8	600	150	3	0.779	6.9	0.0943	1.3	.182
12.1	0.56	67	39	0.60	5.6	10.34	1.9	595	11	0.0606	6.9	624	150	5	0.808	7.1	0.0967	1.9	.264
25.1	0.18	296	225	0.78	24.8	10.29	1.3	598	8	0.0595	2	585	44	−2	0.797	2.4	0.0972	1.3	.550
11.1	0.50	147	95	0.67	12.5	10.09	1.5	609	9	0.0603	6.6	615	140	1	0.824	6.8	0.0991	1.5	.226
10.1	1.73	40	55	1.43	3.48	10.06	2.3	611	14	0.0611	13	643	280	5	0.840	13	0.0994	2.3	.180
15.1	0.13	196	103	0.54	16.8	10.03	1.4	612	8	0.0595	2.5	587	54	−4	0.818	2.8	0.0997	1.4	.484
9.1	0.27	413	106	0.27	35.6	10.00	1.2	614	7	0.0607	2.7	628	59	2	0.837	3	0.1000	1.2	.415
5.1	0.56	123	75	0.63	10.8	9.91	1.6	619	9	0.0604	4.9	617	110	0	0.840	5.1	0.1009	1.6	.312
14.1	0.00	251	660	2.72	22.2	9.70	1.4	633	8	0.0603	2.4	613	52	−3	0.857	2.8	0.1031	1.4	.500
6.1	0.99	41	35	0.86	3.71	9.64	2.4	636	14	0.0610	8.9	638	190	0	0.872	9.2	0.1037	2.4	.256
18.1	0.64	76	28	0.38	7.05	9.34	1.8	656	11	0.0606	5.5	624	120	−5	0.895	5.7	0.1071	1.8	.307
16.1	1.72	43	48	1.16	4.22	8.89	2.2	687	15	0.0624	12	688	270	0	0.970	13	0.1125	2.2	.178
20.1	0.26	449	290	0.67	46.6	8.29	1.2	734	9	0.0641	2	745	42	1	1.066	2.3	0.1206	1.2	.535
17.1	0.00	402	437	1.12	41.8	8.26	1.3	737	9	0.0649	1.3	770	27	4	1.083	1.8	0.1211	1.3	.704
3.1	0.26	305	150	0.51	32.7	8.05	1.3	755	9	0.0647	3.6	763	77	1	1.108	3.9	0.1242	1.3	.340
2.1	0.07	228	102	0.46	25.2	7.79	1.5	779	11	0.0656	2.1	795	44	2	1.162	2.5	0.1284	1.5	.573
4.1	0.08	280	30	0.11	81.8	2.94	1.3	1889	21	0.1125	0.88	1841	16	−3	5.282	1.6	0.3404	1.3	.827
22.1	0.20	78	29	0.38	30.8	2.19	1.5	2427	31	0.1805	1.5	2657	25	10	11.380	2.1	0.4571	1.5	.719
Sample RDZ214																			
13.1	3.17	147	113	0.79	7.5	17.51	1.9	358	7	0.0539	16.2	366	365	2	0.424	16.3	0.0571	1.9	.115
12.1	0.21	163	35	0.22	11.1	12.59	1.5	493	7	0.0574	4.1	506	90	3	0.628	4.4	0.0794	1.5	.338
22.1	0.82	149	41	0.28	10.3	12.55	1.5	494	7	0.0565	6.6	472	145	−4	0.621	6.8	0.0797	1.5	.227
17.1	0.26	379	96	0.26	26.4	12.37	1.2	501	6	0.0566	2.5	478	55	−5	0.631	2.8	0.0808	1.2	.448
18.1	0.20	266	88	0.34	18.5	12.35	1.3	502	6	0.0575	4.4	512	96	2	0.642	4.6	0.0810	1.3	.292
3.1	5.99	8	3	0.39	0.6	12.30	7.4	504	36	0.0582	81.8	538	1789	7	0.653	82.1	0.0813	7.4	.090
10.1	0.00	344	77	0.23	24.1	12.28	1.3	505	6	0.0572	1.8	498	40	−1	0.642	2.2	0.0815	1.3	.568
23.1	0.26	191	66	0.36	13.4	12.23	1.5	507	7	0.0578	5.5	521	120	3	0.651	5.7	0.0818	1.5	.261
19.1	0.36	180	77	0.44	12.9	12.09	1.5	512	8	0.0574	3.5	507	77	−1	0.655	3.8	0.0827	1.5	.401
11.1	0.00	328	44	0.14	23.8	11.80	1.4	524	7	0.0582	1.8	535	39	2	0.679	2.2	0.0847	1.4	.603
08.1	0.39	117	58	0.52	8.7	11.52	1.6	537	8	0.0579	5.1	526	112	−2	0.693	5.4	0.0868	1.6	.297
21.1	0.19	167	112	0.69	12.9	11.18	1.4	552	8	0.0586	2.7	552	59	0	0.723	3.1	0.0895	1.4	.462
07.1	0.24	124	38	0.32	9.6	11.12	1.6	555	8	0.0593	4.4	579	95	4	0.735	4.6	0.0899	1.6	.337
15.1	0.00	326	109	0.35	26.1	10.73	1.3	574	7	0.0586	1.6	551	35	−4	0.752	2.1	0.0932	1.3	.634
6.1	0.24	254	198	0.80	20.6	10.63	1.4	579	8	0.0587	3.4	555	75	−4	0.761	3.7	0.0941	1.4	.379
14.1	1.47	167	31	0.19	13.8	10.56	1.5	583	8	0.0591	7.4	571	161	−2	0.771	7.6	0.0947	1.5	.199
9.1	0.19	153	95	0.64	12.6	10.46	1.5	589	9	0.0590	2.8	568	60	−4	0.778	3.2	0.0956	1.5	.487
20.1	2.33	29	61	2.16	2.5	10.40	2.7	592	15	0.0585	17.9	548	390	−7	0.775	18.1	0.0961	2.7	.151
2.1*A*	0.24	336	242	0.74	29.7	9.75	1.2	629	7	0.0603	2.6	613	56	−3	0.852	2.9	0.1025	1.2	.434
16.1	0.43	74	33	0.46	6.6	9.62	1.7	637	11	0.0611	4.6	643	99	1	0.876	4.9	0.1039	1.7	.353
2.1	0.71	158	32	0.21	23.5	5.81	1.4	1024	13	0.0744	3.6	1053	73	3	1.766	3.9	0.1721	1.4	.362
5.1	0.36	93	81	0.90	32.2	2.50	1.5	2169	28	0.1318	1.9	2122	33	−2	7.269	2.4	0.4000	1.5	.627
1.1	0.11	586	129	0.23	253.3	1.99	1.1	2626	24	0.1818	0.4	2669	6	2	12.604	1.2	0.5028	1.1	.949
4.1	0.00	69	57	0.85	39.2	1.51	1.6	3270	41	0.2745	0.8	3332	12	2	25.000	1.8	0.6606	1.6	.901

Errors are 1σ; Pb_c and Pb^* indicate the common and radiogenic portions, respectively.
(1) Common Pb corrected using measured ^{204}Pb.
Error in standard (Temora zircon) calibration 0.66% (1σ) calculated on 14 out of 15 measurements.
D% – Discordancy, %; Err. corr. – error correlation.

The main zircon populations are older than *c.* 490 Ma, and they cluster around 493–512, 524–592 (peak at *c.* 570 Ma) and 630 Ma. Four analyses yielded considerably older ages of 1024 ± 13, 2169 ± 28, 2626 ± 24 and 3271 ± 41 Ma.

The youngest calculated ^{206}Pb–^{238}U date of 358 ± 7 Ma (Table 1, Fig. 5) from a single grain is high in common Pb. This date (and also those of two other grains with high Pb_c, 3.1 and 20.1) is unreliable and should be rejected (see Section 4.a).

5. Discussion

The detrital zircon ages obtained show that the Radzimowice Slates are indeed Palaeozoic in depositional age (Fig. 6), as Urbanek & Baranowski

https://doi.org/10.1017/S0016756807003962 Published online by Cambridge University Press

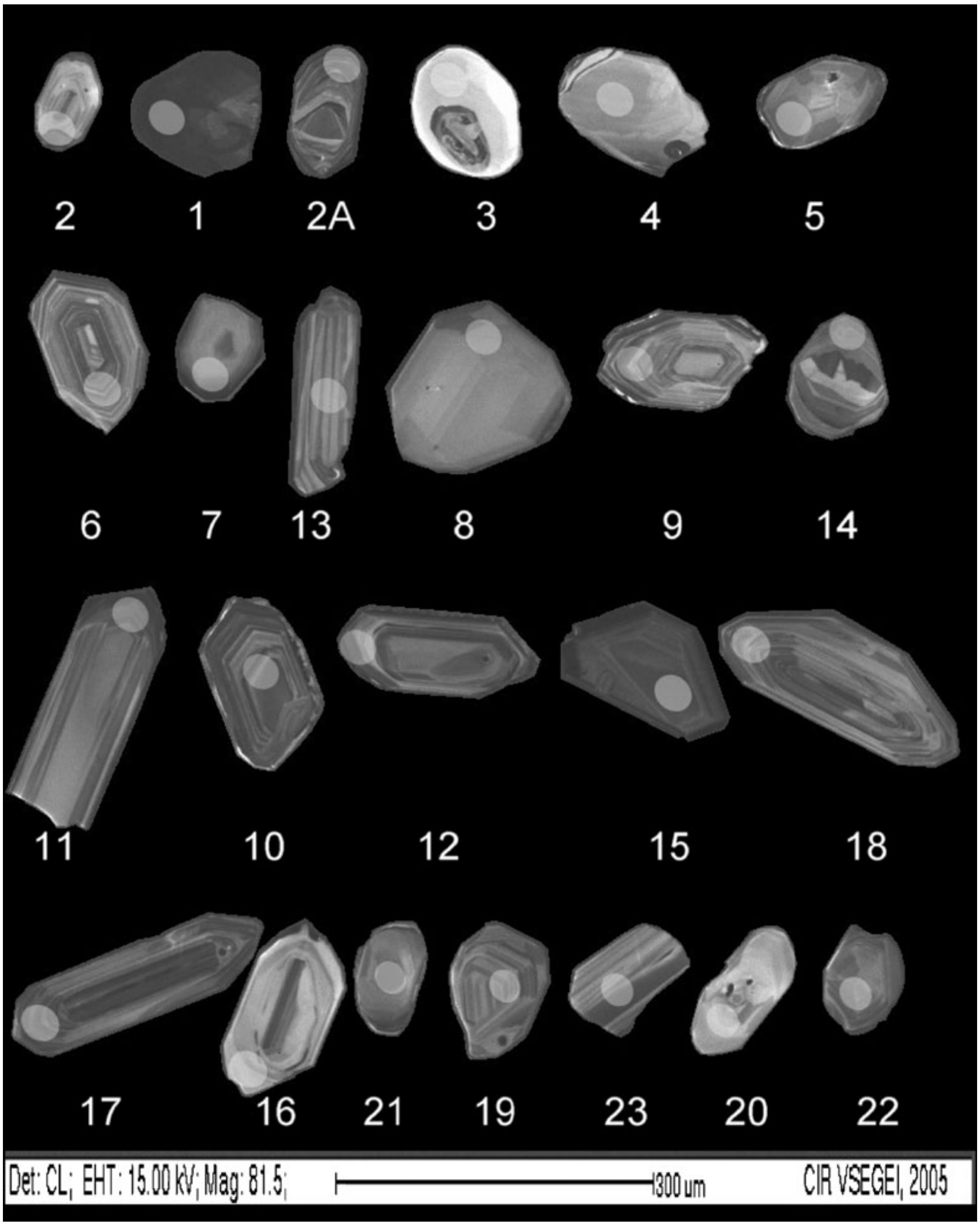

Figure 4. CL images of selected zircons of sample RDZ214. Analytical points indicated by brighter ovals: their symbols correspond to those given in Table 1.

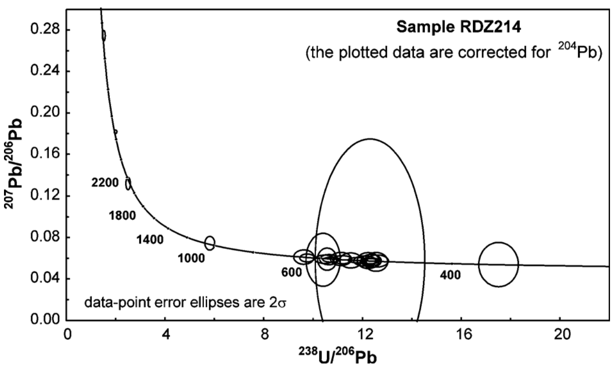

Figure 5. Terra-Wasserburg plot showing results of SHRIMP II zircon analyses from sample RDZ214.

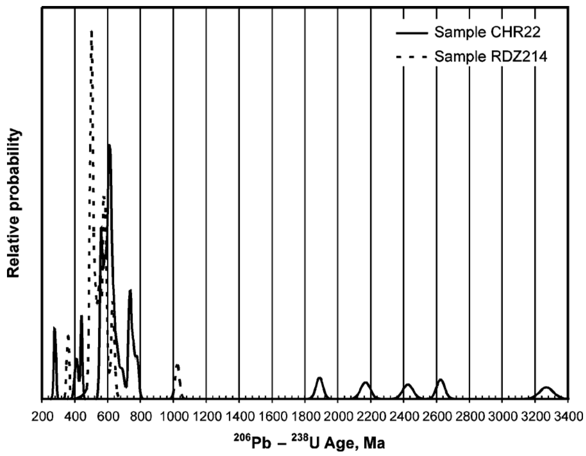

Figure 6. Probability density plot of ^{206}Pb–^{238}U ages of zircons from the Radzimowice Slates, samples CHR22 and RDZ214.

https://doi.org/10.1017/S0016756807003962 Published online by Cambridge University Press

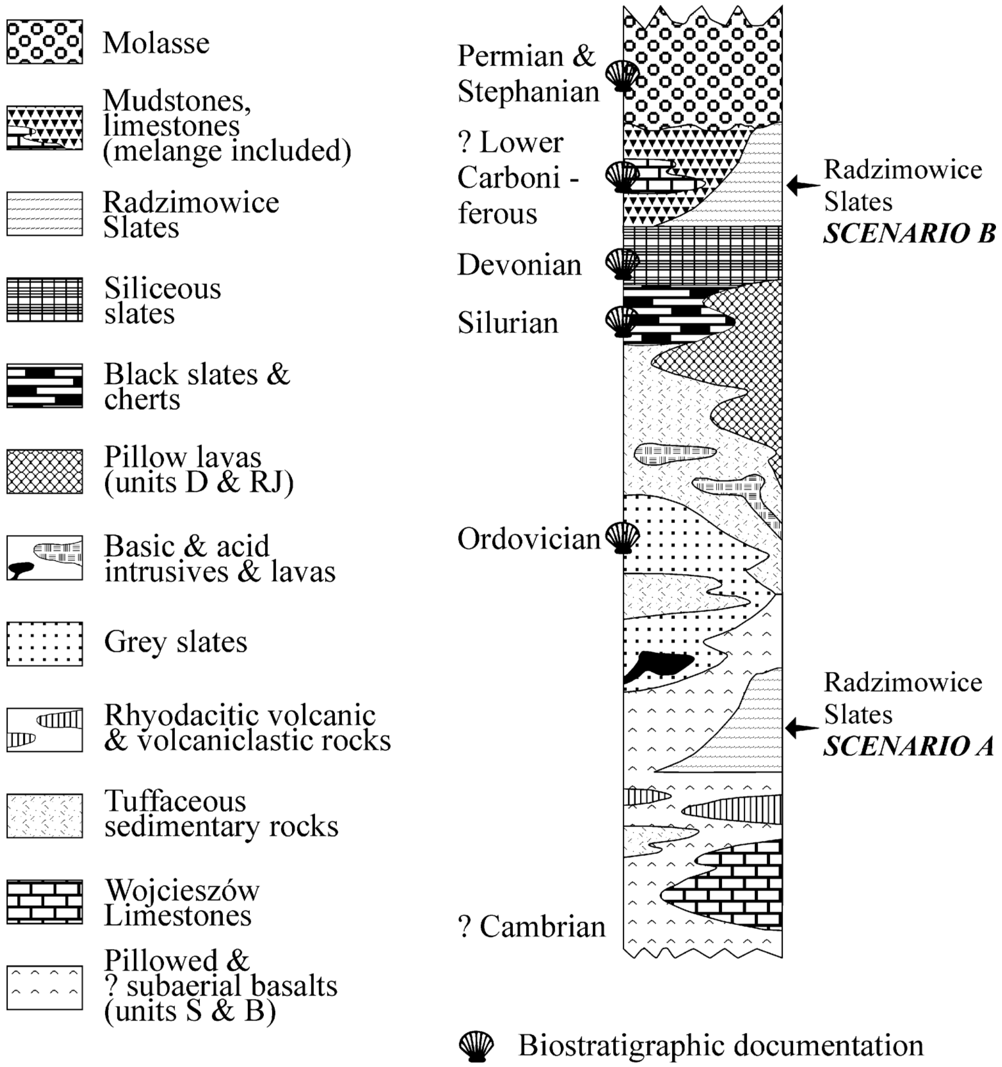

Figure 7. Alternative stratigraphic correlations of the Radzimowice Slates with the regional successions of the Kaczawa Complex. Generalized stratigraphic log adapted from Kryza & Muszyński (2003). Scenario A is considered to be the most likely correlation.

(1986) had suggested on the basis of poor conodont evidence, the maximum age reliably indicated (493–512 Ma) being latest Cambrian (cf. Gradstein, Ogg & Smith, 2005).

Thus, the Radzimowice Slates cannot form the base of the Kaczawa succession (Teisseyre, 1963) or of a major component of this, the Bolków Unit (Fig. 1), but must be at least synchronous with, and most likely post-date, acid igneous rocks in the middle of the Bolków Unit succession recently dated at *c.* 500 Ma (Kryza *et al.* 2007*a*,*b*).

The minimum age of sedimentation is uncertain. Baranowski (1988) suggested deposition in an ocean trench environment, which would imply association with ocean closure. The combination of our new dates and current understanding of the geological evolution of the Sudetes (Franke & Żelaźniewicz, 2000; Seston *et al.* 2000; Crowley *et al.* 2001; Aleksandrowski & Mazur, 2002; Kryza, Mazur & Oberc-Dziedzic, 2004; Mazur *et al.* 2006) imply that, if so, this contractional phase, following the protracted extensional regime (Cambrian to late Devonian), would be the late Devonian to early Carboniferous subduction that preceded final Variscan orogenesis in this region. In such an interpretation, the Radzimowice Slates would effectively form part of the mudrock-dominated mélange deposits of this age that are widespread in the region (Baranowski *et al.* 1990; Collins, Kryza & Zalasiewicz, 2000; Kryza & Muszyński, 2003; J. Kostylew, unpub. Ph.D. thesis, Wrocław Univ. 2006; Fig. 7, scenario B).

However, we consider it likely that the Radzimowice Slates provenance ages are more consistent with rift-related deposition following the break-up of Gondwana, associated magmatism occurring at *c.* 500 Ma (Pereira *et al.* 2006, and references therein). Thus, the depositional environment would not be an ocean trench, as Baranowski (1988) suggested, but rather a turbidite-fed extensional basin, with which the sedimentary facies seem, in our opinion, to be equally consistent (Fig. 7, scenario A).

Given the maximum age we establish for the Radzimowice Slates, its extensive outcrop, isolated from the main Kaczawa successions (e.g. in the Świerzawa

https://doi.org/10.1017/S0016756807003962 Published online by Cambridge University Press

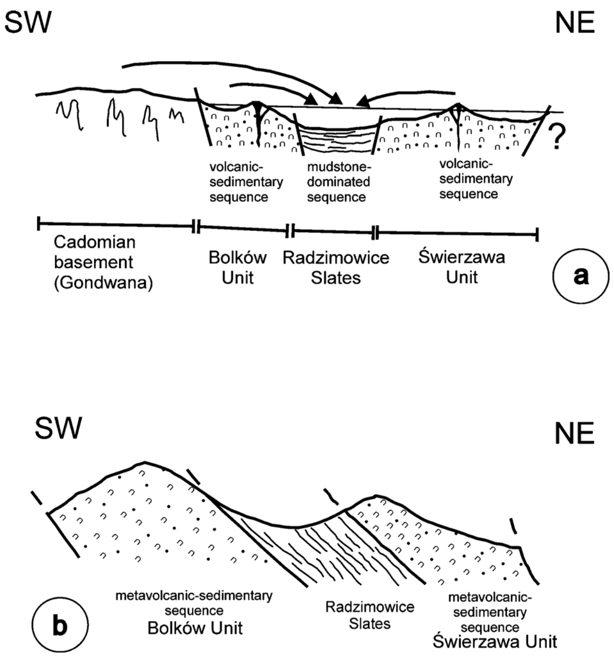

Figure 8. Cartoon showing our interpretation of the palaeogeographic and depositional setting of the Radzimowice Slates (a) and their recent tectonic position (b).

and Bolków units; Fig. 1), needs explanation. We consider as most likely an origin in a restricted basin, adjacent to and sourced from a combination of older Precambrian crust and early Palaeozoic volcanic–sedimentary successions (Fig. 8).

The age spectra of the two samples differ somewhat in detail with, for instance, only one sample yielding a clear late Cambrian/early Ordovician assemblage (Fig. 6). This most likely reflects the sourcing of different parts of the Radzimowice Slates from different parts of a geologically diverse hinterland, the nature of which is discussed below.

Both the samples studied have major populations of zircons with ages dispersed within the ‘Cadomian range’, roughly between 550 and 650 Ma. The ages are evenly distributed within that 100 Ma interval, suggesting that the source rocks comprised magmatic protoliths of various ages. The dates reflect a shared history between the Bohemian Massif, of which the Radzimowice Slates forms a part, and that part of Gondwana affected by intense Cadomian magmatism between 700 and 540 Ma (e.g. Pereira *et al.* 2006).

The Radzimowice Slates also contain a variety of older components of *c.* 750 Ma, 1050 Ma, 1900 Ma, 2150 Ma, 2450 Ma, 2650 Ma, the oldest date recorded being 3271 ± 41 Ma (Fig. 6). Similar zircon ages have been reported from North Africa, which formed a part of Gondwana (Linnemann *et al.* 2000, 2004; Nance, Murphy & Keppie, 2002; Von Raumer, Stampfli & Bussy, 2003; Friedl *et al.* 2004; Inglis *et al.* 2005; Samson *et al.* 2005). Thus, our new data support a close similarity in zircon ages and, consequently, genetic links between this part of the Bohemian Massif and the North African part of Gondwana (Kryza *et al.* 2007*b*).

6. Conclusions

(1) SHRIMP-dated detrital zircon ages from the Radzimowice Slates of the Kaczawa Complex, part of the Bohemian Massif, include a clear late Cambrian to early Ordovician component, thus constraining a maximum depositional age for this unit. They are consistent with derivation from local continental rift-related acid volcanic rocks and deposition in a restricted extensional basin during the break-up of Gondwana.

(2) The Radzimowice Slates also include major populations of zircons of Cadomian age, more or less continuously dispersed between 550 and 650 Ma. This suggests derivation from a wide range of the igneous (considering Th/U above 0.20) rocks of that age that were widespread throughout that part of Gondwana.

(3) Smaller populations of older zircons range through the Proterozoic and Archaean to a maximum of 3.3 Ga. This pattern closely resembles zircon age spectra recovered from North Africa, and emphasizes the close genetic links between this part of the Bohemian Massif and the North African segment of Gondwana.

Acknowledgements. The study was supported by the KBN research project 2P04D 015 27, and internal Wrocław University grants 1017/S/ING, and 2022/W/ING. Quentin Crowley and John Winchester are thanked for their constructive reviews.

References

Aleksandrowski, P., Kryza, R., Mazur, S., Pin, C., Zalasiewicz, J. A. 2000. The Polish Sudetes: Caledonian or Variscan? *Transactions of the Royal Society of Edinburgh, Earth Sciences* **90**, 127–46.

Aleksandrowski, P. & Mazur, S. 2002. Collage tectonics in the northeasternmost part of the Variscan Belt: the Sudetes, Bohemian Massif. In *Palaeozoic Amalgamation of Central Europe* (eds J. A. Winchester, T. C. Pharaoh & J. Verniers), pp. 237–77. Geological Society of London, Special Publication no. 201.

Baranowski, Z. 1988. Lithofacies characteristics of trench-fill metasediments in the Radzimowice Slate (Palaeozoic), Sudetes, SW Poland. *Annales Societas Geologorum Poloniae* **58**, 325–83.

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). *Neues Jahrbuch für Mineralogie, Abhandlungen* **179**, 223–57.

Collins, A. S., Kryza, R. & Zalasiewicz, J. A. 2000. Macrofabric fingerprints of Late Devonian–Early Carboniferous subduction in the Polish Variscides, the Kaczawa complex, Sudetes. *Journal of the Geological Society, London* **157**, 283–8.

Crowley, Q. G., Floyd, P. A., Winchester, J. A., Franke, W. & Holland, J. G. 2001. Early Palaeozoic rift-related

https://doi.org/10.1017/S0016756807003962 Published online by Cambridge University Press

magmatism in Variscan Europe: fragmentation of the Armorican Terrane Assemblage. *Terra Nova* **12**, 171–80.

FRANKE, W. & ŻELAŹNIEWICZ, A. 2000. The eastern termination of the Variscides: terrane correlation and kinematic evolution. In *Orogenic Processes: Quantification and Modelling in the Variscan Belt* (eds W. Franke, V. Haak, O. Oncken & D. Tanner), pp. 63–86. Geological Society of London, Special Publication no. 179.

FRIEDL, G., FINGER, F., PAQUETTE, J. L., VON QUADT, A., MCNAUGHTON, N. J. & FLETCHER, I. R. 2004. Pre-Variscan geological events in the Austrian part of the Bohemian Massif deduced from U–Pb zircon ages. *International Journal of Earth Sciences (Geologische Rundschau)* **93**, 802–23.

FURNES, H., KRYZA, R., MUSZYŃSKI, A., PIN, C. & GARMANN, L. B. 1994. Geochemical evidence for progressive rift-related volcanism in the eastern Variscides. *Journal of the Geological Society, London* **151**, 91–109.

GRADSTEIN, F. M., OGG, J. G. & SMITH, A. G. (eds) 2005. *A geologic time scale 2004*. Cambridge University Press, 610 pp.

INGLIS, J. D., SAMSON, S. D., D'LEMOS, R. S. & MILLER, B. V. 2005. Timing of Cadomian deformation and magmatism within La Hague, NW France. *Journal of the Geological Society, London* **162**, 389–400.

KRYZA, R., MAZUR, S., ALEKSANDROWSKI, P., ZALASIEWICZ, J. A., SERGEEV, S. & PRESNYAKOV, S. 2007*a*. Early Palaeozoic initial-rift volcanism in the Central European Variscides (the Kaczawa Mountains, Sudetes, SW Poland): evidence from SIMS dating of zircons. *Journal of the Geological Society, London* **164**, in press.

KRYZA, R., MAZUR, S. & OBERC-DZIEDZIC, T. 2004. The Sudetic geological mosaic: insights into the root of the Variscan orogen. *Przegląd Geologiczny* **52**(8/2), 761–73.

KRYZA, R. & MUSZYŃSKI, A. 1992. Pre-Variscan volcanic-sedimentary succession of the central southern Góry Kaczawskie, SW Poland: Outline Geology. *Annales Societas Geologorum Poloniae* **62**, 117–40.

KRYZA, R. & MUSZYŃSKI, A. 2003. Kompleks metamorficzny Gór Kaczawskich – fragment waryscyjskiej pryzmy akrecyjnej. [The metamorphic Kaczawa Complex – fragment of Variscan accretionary prism.] In *Sudety Zachodnie: od wendu do czwartorzędu* (eds W. Ciężkowski, J. Wojewoda & A. Żelaźniewicz.), pp. 95–104. Wrocław: WIND (in Polish, English summary).

KRYZA, R., ZALASIEWICZ, J. A., MAZUR, S., ALEKSANDROWSKI, P., SERGEEV, S. & LARIONOV, A. 2007*b*. Precambrian crustal contribution to the Variscan accretionary prism of the Kaczawa Mountains (Sudetes, SW Poland): evidence from SHRIMP dating of detrital zircons. *International Journal of Earth Sciences* (in press, DOI 10.1007/s00531-006-0147-x).

LARIONOV, A. N., ANDREICHEV, V. A. & GEE, D. G. 2004. The Vendian alkaline igneous suite of northern Timan: ion microprobe U–Pb zircon ages of gabbros and syenite. In *The Neoproterozoic Timanide Orogen of Eastern Baltica* (D. G. Gee & V. L. Pease), pp. 69–74. Geological Society of London, Memoir no. 30.

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 *Orogenic Processes: Quantification and Modelling in the Variscan belt* (eds W. Franke, V. Haak, O. Oncken & D. Tanner.), pp. 131–53. Geological Society of London, Special Publication no. 179.

LINNEMANN, U., MCNAUGHTON, N. J., ROMER, R. L., 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. *International Journal of Earth Sciences* **93**, 683–705.

LUDWIG, K. R. 2005*a*. SQUID 1.12 A User's Manual. A Geochronological Toolkit for Microsoft Excel. *Berkeley Geochronology Center Special Publication*. 22 pp. http://www.bgc.org/klprogrammenu.html.

LUDWIG, K. R. 2005*b*. User's Manual for ISOPLOT/Ex 3.22. A Geochronological Toolkit for Microsoft Excel. *Berkeley Geochronology Center Special Publication*. 71 pp. http://www.bgc.org/klprogrammenu. html.

MAZUR, S., ALEKSANDROWSKI, P., KRYZA, R. & OBERC-DZIEDZIC, T. 2006. The Variscan Orogen in Poland. *Geological Quarterly* **50**(1), 89–118.

MUSZYŃSKI, A., MACHOWIAK, K., KRYZA, R. & ARMSTRONG, R. 2002. SHRIMP U–Pb geochronology of the late-Variscan Żeleźniak rhyolitic intrusion. W Sudetes – preliminary results. *Mineralogical Society of Poland Special Papers* **20**, 156–8.

NANCE, R. D., MURPHY, J. B. & KEPPIE, J. D. 2002. A Cordilleran model for the evolution of Avalonia. *Tectonophysics* **352**, 11–31.

OLIVER, G. J. H., CORFU, F. & KROGH, T. E. 1993. U–Pb ages from SW Poland: evidence for a Caledonian suture zone between Baltica and Gondwana. *Journal of the Geological Society, London* **150**, 355–69.

PEREIRA, M. F., CHICHORRO, M., LINNEMANN, U., EGUILUZ, L. & SILVA, J. B. 2006. Inherited arc signature in Ediacaran and Early Cambrian basins of the Ossa-Morena Zone (Iberian Massif, Portugal): Paleogeographic link with European and North African Cadomian correlatives. *Precambrian Research* **144**, 297–315.

SAMSON, S. D., D'LEMOS, R. S., MILLER, B. V. & HAMILTON, M. A. 2005. Neoproterozoic paleogeography of the Cadomia and Avalon terranes: constraints from detrital zircon U–Pb ages. *Journal of the Geological Society, London* **162**, 65–71.

SESTON, R., WINCHESTER, J. A., PIASECKI, M. A. J., CROWLEY, Q. G. & FLOYD, P. A. 2000. A structural model for the western-central Sudetes: a deformed stack of Variscan thrust sheets. *Journal of the Geological Society, London* **157**, 1155–67.

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).

URBANEK, Z. & BARANOWSKI, Z. 1986. Revision of the age of the Radzimowice slates from the Góry Kaczawskie, Western Sudetes. *Annales Societas Geologorum Poloniae* **56**, 399–408.

VON RAUMER, J. F., STAMPFLI, G. M. & BUSSY, F. 2003. Gondwana-derived microcontinents – the constituents of the Variscan and Alpine collisional orogens. *Tectonophysics* **365**, 7–22.

ZIMMERMANN, E. 1932. *Geologische Karte von Preussen und benachbarten deutschen Landern, 1:25 000, Blatt Hirschberg*. Berlin: Preussische Geologische Landesanstalt.