



CADOMIAN PROTOLITH AGES OF EXOTIC MEGA BLOCKS FROM BUGAJ AND ANDRYCHÓW (WESTERN OUTER CARPATHIANS, POLAND) AND THEIR PALAEOGEOGRAPHIC SIGNIFICANCE

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Abstract: This study presents the first zircon U-Pb LA-MC-ICP-MS ages and whole-rock Rb/Sr and Sm/Nd data from exotic blocks (Bugaj and Andrychów) from the Western Outer Carpathians (WOC) flysch. The CL images of the zircon crystals from both samples reveal typical magmatic textures characterized by a well-defined concentric and oscillatory growth zoning. A concordia age 580.1 ± 6.0 Ma of the zircons from the Bugaj sample is considered to represent the crystallization age of this granite. The zircon crystals from the Andrychów orthogneiss yield an age of 542 ± 21 Ma, interpreted as the uppermost Proterozoic, magmatic crystallization age of the granitoid protolith. The initial (at ca. 580 Ma) $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the Bugaj granitoids (0.72997 and 0.72874) are highly radiogenic, pointing to the assimilation of an older, possibly strongly Rb enriched source to the Bugaj melt. The Nd isotope systematics ($\epsilon_{\text{Nd}580} -1.4$ and 0.4) also point to a significant contribution of such a distinct mantle source. On the basis of the sequence of magmatic events obtained from U-Pb zircon ages, we suggest that exotic mega blocks deposited to the WOC basins were related to the Brunovistulicum Terrane. They belong to the group of Vendian/Cambrian granitoids representing the latest, post-tectonic expression of the Cadomian cycle.

Keywords: exotics, zircon U-Pb dating, Western Outer Carpathians, palaeogeography, Brunovistulicum.

1. INTRODUCTION

Despite the long period of research conducted in the Western Outer Carpathians (WOC) the genesis and tectonic evolution of their crystalline basement is still poorly recognized (e.g. Żelaźniewicz *et al.*, 2009; Buła *et al.*, 2015). At present the crystalline basement is hidden below thick Upper Jurassic-Neogene flysch deposits of the WOC proper (e.g. Książkiewicz, 1977; Oszczytko and Ślęczka, 1985; Golonka *et al.*, 2009). Fragments of crystalline rocks, so-called exotics (e.g. Burtanówna *et al.*,

1937; Wieser, 1948), interpreted to be derived from uplifted ridges (cordilleras, Książkiewicz, 1953) and transported by turbidity currents and debris flows into the adjoining flysch basins, offer the opportunity to investigate the geotectonic history of these no longer existing provenance areas of the Carpathian flysch (e.g. Wieser, 1949, 1985; Książkiewicz, 1965; Oszczytko, 1975; Malik, 1978; Oszczytko *et al.*, 2016).

A number of studies concerning the palaeogeography of the WOC have used a range of geochronological methods including K-Ar mica dating (Poprawa *et al.*, 2004, 2005, 2006; Haber and Hałas, 2001), Th-U-total Pb monazite dating (Hanžl *et al.*, 2000; Budzyń *et al.*, 2008; Salata and Oszczytko, 2010; Oszczytko *et al.*, 2016) and U-Pb zircon geochronology (Michalik *et al.*, 2006; Poprawa *et al.*, 2006; Budzyń *et al.*, 2011) to constrain

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the timing of magmatic and metamorphic processes recorded in the exotics. The general outcome of these investigations is that numerous exclusively pre-Alpine, in parts pre-Variscan ages were determined, but no obvious correlation of stratigraphic and tectonic position and/or geography emerged. From a methodological point of view this is due to the fact that especially K-Ar mica ages are sensitive to thermal and metasomatic overprint thus obscuring any primary geochronological signal directly dating igneous or metamorphic events. This published radiometric age data set is therefore not conclusive for the unambiguous identification of protolith and metamorphic ages.

The main purpose of our study is to present and discuss zircon U-Pb ages from two exotic mega blocks (a granite from Bugaj and an orthogneiss from Andrychów), representing the alimentary crystalline basement area of the WOC flysch. Due to the size of these two exotics (> 100 m) it can safely be assumed that their loci of deposition is far more proximal to their respective shedding ridge(s) than the probably more distally derived pebbles dated in previous studies. Additionally, the latter might easily be re-sedimented making any palaeogeographic implications drawn from ages derived from such rocks severely ambiguous. The presented results provide new information to the ongoing discussion of the late Neoproterozoic palaeogeography of tectonic units which intervene between the East European Craton (Baltica) and the lithotectonic units of the Variscan orogeny (e.g. Belka *et al.*, 2000; Nawrocki *et al.*, 2004; Żelaźniewicz *et al.*, 2009; Buła *et al.*, 2015).

2. GEOLOGICAL BACKGROUND

The Western Carpathian Mountains are subdivided into the Inner Carpathians, consisting of pre-Alpine crystal-

line basement units covered by Late Paleozoic to mid-Cretaceous sediments (e.g. Oszczytko, 2004; Poprawa and Malata, 2006) and the Outer Carpathians, separated by the narrow, strongly tectonized Pieniny Klippen Belt (Fig. 1). The WOC are depicted as a complex nappe structure consisting of Upper Jurassic to Neogene flysch deposits, that were folded and thrust onto the pre-Alpine European foreland during the upper Oligocene to the middle Miocene (e.g. Oszczytko, 1998, 2004; Oszczytko and Oszczytko-Clowes, 2003; Golonka *et al.*, 2005; 2009; Oszczytko *et al.*, 2006, Ślącza *et al.*, 2006).

The crystalline basement constituting the pre-Alpine foreland (known only from boreholes) is divided into two basement blocks: the Upper Silesia Block (the northern part of the Brunovistulicum Terrane) to the West and the Małopolska Block to the East (Dudek, 1980; Buła, 2000; Finger *et al.*, 2000; Żelaźniewicz *et al.*, 2009; Buła *et al.*, 2015). The Precambrian basement of the Upper Silesia Block is represented by a) Neoproterozoic (660–556 Ma) metamorphic and igneous rocks, b) Ediacaran anchimetamorphic flysch-type siliciclastics and c) Paleoproterozoic (2.0 Ga) metamorphic rocks with Archean (2.7 Ga) inheritance (Buła *et al.* 2015). The Neoproterozoic rocks of Małopolska Block are mainly represented by flysch-type series (Żelaźniewicz *et al.*, 2009).

In the WOC several flysch basins were identified on the basis of lithostratigraphy (from south to north), *i.e.* the Magura, Sub-Silesian and Skole basins (e.g. Bieda *et al.*, 1963; Książkiewicz, 1972; Cieszkowski *et al.*, 1985; Oszczytko, 2006). The basins were supplied with sediments from continental margins as well as from the inter-basinal elevations (ridges) separating subbasins (e.g., Książkiewicz, 1962, 1965; Unrug, 1963, 1968; Ślącza, 1986; Olszewska and Wiczorek, 2001; Poprawa *et al.*, 2002, 2004; Golonka *et al.*, 2008). Based

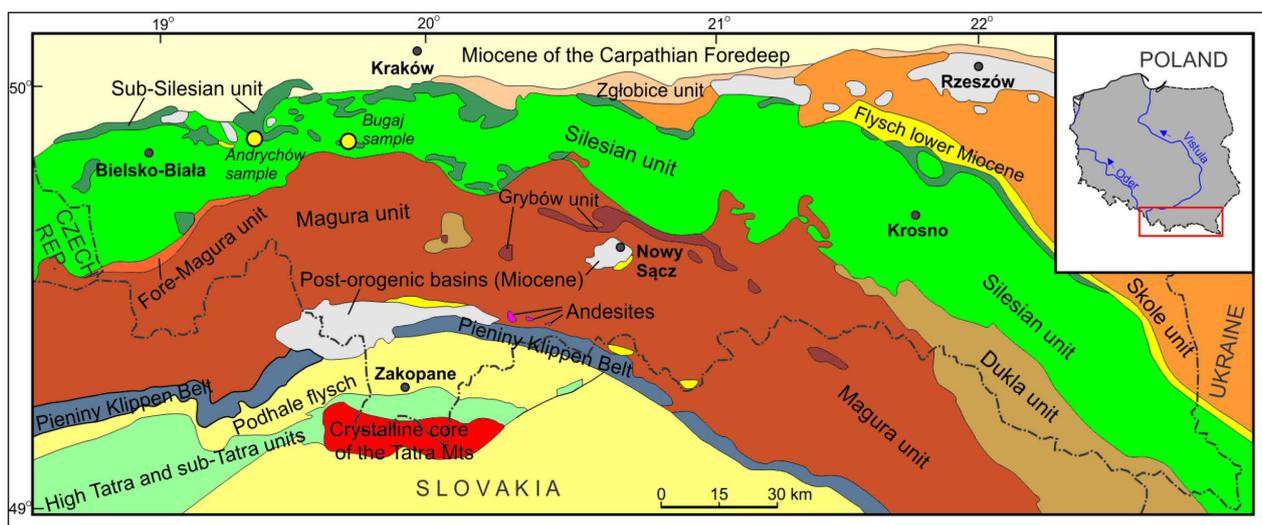


Fig. 1. Simplified geological map of the Polish part of the Western Carpathians (after Żelaźniewicz *et al.*, 2011, modified) with the location of the investigated samples (shown as yellow dots).

on studies of palaeotransport directions it was concluded that the Brunovistulicum and/or Małopolska Terranes (external to the WOC) and the inter-basinal Silesian Ridge were the most prominent source areas of the terrigenous material (e.g. Wieser, 1949, 1985; Książkiewicz, 1965; Sikora, 1976). The Silesian Ridge developed at the boundary between Variscan and Cadomian crustal blocks of the so-called North European platform (e.g. Golonka *et al.*, 2005; Budzyń *et al.*, 2011). The less prominent Andrychów Ridge, recognized in the Polish WOC emerged between the Silesian and Subsilesian-Skole basins (e.g. Książkiewicz, 1960, 1977; Golonka *et al.*, 2005) to the NNE of the Silesian Ridge. This unit is represented by several huge (> 100 m) exotic blocks, containing granite-gneiss or mylonitized rocks of unknown age and Jurassic, Cretaceous and Paleogene limestones (Olszewska and Wiczcerek, 2001; Ślaczka *et al.*, 2006).

3. SAMPLING AND ANALYTICAL TECHNIQUES

Three samples of crystalline rocks (Bu1, Bu2 and An) from exotic mega blocks (*Bugaj* and *Andrychów*) were investigated. These blocks, located on the boundary between the Silesian and Subsilesian units, are interpreted as olistoliths of the Silesian nappe (Ślaczka and Kaminski, 1998; Golonka *et al.*, 2005; Cieszkowski *et al.*, 2009, 2012). The samples Bu1 and Bu2 were collected in the western flow of the Cedron stream in Bugaj near Kalwaria Zebrzydowska (coordinates: 49°50'56.40"N 19°40'40.70"E; Fig. 1). The sample An, representative for the metamorphic basement rocks of the Andrychów Ridge was collected from Pańska Góra Hill, SE of Andrychów (coordinates: 49°51'10.17"N 19°21'28.95"E, Fig. 1). The two samples Bu1 and An, weighting about 25 kg each, were selected for U-Pb dating.

Whole-rock and mineral analysis

Whole-rock samples were analysed by X-ray fluorescence (XRF) for major and large ion lithophile trace Elements (LILE) and by fusion and ICP-MS for high field strength elements (HFSE) and rare earth elements (REE) in the Bureau Veritas Minerals (Canada). Preparation involved lithium borate fusion and dilute digestions for XRF and lithium borate decomposition or aqua regia digestion for ICP-MS. LOI was determined at 1000°C. REE were normalized to C1 chondrite (Sun and McDonough, 1989).

Microprobe analyses of rock-forming and accessory minerals were undertaken in the Inter-Institutional Laboratory of Microanalyses of Minerals and Synthetic Substances, Warsaw, using a Cameca SX 100 electron microprobe operating in the wavelength-dispersive spectroscopic (WDS) mode with the following conditions: 15 kV accelerating voltage, 20 nA beam current, 1–5 µm beam diameter, peak count-time of 20 s and background count-time of 10 s.

Rb-Sr and Sm-Nd whole rock isotope analysis

The Rb-Sr and Sm-Nd analytical work was performed at the Laboratory of Geochronology, Department of Lithospheric Research, University of Vienna. Rb, Sr, Sm and Nd concentrations were determined from two different sample aliquots by isotope dilution (ID) using ^{87}Rb - ^{84}Sr and ^{147}Sm - ^{150}Nd spikes. Rb, Sm and Nd ID samples were measured as metals from a Re (single: Rb; double: Nd and Sm) filament using a FinniganTM MAT262 mass spectrometer, while Sr ID and isotope composition (IC) and Nd IC samples were run on a ThermoFinniganTM Triton TI TIMS machine. Maximum total procedural blanks were < 1 ng for Sr and 50 pg for Nd and were taken as negligible. Within-run mass fractionation for Nd and Sr isotope compositions (IC) was corrected to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, and $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$, respectively. Uncertainties on the Nd and Sr isotope ratios are quoted typical as $2\sigma_m$. Errors for the $^{87}\text{Rb}/^{86}\text{Sr}$ and $^{147}\text{Sm}/^{144}\text{Nd}$ ratios, respectively, are taken as $\pm 1\%$, or smaller, based on iterative sample analysis and spike recalibration. During the period of investigation a $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.511850 ± 0.000005 ($n = 5$) and a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.710274 ± 0.000008 ($n = 5$) were determined for the La Jolla (Nd) and the NBS987 (Sr) international standards, respectively. Details of techniques, accuracy and data precision of Rb-Sr and Sm-Nd isotopic measurements are given by Thöni *et al.* (2008).

Zircon separation, CL imaging and U-Th-Pb MC-ICP-MS dating

Zircon crystals were separated using standard techniques (crushing, hydrofracturing, washing, Wilfley table, magnetic separator and handpicking). The separation was carried out in the Institute of Geological Sciences, Polish Academy of Sciences, Cracow. Zircon grains were selected for the morphological study using scanning electron microscopy and then imaged by cathodoluminescence using a FET Philips 30 electron microscope (15 kV and 1 nA) at the Faculty of Earth Sciences, University of Silesia, Sosnowiec, Poland.

The LA-MC-ICP-MS (Laser Ablation Multi Collector ICP-MS) analytical work was performed in two sessions at the joint ICP-MS laboratory of the Department of Earth Sciences, Karl-Franzens-University Graz and the Institute of Applied Geosciences, Graz Technical University. Analytical procedures followed the methodology outlined in Klötzli *et al.* (2009). Zircon $^{206}\text{Pb}/^{238}\text{U}$, $^{207}\text{Pb}/^{206}\text{Pb}$, and $^{208}\text{Pb}/^{232}\text{Th}$ ratios and ages were determined using a 193nm Ar-F excimer laser (NewWave) coupled to a multi-collector ICP-MS (Nu Instruments Plasma II). Ablation using He as carrier gas was raster-wise according to the CL zonation pattern of the zircons. Line widths for rastering were 10–15 µm with a rastering speed of 5 µm/sec. Energy densities were 5–5.5 J/cm² with a repetition rate of 10 Hz. The He carrier gas (0.7 l/min) was mixed with the Ar carrier gas flow prior to the ICP plasma torch.

Ablation duration was 30 to 70 sec with a 30 sec gas and Hg blank measurement preceding ablation. Ablation count rates were corrected accordingly using the mean blank measurement intensities of the individual masses. Remaining counts on mass 204 were interpreted as representing ^{204}Pb . Static mass spectrometer analysis was as follows: ^{238}U and ^{232}Th were measured in Faraday detectors, ^{208}Pb , ^{207}Pb , ^{206}Pb , $^{204}\text{Pb}+^{204}\text{Hg}$ and ^{202}Hg in discrete ion counter detectors. An integration time of 1 sec was used for all measurements. The ion counter - Faraday and inter-ion counter gain factors were determined before the analytical session using the reference zircon Plešovice (Sláma *et al.*, 2008). The overall sensitivity for ^{206}Pb on reference zircon Plešovice was *c.* 0.18 mV/weight-ppm ^{206}Pb . For ^{238}U the corresponding value was *c.* 0.39 mV/weight-ppm U. Isotopic ratios were calculated using the MS Excel spreadsheet LamTool U-Th-Pb version VI (Košler *et al.*, 2008; Košler and Klötzli, unpublished). In order to avoid potential surface contamination, the signals from the first laser pass was rejected and untypical Pb-peaks, from Pb-rich inclusions, were removed in the LamTool spreadsheet. Mass and elemental bias and mass spectrometer drift of U/Pb, Th/Pb and Pb/Pb ratios, respectively, were corrected applying the “intercept method” of Sylvester and Ghaderi (1997). The calculated $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ intercept values, respectively, were corrected for mass discrimination from analyses of reference zircon Plešovice zircon (Sláma *et al.*, 2008) measured during the analytical session using a standard bracketing method (Klötzli *et al.*, 2009). The correction utilizes regression of standard measurements by a quadratic function. No common Pb correction was applied to the data. Final age calculations were performed with Isoplot© 3.75 (Ludwig, 2012). Reference zircon Plešovice (Sláma *et al.*, 2008) was also used as secondary standard in order to derive an estimate of the overall uncertainties associated with the age determinations. 4 and 7 measurements were additionally made during the two analytical session, which resulted in concordia

ages of 337.2 ± 3.6 Ma and 337 ± 10 Ma, respectively. These are within error identical to the accepted reference $^{206}\text{Pb}/^{238}\text{U}$ age of 337.13 ± 0.37 Ma (Sláma *et al.*, 2008). These uncertainties were propagated in quadrature to the single dates in order to account for the overall analytical dispersion of the LA method (Klötzli *et al.*, 2009). All errors reported for LA data are at the 2-sigma level.

4. PETROGRAPHY AND WHOLE-ROCK GEO-CHEMISTRY

Bugaj granite mega block

The samples collected from the Bugaj mega block are coarse-grained granite (*Bu1*, Fig. 2a, Fig. 3) to granodiorite (*Bu2*, Fig. 3), lacking any visible orientation, locally porphyritic. They are composed of pinkish K-feldspars ($\text{Or}_{91-93}\text{Ab}_{5-6}\text{Cn}_{1-2}$), weakly zoned oligoclase (An_{18-25}), biotite showing a brown-yellow pleochroism ($\text{Ti} = 0.38\text{--}0.42$ a.p.f.u.; $\#fm = 0.65\text{--}0.66$), locally replaced by chlorite and associated with secondary rutile. Accessory minerals are (Ca, F)-apatite and zircon. Sporadically rounded monzonitic enclaves up to 5–10 cm in size can be found, showing a sharp contact with the surrounding host rock. The enclaves are composed of fine-grained biotite ($\text{Ti} = 0.30\text{--}0.38$ a.p.f.u.), oligoclase (An_{20-26}), and quartz. Accessory (Ca, F)-apatite is also observed (*BuC*, Fig. 3).

Studied rocks are peraluminous ($\text{ASI} = 1.16\text{--}1.23$) with silica contents around 60–71 wt.%, $\text{K}_2\text{O} \geq \text{Na}_2\text{O}$ and Rb/Sr ratios = 1.1–1.4 (Table 1). The rocks belong to the high K-calc-alkaline series and are intermediate between the ferroan and magnesian families of the Frost and Frost (2008) geochemical classification. Chondrite-normalized (Sun and McDonough, 1989) REE patterns show low LREE enrichment ($\text{Ce}_N/\text{Yb}_N = 3.18\text{--}6.34$) and a strong negative Eu anomaly ($\text{Eu}/\text{Eu}^* = 0.38\text{--}0.57$; Table 1; Fig. 3b). Magma crystallization temperatures calculated on the basis of the Zr-saturation geothermometer of Watson and Harrison (1983) are in the range of 800–850°C

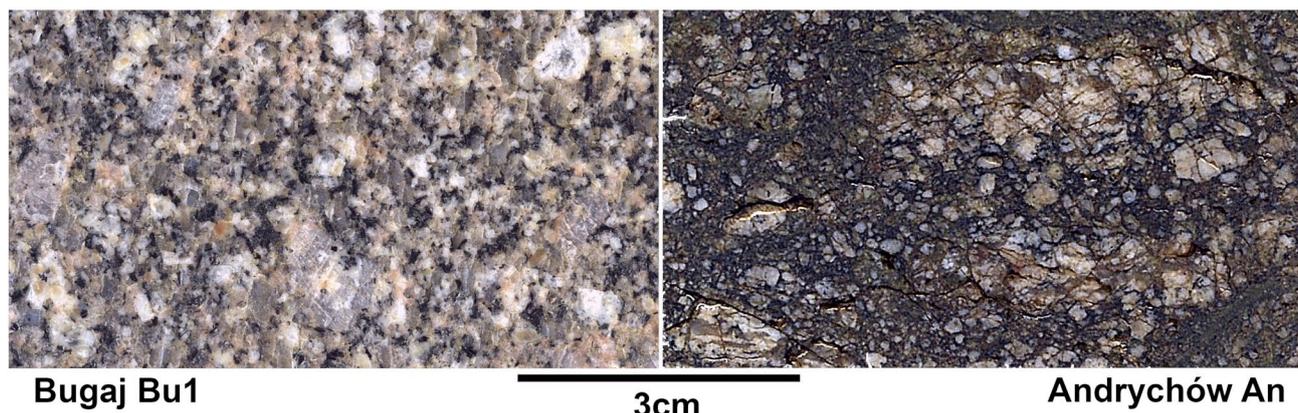


Fig. 2. Field photo (a) of the Bugaj granitoid (sample Bu1) and field photo (b) of the Andrychów orthogneiss (sample An).

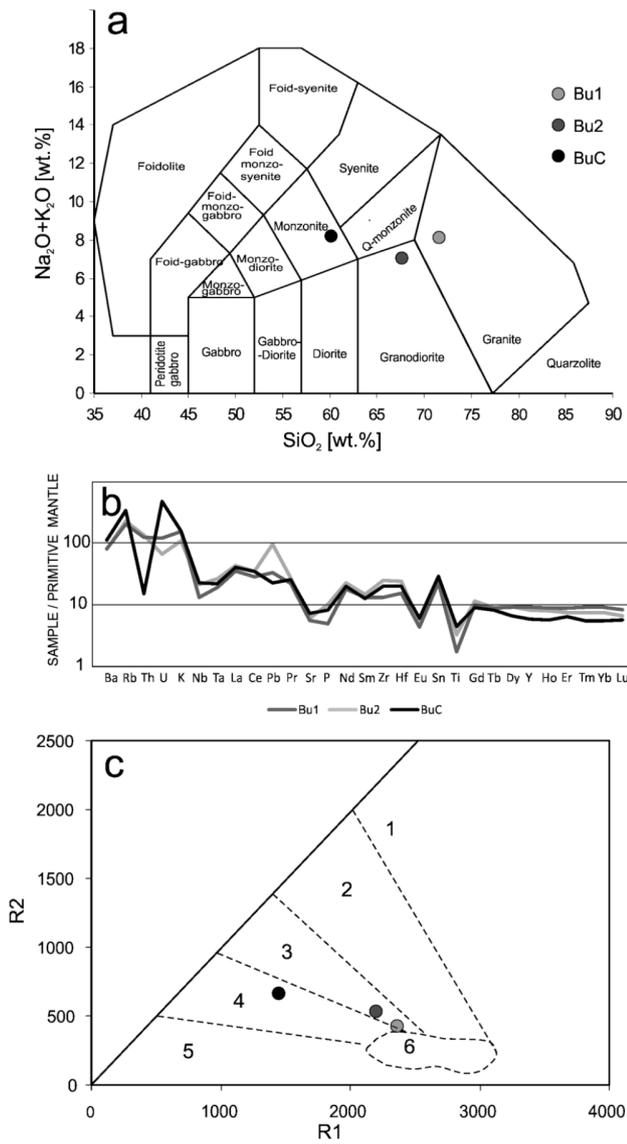


Fig. 3. Classification position of the Bugaj granitoids in: (a) alkali ($K_2O + Na_2O$) versus SiO_2 (TAS) classification diagram (Middlemost, 1985); (b) Primitive mantle-normalized (Sun and McDonough, 1989) multi-element “spider” diagrams; (c) classification position of the Bugaj granitoids in Multicationic R1–R2 diagram (De La Roche et al., 1980), with fields numbered according to Batchelor and Bowden (1985); 1 – mantle fractionates, 2 – pre-plate collision suites, 3 – post-collision suites, 4 – late orogenic magmas, 5 – anorogenic suites, 6 – syncollisional (anatectic) suites. $R1 = 4Si - 11(Na + K) - 2(Fe + Ti)$; $R2 = 6Ca + 2Mg + Al$.

(Table 1). The primitive-mantle-normalized multi-element diagram points to an arc-setting of the magma, with typical Nb and Ta negative anomalies, whereas the Batchelor and Bowden (1985) classification suggests a post-collisional to late-orogenic magmatic suite (Fig. 3b, 3c). Granodiorite-granite rocks show relatively high

Table 1. Chemical composition and selected petrological indicators of Bugaj granitoid rocks.

Sample No.	Bu1	Bu2	BuC
SiO ₂	71.56	67.58	60.03
TiO ₂	0.38	0.7	0.98
Al ₂ O ₃	14.13	14.89	16.63
Fe ₂ O _{3T}	3.04	5.31	8.32
MnO	0.06	0.09	0.14
MgO	0.77	1.34	2.46
CaO	0.92	1.5	1.89
Na ₂ O	3.36	3.83	3.33
K ₂ O	4.79	3.36	4.86
P ₂ O ₅	0.11	0.22	0.18
LOI	0.71	1.13	0.9
Total	99.83	99.95	99.72
Sr	121.2	128	152.3
Ba	578	562	793
Rb	135.6	146.9	219.3
Cs	8.3	10.3	13.1
Th	11	11.7	1.3
U	2.6	1.4	10.1
Ga	16	20.4	20.5
Cr	82	109.5	116.3
Ni	11	14	27.9
V	43	75	135
Zr	150.9	283.6	226.8
Hf	4.9	7.6	6.2
Y	42.9	37.9	27
Nb	9.8	15.4	16.1
Ta	0.8	1.1	0.9
La	24.6	30.3	27.9
Ce	52.6	62.4	61.9
Pr	6.35	7.56	7.06
Nd	24.7	30.6	27.3
Sm	5.96	6.63	5.64
Eu	0.75	0.87	1.01
Gd	6.04	6.9	5.45
Tb	0.99	0.99	0.89
Dy	6.96	6.97	4.9
Ho	1.49	1.3	0.95
Er	4.32	3.62	3.1
Tm	0.69	0.56	0.41
Yb	4.56	3.67	2.69
Lu	0.64	0.5	0.42
ASI	1.17	1.23	1.21
#mg	0.56	0.7	0.31
Rb/Sr	1.12	1.15	1.44
ΣREE	140.65	162.87	149.62
Eu/Eu*	0.8	0.39	0.56
CeN/YbN	3.18	4.68	6.34
ThN/UN	1.04	2.06	0.03
T _{Zr} [°C]	798	850	818

Explanations:

LoD – limits of detection; LOI – loss of ignition; $Eu/Eu^* = Eu/\sqrt{Sm \cdot Gd}$; $ASI = Al_2O_3/(CaO + Na_2O + K_2O - 3.33 P_2O_5)$ (in molecular values); T_{Zr} = temperature calculated according to Watson and Harrison (1983) procedure.

Th_N/U_N ratios (2.06 and 1.05 respectively), whereas the monzonitic enclave shows a strong positive U anomaly and a Th_N/U_N ratio of 0.03, suggesting a highly oxidised source (possibly mantle-type?) of the monzonitic magma (Fig. 3b; Table 1).

The whole-rock isotope geochemistry data of two Bugaj mega block samples are presented in Table 2. Both samples (Bu1, Bu2) show nearly identical ⁸⁷Rb/⁸⁶Sr ratios (3.154 ± 0.032 and 3.236 ± 0.032) as well as ⁸⁷Sr/⁸⁶Sr ratios (0.756053 ± 0.000004 and 0.755499 ± 0.000004). The initial ⁸⁷Sr/⁸⁶Sr_(580 Ma) ratios are 0.72997 and 0.72874.

Contrary to the above the Sm-Nd isotope systematics of the two Bugaj mega block samples are dissimilar: ¹⁴⁷Sm/¹⁴⁴Nd ratios are 0.1521 ± 0.0015 (Bu1) and 0.1366 ± 0.0014 (Bu2). The ¹⁴³Nd/¹⁴⁴Nd ratios are 0.512397 ± 0.000004 and 0.512428 ± 0.000005, respectively. The resulting ε_{Nd580} are -1.4 and 0.4.

Andrychów orthogneiss mega block

The sample (An) is a medium-grained augen gneiss (Fig. 2b), consisting of quartz, K-feldspar, plagioclase (An₁₀₋₁₈) and biotite. The foliation is defined by biotite, quartz ribbons and elongate feldspars. Accessory minerals are apatite and zircon. Due to the penetrative low-temperature and structural overprinting of the Andrychów mega block rocks, no detailed micro-chemical analyses, whole rock chemistry as well as Rb-Sr and Sm-Nd isotope whole rock geochemistry were obtained.

5. ZIRCON CHARACTERISTICS AND U-PB AGES

Bugaj mega block

The zircons are colourless or slightly pink, euhedral, normal to very long-prismatic, even to acicular (aspect ratios 1:1 to 1:10). Grain sizes vary in length from ca. 50 to 350 μm (Fig. 4). A small percentage of zircon grains show an unusual habit contrasting markedly with the prismatic and acicular crystals (Fig. 4, p6Bu81). This habit is tabular, strongly flattened on the [110] crystal face (elongation ratio < 1). The typology falls into the S4 subtype group of Pupin (1980).

The cathodoluminescence (CL) images reveal a complexity of the internal structure. A significant number of crystals shows igneous oscillatory growth zoning, with growth bands varying between fine and broad within individual grains (Fig. 5). Luminescence is variable, but mostly moderate. Some grains display a blurred, light grey zonation, present in the centre of the zircon crystals (Fig. 5, p3Bu01). A small number of inherited cores were observed in normal-prismatic crystals (Fig. 5).

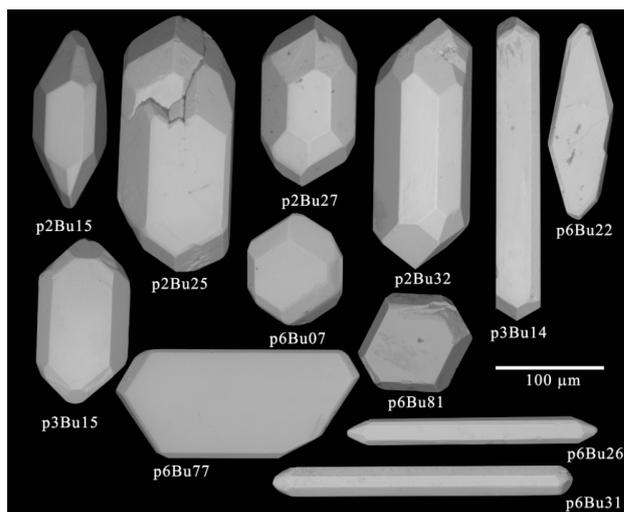


Fig. 4. Secondary electron (SE) images of selected zircon crystals from granite sample Bu1. See text for description.

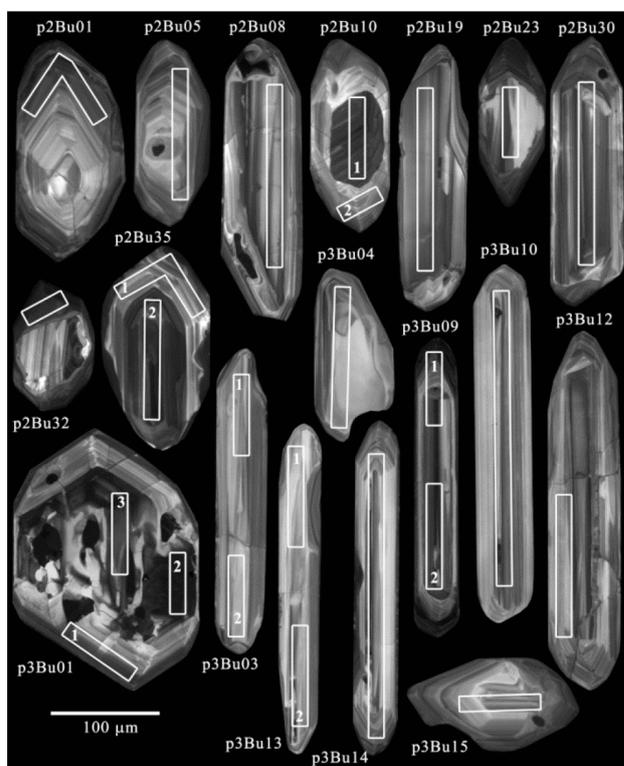


Fig. 5. Compiled cathodoluminescence (CL) images showing the range of textures observed in zircon crystals from granite sample Bu1. See text for details. The white rectangles show the approximate location of laser ablation trenches (confirmed by re-inspecting grains under CL after the LA analysis) and are not to scale. The numbers refer to the analytical data presented in Table 3.

Table 2. Rb-Sr and Sm-Nd whole rock isotope analysis of Bugaj granitoid rocks.

Isotope data	⁸⁷ Rb/ ⁸⁶ Sr	±2sm	⁸⁷ Sr/ ⁸⁶ Sr	±2sm	¹⁴⁷ Sm/ ¹⁴⁴ Nd	±2sm	¹⁴³ Nd/ ¹⁴⁴ Nd	±2sm	Sr(580 Ma)	Nd(580 Ma)	Nd(CHUR)
Bugaj1	3.154	0.032	0.756053	0.000004	0.1521	0.0015	0.512397	0.000004	0.729966	0.511819	-1.4
Bugaj2	3.236	0.032	0.755499	0.000004	0.1366	0.0014	0.512428	0.000005	0.728739	0.511909	0.4

Crystal domains targeted for dating are characterized by the presence of a well-developed fine-scale oscillatory growth zonation (Fig. 5). 25 dates on 19 crystals were gained (Table 3, Fig. 5). Individual $^{206}\text{Pb}/^{238}\text{U}$ dates range from 1751 ± 78 Ma to 431 ± 19 Ma, whereas $^{207}\text{Pb}/^{206}\text{Pb}$ dates range from 1773 ± 25 Ma to 510 ± 9 Ma, respectively. No systematic difference between the two populations could be detected. Thus the final age calculation took into account all analysed crystals of the Bugajl sample. One analysis (Bugajl_p2bu_023A) is concordant at an age of ca. 1760 Ma (Fig. 6a). 14 dates form a sub-concordant (discordance < 5%) cluster with a lower intercept date of 580.1 ± 6.0 Ma (Fig. 6b, model 1 solution, anchored at $^{207}\text{Pb}/^{206}\text{Pb} = 0.85 \pm 0.05$, MSWD = 1.8, Probability of fit = 0.031). These crystals show a mean Th/U of 0.16 ± 0.07 . Three sub-concordant analyses (discordance < 5%), characterized by comparably high Th/U (0.30 ± 0.04), form a cluster with a lower intercept date of 662 ± 37 Ma (not shown, model 1 solution, anchored at $^{207}\text{Pb}/^{206}\text{Pb} = 0.85 \pm 0.05$, MSWD = 0.12, Probability of fit = 0.89). This lower intercept date is statistically distinguishable from the former one, also based on the disparate Th/U ratios of the two clusters. The remaining 7 analyses are highly discordant with high Th/U ratios (0.72 ± 0.35), again statistically distinguishable from the former two clusters.

Andrychów mega block

Zircon grains are euhedral, up to 300 μm long, with aspect ratios from 1:1 to 1:3 (Fig. 7). They are clear, yellow and greenish yellow in colour.

In CL images a variably developed oscillatory growth zonation is the prominent feature of all analysed grains, as shown by moderate to weak luminescence. Some crystals display core-rim structures. The cores are characterized

by oscillatory growth zonation with high/moderate CL intensity (Fig. 8).

Crystal domains targeted for dating are characterized by the presence of a well-developed fine-scale oscillatory growth zonation (Fig. 8). 15 dates on 10 crystals were gained (Table 3, Fig. 8). Individual $^{206}\text{Pb}/^{238}\text{U}$ dates range from 2149 ± 284 Ma to 319 ± 73 Ma, whereas $^{207}\text{Pb}/^{206}\text{Pb}$ dates range from 2324 ± 295 Ma to 554 ± 29 Ma, respectively. One analysis (Andrychów_p3an_06A) is concordant at an age of 2123 ± 23 Ma (Fig. 9a). 7 dates form a sub-concordant (discordance < 5%) cluster with a mean Th/U of 0.23 ± 0.11 . Two lower intercept dates can be calculated: i) 549 ± 29 Ma with an upper intercept at 2432 ± 1500 Ma (not shown, model 1 solution, MSWD = 0.99, Probability of fit = 0.42); ii) 542 ± 21 Ma with the upper intercept fixed at 2123 ± 23 Ma of analysis Andrychów_p3an_06A (Fig. 9b, model 1 solution, MSWD = 0.86, Probability of fit = 0.53).

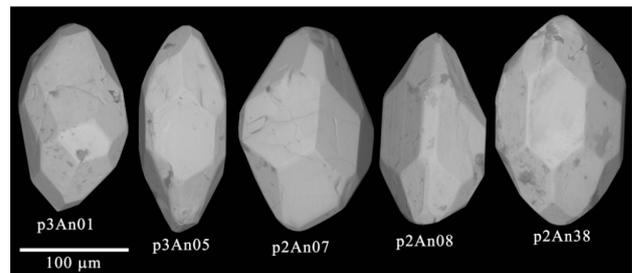


Fig. 7. Secondary electron (SE) images of selected zircon crystals from orthogneiss sample An. See text for description.

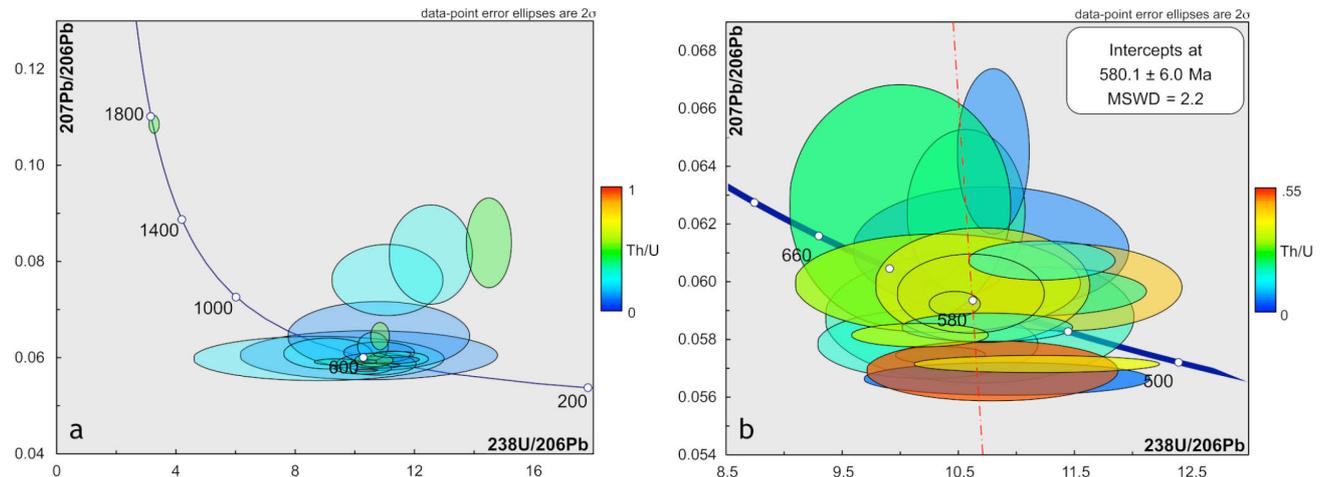


Fig. 6. Tera-Wasserburg diagrams presenting the U/Pb age of the zircons from granite sample Bu1: a) all data points; b) concordant to sub-concordant data points. The inherited xenocryst (p2Bu_23) and the three data points showing recent lead loss (p3Bu_01/1, p3Bu_01/1, p3Bu_09/1) are not shown.

Table 3. LA-MC-ICP-MS U–Pb zircon data from exotic mega blocks (samples An and Bu1).

Sample	Blank corrected intensities				Concentrations				Atomic ratios										Ages												
	²⁰⁶ Pb ×10 ⁻⁶	²⁰⁷ Pb ×10 ⁻⁵	²⁰⁸ Pb ×10 ⁻⁵	²³⁸ Th ×10 ⁻³	Pb	Th	U	Th/U	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²³⁵ U	²⁰⁶ Pb/ ²³⁸ U	2RSE	(%)	²⁰⁶ Pb/ ²³² Th	²⁰⁷ Pb/ ²³⁵ Th	2RSE	(%)	²⁰⁶ Pb/ ²³⁸ U	2RSE	(%)	²⁰⁶ Pb/ ²³⁸ U	2RSE	(%)	206/238 age	206/207 2SD age						
Andrychów An																															
p3An_02	6.10	39.0	23.0	51.0	11.0	6.30	10.1	24.4	139.9	0.17	908	8	0.6716	3.9	0.0795	3.8	0.48	0.0606	1.3	0.4316	4.9	0.0316	6.9	12.575	3.8	0.0606	1.3	493	19	624	29
p3An_031	7.00	68.0	41.0	97.0	28.0	10.0	17.7	64.8	140.6	0.46	1037	20	0.8044	6.3	0.0894	8.3	0.65	0.0642	4.3	0.4994	16.0	0.0228	13.1	11.189	8.3	0.0642	4.3	552	46	750	92
p3An_032	15.0	65.0	47.0	92.0	18.0	13.0	17.2	41.5	141.1	0.29	810	27	0.6698	10.3	0.0725	17.4	0.85	0.0681	16.1	0.4145	11.5	0.0357	22.5	13.799	17.4	0.0681	16.1	451	78	871	334
p3An_041	4.20	42.0	23.0	37.0	9.60	6.20	10.4	21.9	139.9	0.16	1241	8	0.7043	11.8	0.0873	10.8	0.46	0.0587	1.3	0.2440	11.8	0.0253	10.6	11.448	10.8	0.0587	1.3	540	58	584	29
p3An_042	4.90	35.0	20.0	41.0	11.0	4.90	9.1	25.3	139.7	0.11	1130	4	0.7178	12.0	0.0888	9.6	0.40	0.0591	2.5	0.3477	6.1	0.0224	10.3	11.295	9.6	0.0591	2.5	547	53	572	54
p3An_061	4.40	120	140	220	140	3.70	33.3	31.8	139.5	0.23	3187	14	7.2106	12.5	0.3956	13.2	0.53	0.1319	1.3	0.5778	4.2	0.0870	25.5	2.528	13.2	0.1319	1.3	2149	284	2123	23
p3An_062	5.00	190	200	98.0	7.90	9.20	47.1	18.1	140.4	0.13	nd	nd	4.2498	7.3	0.2650	8.7	0.59	0.1138	1.1	0.1669	23.5	0.0849	10.1	3.774	8.7	0.1138	1.1	1515	132	1861	20
p3An_07	4.70	64.0	38.0	80.0	25.0	10.0	16.5	58.1	140.5	0.41	1767	16	0.7138	9.9	0.0860	14.2	0.71	0.0646	3.7	0.3529	8.5	0.0219	14.5	12.500	14.2	0.0646	3.7	496	70	761	79
p3An_08	5.00	150	140	170	17.0	8.00	39.9	39.3	140.2	0.28	3863	15	3.0943	15.2	0.2317	15.5	0.51	0.0947	0.5	0.3318	5.8	0.0696	10.8	4.316	15.5	0.0947	0.5	1343	208	1521	9
p3An_09	6.60	70.0	43.0	120	31.0	10.0	18.8	70.9	140.5	0.50	1540	15	0.8438	9.6	0.0933	11.5	0.60	0.0644	3.7	0.4983	7.2	0.0267	10.5	10.717	11.5	0.0644	3.7	575	66	753	79
p3An_10	5.80	55.0	32.0	93.0	28.0	7.20	14.7	63.3	140.1	0.45	1259	2	0.8063	5.7	0.0950	5.6	0.49	0.0613	0.9	0.4459	2.9	0.0224	8.3	10.523	5.6	0.0613	0.9	585	33	649	20
p3An_11	6.90	24.0	17.0	33.0	8.5	3.50	6.3	19.4	139.5	0.14	580	19	0.9325	10.9	0.0969	9.3	0.43	0.0690	8.6	0.3371	12.2	0.0261	15.1	10.317	9.3	0.0690	8.6	596	55	899	177
p3An_12/1	4.60	47.0	27.0	10.0	2.2	6.90	11.0	5.1	140.0	0.04	nd	nd	0.6993	8.5	0.0850	9.1	0.53	0.0595	0.7	0.0568	8.1	0.0301	7.2	11.764	9.1	0.0595	0.7	526	48	587	15
p3An_12/2	4.90	19.0	12.0	16.0	5.5	2.40	4.8	12.5	139.3	0.09	473	11	1.0174	17.2	0.1134	15.9	0.46	0.0642	3.8	0.2989	4.0	0.0204	18.4	8.821	15.9	0.0642	3.8	692	110	750	80
p3An_13	25.0	52.0	67.0	110	19.0	13.0	15.1	43.7	141.1	0.31	193	40	0.9691	11.9	0.0507	22.8	0.96	0.1481	17.2	0.6235	26.8	0.0780	39.6	19.741	22.8	0.1481	17.2	319	73	2324	295
Bugaj Bu1																															
p2Bu_01	14.0	44.0	37.0	63.0	12.0	5.80	11.8	27.5	139.8	0.20	341	14	0.8737	5.0	0.0947	4.0	0.40	0.0624	3.7	0.2605	7.2	0.0209	7.4	10.560	4.0	0.0624	3.7	583	23	688	79
p2Bu_05	nd	44.0	28.0	85.0	12.0	4.50	12.0	27.2	139.6	0.19	nd	nd	0.8737	6.3	0.1071	6.6	0.52	0.0592	0.9	0.5936	20.8	0.0263	8.7	9.341	6.6	0.0592	0.9	656	43	573	19
p2Bu_08	6.80	58.0	38.0	81.0	11.0	6.60	15.3	26.3	140.0	0.19	1018	11	0.7378	6.4	0.0896	7.1	0.55	0.0597	1.1	0.3524	8.2	0.0217	6.6	11.157	7.1	0.0597	1.1	553	39	592	25
p2Bu_10/1	5.00	85.0	93.0	180	190	16.0	24.6	435.3	141.5	3.08	931	187	0.7942	38.6	0.1102	177.8	2.31	0.0287	1356	0.0650	3667	0.0207	217.6	9.073	177.8	0.0287	1356	674	1189	-	
p2Bu_10/2	25.0	180	120	270	38.0	20.0	47.8	87.8	142.3	0.62	946	6	0.7912	8.6	0.0928	9.0	0.52	0.0611	2.9	0.3029	10.6	0.0221	7.9	10.776	9.0	0.0611	2.9	572	52	643	62
p2Bu_19	17.0	89.0	57.0	76.0	9.70	10.0	22.4	22.1	140.6	0.16	nd	nd	0.7638	3.2	0.0967	3.1	0.49	0.0575	0.4	0.3044	4.21	0.0244	5.9	10.339	3.1	0.0575	0.4	595	18	510	9
p2Bu_23	14.0	110	130	270	11.0	4.30	33.5	26.1	139.6	0.19	992	1	4.6704	5.0	0.3121	4.5	0.45	0.1084	1.3	0.5018	4.7	0.0751	6.1	3.204	4.5	0.1084	1.3	1751	78	1773	25
p2Bu_30	7.80	88.0	56.0	170	22.0	10.0	24.0	50.8	140.6	0.36	nd	nd	0.7806	9.3	0.0978	7.6	0.41	0.0578	1.7	0.3649	3.33	0.0237	14.5	10.229	7.6	0.0578	1.7	601	46	524	37
p2Bu_32	9.90	54.0	35.0	50.0	5.80	5.90	13.7	13.3	139.9	0.09	801	3	0.7487	5.2	0.0931	5.6	0.54	0.0584	0.7	0.2113	2.27	0.0269	5.1	10.742	5.6	0.0584	0.7	574	32	546	15
p2Bu_35/1	8.60	59.0	38.0	53.0	6.10	6.90	14.8	14.1	140.0	0.10	723	8	0.7295	5.2	0.0877	7.3	0.70	0.0598	2.1	0.2684	2.58	0.0252	16.0	11.405	7.3	0.0598	2.1	542	40	597	45
p2Bu_35/2	7.80	84.0	56.0	39.0	4.10	8.90	20.4	9.5	140.4	0.07	863	74	0.8119	24.6	0.0960	34.0	0.69	0.0606	6.9	0.1682	12.26	0.0356	36.3	10.420	34.0	0.0606	6.9	591	201	624	149
p3Bu_01/1	11.0	61.0	51.0	69.0	55.0	12.0	15.8	125.9	140.9	0.89	546	30	0.7773	8.6	0.0692	4.3	0.25	0.0839	9.0	0.4171	20.2	0.0128	21.3	14.460	4.3	0.0839	9.0	431	19	1290	176
p3Bu_01/2	4.60	15.0	11.0	17.0	11.0	2.10	3.8	25.3	139.2	0.18	nd	nd	0.8730	17.3	0.0946	11.9	0.35	0.0646	19.5	0.3371	54.8	0.0198	24.3	10.569	11.9	0.0646	19.5	583	69	762	412
p3Bu_03/1	17.0	48.0	42.0	120	83.0	8.30	14.0	189.3	140.3	1.35	453	22	0.8695	6.4	0.0800	9.1	0.71	0.0814	10.4	0.9599	19.5	0.0218	15.0	12.506	9.1	0.0814	10.4	496	45	1232	204
p3Bu_03/2	4.20	0.780	0.51	0.57	0.390	0.110	0.2	0.9	138.9	0.01	nd	nd	0.9325	36.6	0.1145	39.4	0.54	0.0599	6.2	0.2290	15.0	0.0153	106.6	8.736	39.4	0.0599	6.2	699	276	599	135
p3Bu_04	4.00	0.980	0.67	0.50	0.350	0.150	0.2	0.8	138.9	0.01	nd	nd	0.8442	21.7	0.0930	23.3	0.54	0.0646	9.0	0.1726	20.3	0.0140	70.5	10.749	23.3	0.0646	9.0	573	133	761	189
p3Bu_09/1	42.0	33.0	52.0	120	76.0	7.30	10.8	175.0	140.1	1.25	199	25	2.1793	196.9	0.1178	133.3	0.34	0.1021	96.8	0.7533	129.5	0.0158	695.3	8.488	133.3	0.1021	96.8	718	957	1663	1791
p3Bu_09/2	5.80	30.0	24.0	75.0	29.0	5.90	9.7	66.8	139.8	0.48	720	4	0.8187	4.0	0.0926	2.4	0.29	0.0645	3.6	0.9196	17.5	0.0279	4.4	10.799	2.4	0.0645	3.6	571	13	758	76
p3Bu_10	nd	16.0	10.0	30.0	12.0	2.50	4.4	26.7	139.3	0.19	nd	nd	0.7826	1.9	0.0956	1.7	0.44	0.0592	0.6	0.6439	3.7	0.0284	2.2	10.459	1.7	0.0592	0.6	589	10	576	13
p3Bu_12	5.40	32.0	20.0	31.0	12.0	4.90	8.1	26.9	139.7	0.19	557	6	0.7593	11.7	0.0936	10.2	0.44	0.0588	3.2	0.4832	241.3	0.0287	19.4	10.679	10.2	0.0588	3.2	577	59	559	69
p3Bu_13/1	4.60	24.0	15.0	23.0	8.10	3.60	6.0	18.6	139.5	0.13	nd	nd	0.7																		

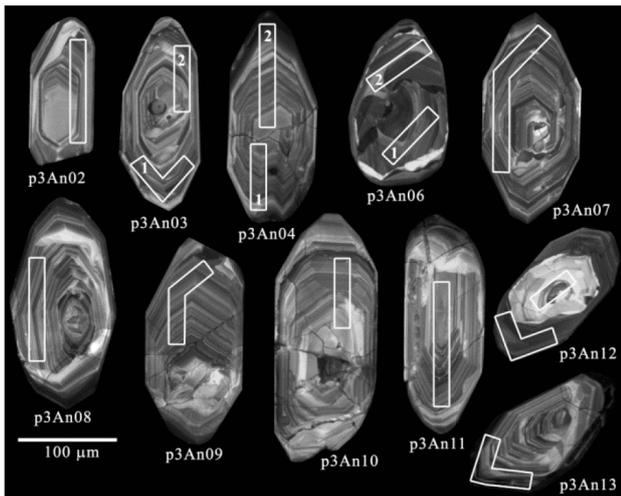


Fig. 8. Compiled cathodoluminescence (CL) images showing the range of textures observed in zircon crystals from orthogneiss sample An. See text for details. The white rectangles show the approximate location of laser ablation trenches (confirmed by re-inspecting grains under CL after the LA analysis) and are not to scale. The numbers refer to the analytical data presented in Table 3.

The calculated upper intercept value of 2432 ± 1500 Ma of i) is well within uncertainty with the concordant age value of 2123 ± 23 Ma used for the calculation in ii). Also the two lower intercept ages are identical within their uncertainty limits.

The remaining analyses either are strongly discordant (discordance $> 10\%$) or sub-concordant (discordance $< 5\%$) at $^{207}\text{Pb}/^{206}\text{Pb}$ ages between 2324 ± 295 Ma and 624 ± 29 Ma. The Th/U ratios of these analyses are identical to the former one (0.18 ± 0.06).

6. DISCUSSION

Exotics represent one of the most important sources of information about Carpathian alimentary areas, indirectly indicating their geotectonic history. For both exotic mega blocks (sample Bugaj and sample Andrychów) igneous formation ages were derived from the zircon U-Pb data.

The Cadomian age (580.1 ± 6.0 Ma) from sample *Bul* is interpreted as magmatic crystallization age of the Bugaj granitoids. A fine-scale oscillatory zonation in the CL images as well as Th/U ratio of 0.16 ± 0.07 point to igneous crystal growth (Corfu *et al.*, 2003). Three analyses (Th/U ratios 0.30 ± 0.04), forming a cluster with a lower intercept age of 662 ± 37 Ma are interpreted to reflect a major contribution from a single inheritance source to the ca. 580 Ma igneous event. The singular $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1773 ± 25 Ma (p2Bu_23) represents a xenocryst.

The Sr and Nd whole-rock isotope data are controversial. The initial (at ca. 580 Ma) $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the Bugaj granitoids (0.72997 and 0.72874) are highly radiogenic, pointing to the assimilation of an older, possibly strongly Rb enriched source to the Bugaj melt. On the other hand, the Nd isotope systematics ($\epsilon_{\text{Nd}580} -1.4$ and 0.4) rather point to a significant contribution of a distinct mantle source to the Bugaj melt. These geochemical data thus allow to recognize a hybrid geochemical character of the investigated rocks and/or decoupling of the Rb-Sr and Sm-Nd isotopic systems during post-magmatic alteration also supported by the presence of mafic enclaves. Such a hybrid character is also reflected in the high K-calc-alkaline series affinity with the intermediate association of the ferroan and magnesian families (Frost and Frost, 2008). Also the relatively high Th_N/U_N ratios (2.06 and

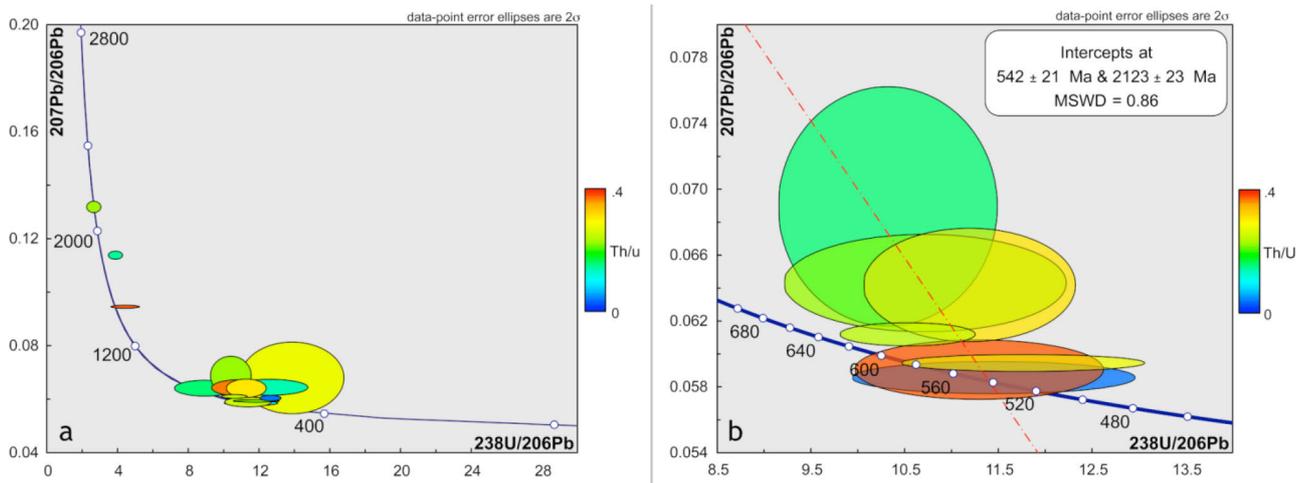


Fig. 9. Tera-Wasserburg diagrams for isotopic ratio for zircon crystals from orthogneiss sample An: a) all data points; b) concordant to sub-concordant data points defining a discordia line with a lower intercept of 542 ± 21 Ma (forced through data point p3An_06/1). The inherited xenocrysts (p3An_06/1, p3An_06/2) and the two data points showing recent lead loss (p3An_08, p3An_13) are not shown.

1.05) are remarkably well reflected in the high Th/U ratios of some zircon domains (0.72 ± 0.35). It is not clear, whether this hybridisation is a primary one, *i.e.* occurring during protolith formation or a secondary one.

The biotite K-Ar age of 485 ± 10 Ma (Haber and Hałas, 2001) indicates either slow cooling to *ca.* 300°C after the 580 Ma magmatic event or a Lower Ordovician thermal and possibly fluid-related overprint, which might have caused the resetting of the Rb-Sr system which resulted in highly radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. It has to be noticed however, that such an event is not detected in the U-Pb zircon data. This fact is in favour of the slow cooling model.

In the Andrychów sample, the lower intercept age of 542 ± 21 Ma, obtained from zircon domains exhibiting a fine-scale oscillatory growth zonation in the CL images, is interpreted as the uppermost Proterozoic to Cambrian magmatic crystallization age of the granitic precursor of the orthogneiss. The concordant age at 2123 ± 23 Ma represents Palaeoproterozoic inheritance. There is no evidence for a Variscan (Devonian-Carboniferous) or Alpine (Neogene) metamorphic overprint, neither from the zircon U-Pb age systematics nor from the zircon mineral chemistry, *i.e.* the Th/U ratios (samples *Bul* and *An*), and the whole-rock isotope geochemistry (sample *Bul*). Lack of any Variscan overprint suggests no similarities of the analysed exotic mega blocks to the crystalline basement of the Inner Western Carpathians, showing the Variscan consolidation, *e.g.* from granitoids of the Tatra Massif (*e.g.* Burda and Klötzli, 2011; Burda *et al.*, 2013).

The U-Pb zircon ages presented in this study are consistent with published results (monazite Th-U-total Pb dating, K-Ar dating of muscovite and biotite), reported from clastic material supplying Silesian basin from the Brunovistulicum and/or Małopolska Terranes as northern source areas (Poprawa *et al.*, 2004, 2005, 2006; Budzyń *et al.*, 2008, 2011).

The sequence of events obtained from U-Pb zircon ages from Bugaj and Andrychów exotic mega blocks shows similarities to magmatic-metamorphic events identified in the Brunovistulicum Terrane. These events include: a) terrane collision with deformation, metamorphism and plutonism at *ca.* 650–620 Ma; b) arc-type granitoid intrusions at *ca.* 590–580 Ma and c) late bimodal magmatism and strike-slip deformation at *ca.* 560–550 Ma. No evidence for Variscan magmatism and/or metamorphism has emerged (*e.g.* Finger *et al.*, 2000; Żelaźniewicz *et al.*, 2009 and references therein). Also the $\varepsilon_{\text{Nd}580}$ (–1.4 and 0.4) obtained for the Bugaj granitoid is similar to the Neoproterozoic igneous rocks from the Brunovistulicum Terrane having $\varepsilon_{\text{Nd}580}$ values ranging from –1 to +3 (Finger *et al.*, 2000).

Our investigations thus support the connection of the exotic mega blocks with the Avalonian-Cadomian orogenic belt during the Neoproterozoic (Żelaźniewicz *et al.*, 2009).

7. CONCLUSIONS

- 1) For both exotic mega blocks (Bugaj and Andrychów) igneous formation ages could be derived from the zircon U-Pb data. These are 542 ± 21 Ma for the orthogneiss from Andrychów and 580.1 ± 6.0 Ma for the granitoid from Bugaj.
- 2) The U-Pb zircon ages, derived from > 100 m sized exotic mega blocks, directly reflect the presence of substantial amounts of a proximal ‘Cadomian’ aged crust proper in the vicinity of the WOC basement. This is a marked difference to earlier published data, which are derived from cm-dm sized pebbles only. As these can easily be derived from re-sedimented sources the ages do not necessarily reflect direct derivation from a ‘Cadomian’ basement, inasmuch as transport distances are not known.
- 3) Exotic mega blocks deposited to the WOC basins were related to the Brunovistulicum Terrane. They belong to the group of Vendian/Early Cambrian granitoids, representing the latest, post-tectonic expression of the Cadomian cycle.

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