Acta Geologica Polonica, Vol. 58 (2008), No. 4, pp. 371-384

Geochemistry and U-Pb detrital zircon ages of metasedimentary rocks of the Lower Unit, Western Tatra Mountains (Slovakia)

MILAN KOHÚT[1], ULRIKE POLLER[2], CHRISTIAN GURK[2, 3] & WOLFGANG TODT[2]

[1]*Dionyz Stur State Institute of Geology, Mlynska dolina 1, SK-817 04 Bratislava, Slovakia.*
E-mail: milan.kohut@geology.sk
[2]*Max-Planck-Institut für Chemie, Abt. Geochemie, Postfach 3060, D-55020 Mainz, Germany.*
[3]*Johannes Gutenberg Universität Mainz, Geowissenschaftliches Institut, D-55020 Mainz, Germany.*

ABSTRACT:

KOHÚT, M., POLLER, U., GURK, C. & TODT, W. 2008. Geochemistry and U-Pb detrital zircon ages of metasedimentary rocks of the Lower Unit, Western Tatra Mountains (Slovakia). *Acta Geologica Polonica*, **58** (4), 371-384. Warszawa.

A combined geochemical, isotopic and detrital zircon dating study has been carried out on metasedimentary rocks of the Lower Unit from the Western Tatra Mountains (Slovakia) forming an eastern border of European Variscides. Geochemical data suggest derivation of the protolith – magmatogenic greywackes and claystones from the recycled continental island arc source. $^{87}Sr/^{86}Sr_{(350)}$ isotopic ratios between 0.713 and 0.723 together with low $\varepsilon_{Nd(350)}$ values of –9.5 to –11.1 and/or Pb isotope composition indicate a crustal origin of the investigated rocks. Detrital zircons from the metasediments often display homogeneous magmatic zoning with $^{207}Pb/^{206}Pb$ ages from 660 to 515 Ma and/or inherited components, with old cores displaying ages from ca. 1980 to 1800 Ma. These late Paleoproterozoic detrital source ages are similar to the Nd model ages of the studied metasedimentary rocks with $t_{(DM2st)}$ ca 1960 ~ 1830 Ma. The Late Cambrian (ca 500 Ma) age represents the last magmatic activity of the precursor rocks and/or it defines the maximum age for sedimentation of the present day metasediments. A possible source for the clastic material of the Lower Unit from the Western Tatra Mountains was the peri-Gondwanan continental margin alike the eastern border of the Bohemian Massif – Moravo-Silesian zone or Sudetic block.

Key words: Western Carpathians, Cadomian and Variscan orogeny, Metasedimentary rocks, Geochemistry, Detrital zircon dating.

INTRODUCTION

Understanding the geodynamic evolution in orogenic belts like the Alps, Carpathians or Himalayas that contain multistage metamorphic and magmatic episodes is often problematic. The polyorogenetic history of such orogenic belts, marked by the incorporation of pre-Mesozoic polycrystalline basement rocks into young Alpine structures, resulted in the formation of complexes that are often characterised by juxtaposition of various terranes and/or blocks due to multistage tectonic evolution with large-scale nappe and strike-slip tectonics. Lithological and structural correlations between various fragments are frequently ambiguous, and the timing and duration of the geological events that led to the lithological diversity in these orogens are of crucial importance in understanding the tectonic formation in these belts. The European Variscan and Alpine mountain chains are typical collisional orogens, and are built up of pre-Variscan basement blocks that, in most cases, originated at the Gondwana margin. Such pre-Variscan elements were part of a pre-Ordovician continental belt – the Hun superterrane – in the former eastern prolongation of Avalonia, and their present-day distribution resulted from juxtaposition during Variscan and/or Alpine tectonic evolution (STAMPFLI & BOREL 2002; VON RAUMER & *al.* 2002). The Carpathians form part of an extensive equatorial orogenic belt extending from the Atlas Mountains in Morocco, through the Alps, Dinarides, Pontides, Zagros and Hindu Kush to the Himalayas and China. The Western Carpathians are the northernmost, E–W trending branch of this Alpine belt, linked to the Eastern Alps in the west and to the Eastern Carpathians in the east. The correlation of Variscan and pre-Variscan basement rocks of the Western Carpathians with the pre-Mesozoic basement areas of the Variscan and Alpine orogenic belts is still hampered by a lack of precise age and compositional data of the metamorphic units, whereas knowledge of the age and composition of the igneous rocks is well constrained by recent studies (e.g. POLLER & *al.* 2000, 2001, 2005; GAAB & *al.* 2006; PUTIŠ & *al.* 2008). Detrital zircon dating is a powerful tool that is used to estimate ages of crust-forming events and establish the possible provenance of clastic (meta)sedimentary rocks and hence assist in the development of palaeogeographical reconstructions (GEBAUER & *al.* 1989; VALVERDE-VAQUERO & *al.* 2000; RAINBIRD & *al.* 2001; FRIEND & *al.* 2003). This contribution presents new zircon ages and combined geochemical and Sr, Nd, Pb isotopic data from metamorphic rocks of the Western Tatra Mountains and discusses large-scale basement correlations within the European Variscides and the Alpine orogenic belt.

GEOLOGICAL SETTING

The Western Tatra Mountains are situated in the northern part of Slovakia at the border with Poland (Text-fig. 1). Geologically they belong to the Western Carpathians, which form an eastern continuation of the Alps. The crystalline basement of the Tatra Mountains is composed of pre-Mesozoic metamorphic rocks and granitoids, which are overlain by Mesozoic sediments. Two allochthonous Mesozoic units – the Krízna and Choc nappes – occur in a tectonically higher position. The crystalline basement together with its Mesozoic cover and the nappe complexes was juxtaposed through north-directed thrusting during the Late Cretaceous. The Tatra Mts. form a typical horst structure and were finally exhumed during the Alpine orogeny in the Oligocene–Miocene period (KOVAC & *al.* 1994; KOHÚT & SHERLOCK 2003; JUREWICZ 2005). Metamorphic rocks are most abundant in the western part (Western Tatra Mountains), whereas the granites are more common in the eastern part (High Tatra Mountains). The basement is divided into two tectonic units, which differ in metamorphic grade and lithology (KAHAN 1969; JANÁK 1994). The "Upper Unit" contains granitoids, migmatites and some amphibolites whereas the "Lower Unit" consists mainly of metasediments (mica-schists, metaquartzites). The two units show inverted metamorphism due to tectonic movements in Variscan times (FRITZ & *al.* 1992).

The Lower Unit is only exposed in the Western Tatra Mountains (Text-fig. 1) and comprises exclusively medium-grade mica-schists. A kyanite-staurolite zone and a kyanite-sillimanite zone have been distinguished (JANÁK 1994; JANÁK & *al.* 1988; GAWĘDA & KOZŁOWSKI 1996). P-T estimates indicate lower amphibolite facies conditions in the Lower Unit (ca 570–650°C, and 600–800 MPa; e.g. JANÁK 1994; GURK 1999).

The Upper Unit shows high-grade metamorphism and migmatization due to partial melting. Its lower part is formed by older granites (orthogneisses), kyanite-bearing paragneisses and banded amphibolites with garnet and clinopyroxene-bearing eclogite relics (JANÁK & *al.* 1996), indicating HP (1.0–1.4 GPa) / HT (700–800°C) conditions. Higher levels, belong to the sillimanite zone and contain sillimanite, K-feldspar, and cordierite-bearing migmatites, which indicate medium to low pressure – high temperature conditions (400–600 MPa, 750–800°C; JANÁK & *al.* 1999; BURDA & GAWĘDA 1999; GAWĘDA & *al.* 2000; GAWĘDA & BURDA 2005). The Upper Unit was intruded by a sheet-like granitoid pluton, with a compositional range from muscovite-biotite granite to biotite tonalite and hornblende diorite (KOHÚT & JANÁK 1994). Muscovite-biotite granites to granodiorites (younger granites) are the most abundant intrusive rocks.

The crystalline basement of the Tatra Mountains has been affected by Variscan and Alpine deformations (KAHAN 1969; FRITZ & *al.* 1992; JUREWICZ 2005; JUREWICZ & BAGIŃSKI 2005). The first of two Variscan deformation phases (D1) is related to southeastward thrusting of the Upper Unit onto the Lower Unit, whereas D2 deformation was related to E–W extension. Reliable age constraints on the Variscan P-T and tectonometamorphic evolution in the Tatra Mountains are still lacking.

The Alpine influence is documented by mostly brittle deformation (D3) at lower P-T conditions; indicating northwest-directed shearing during Late Cretaceous compression. Magnetic fabrics (Hrouda & Kahan 1991) record this shear sense. D4 is related to updoming during Tertiary extension and uplift.

Recent age determinations for the granitoids in the Western and the High Tatra Mountains resulted in a Silurian age (406 Ma) for the precursor of the orthogneisses (older granites) in the Western Tatra. This was followed by the metamorphic overprint of these orthogneisses and the intrusion of the Western Tatra granitoids around 355 Ma ago (Poller & *al.* 2000). In the High Tatra Mts. the main phase of granitoid-emplacement occurred before 315 Ma (Poller & Todt 2000).

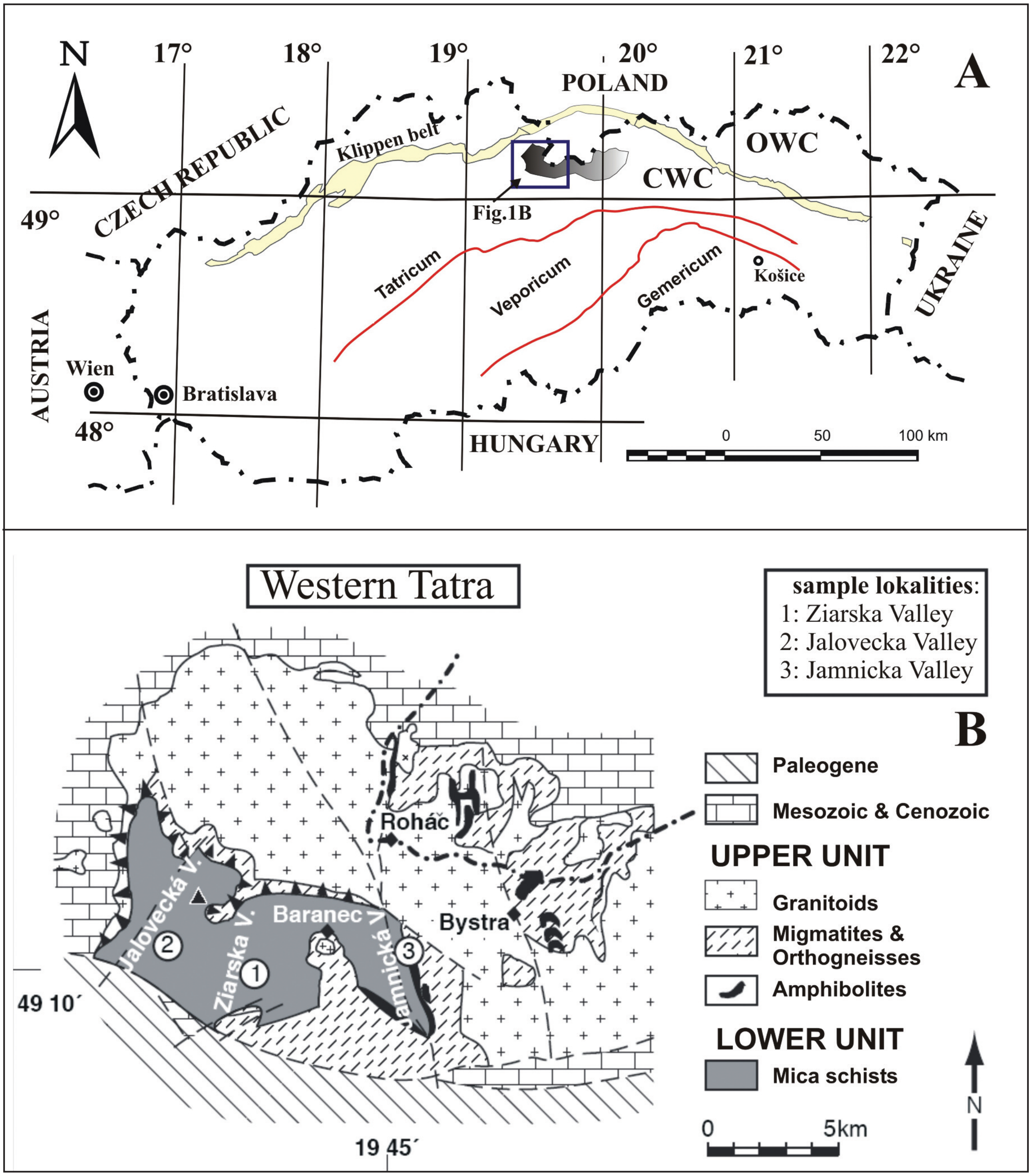

Fig. 1. A – Schematic tectonic-geologic map of the Western Carpathians (Slovakian part) showing the principal tectonic units (Tatricum, Veporicum, Gemericum) and the study area. *OWC* – Outer Western Carpathians, *CWC* – Central Western Carpathians. B – Simplified geological map (after Kohút & Janák, 1994) of the Western Tatra Mts. with the three valleys studied

Cooling ages of micas from the granitoids and migmatites obtained by the $^{40}Ar/^{39}Ar$ method range between 330 and 300 Ma (MALUSKI & *al.* 1993; JANÁK 1994; KOHÚT & SHERLOCK 2003). Apatite fission track data record the final uplift of the Tatra Mountains in the Tertiary, 15–10 Ma ago (KOVÁC & *al.* 1994).

This study focuses on the geochemical composition, isotopic signatures, and U-Pb dating of detrital zircons of metasediments of the Lower Unit.

ANALYTICAL TECHNIQUES

For the geochemical and geochronological investigations samples between 10 and 20 kg of fresh material were collected in the field. The samples were crushed and around 300 g of the resulting material were pulverised using an agate mill for later geochemical investigations. For mineral separation, the crushed material was ground using a rotary mill to a grain-size of under 500 µm. Zircons were first separated using a Wilfley table, and the heaviest fraction was than processed with heavy liquids and a Frantz magnetic separator to obtain the zircon separate. Suitable grains for U-Pb age determinations and cathodoluminescence (CL) documentation were selected by hand picking.

For Pb isotope whole rock analyses, in order to avoid Pb contamination and obtain a spread on the discordia, fresh rock fragments (ca 0.5 g) and not rock powder were taken and dissolved with HF and HNO_3 in Savilex beakers for three days on a hotplate. For Sm-Nd and Rb-Sr isotope analyses and XRF and ICP-MS measurements, the fine-grained powder (<50 µm) from the agate mill was used.

The Rb-Sr chemistry was performed by standard ion exchange methods. For Sm-Nd chemistry HDHP columns were used following the procedures described in WHITE & PATCHETT (1984). The Pb separation was executed with HBr on microcolumns (see ARNDT & TODT 1994). All isotopic measurements were carried out at the Max-Planck-Institut für Chemie in Mainz using a Finnigan MAT 261 mass spectrometer. Pb-Pb, Rb-Sr and Sm-Nd were measured with multiple collectors operating in static mode. Errors on isotopic ratios are given as 2σ of the block mean (10–25 blocks with 10 scans each). Blanks for Nd, Sm, Sr and Rb analyses were below 100 pg and thus not significant. All Nd and Sr measurements were done as IC and ID for getting the isotopic compositions and the element ratios.

Measurements of the La Jolla Nd standard at intensities similar to those of the samples yielded the ratio $^{143}Nd/^{144}Nd = 0.511840 \pm 28$ (n = 9). All $^{143}Nd/^{144}Nd$ ratios are fractionation corrected to $^{146}Nd/^{144}Nd = 0.7219$. The $^{147}Sm/^{144}Nd$ ratios have an estimated precision of 0.1%. The $\varepsilon Nd_{(0)}$ values were calculated using a $^{143}Nd/^{144}Nd = 0.512638$ ratio for present-day bulk silicate earth (JACOBSEN & WASSERBURG 1980).

Measurements of the NBS 987 standard yielded a $^{87}Sr/^{86}Sr = 0.710237 \pm 28$ (n = 10) ratio. All measurements were fractionation corrected to $^{86}Sr/^{88}Sr = 0.1194$. The $\varepsilon Sr_{(0)}$ values were calculated with a $^{87}Sr/^{86}Sr = 0.7045$ ratio for the present-day bulk earth composition (DE PAOLO & WASSERBURG 1976).

For common Pb measurements, two NBS 982 or NBS 981 standards were loaded with the samples and measured at the beginning and at the end of the sample analyses. The resulting mean fractionation of these standard measurements was used for correction of the samples measured on the same turret. For all measurements (standards and samples), the regression was made with reference to the mean of the first block. Additionally, all measurements were performed at tem-

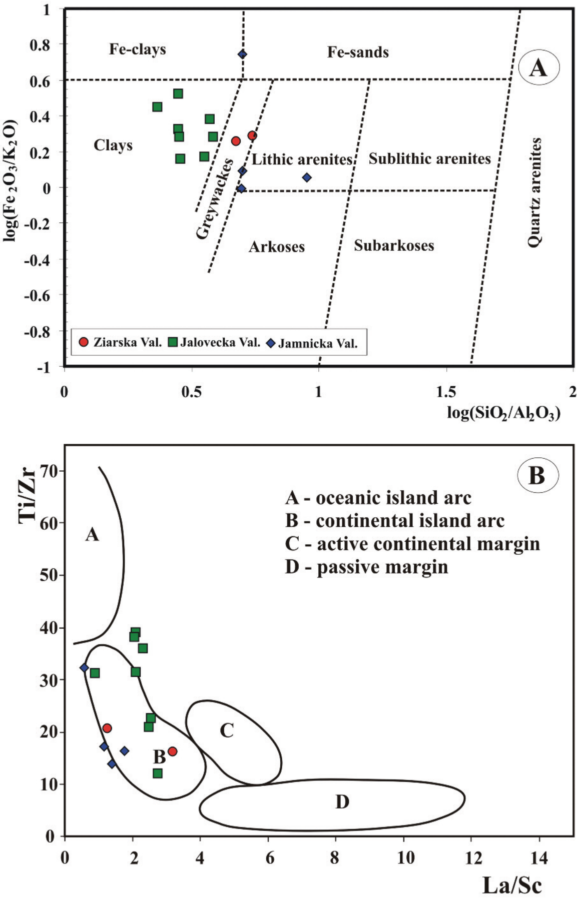

Fig. 2. A – Discrimination diagram after HERRON (1988) to distinguish different sedimentary rocks. B – La/Sc vs. TiO_2 diagram after BHATIA & CROOK (1986) for determination of the geodynamic setting

peratures controlled and measured at the same temperature as the standards. The Pb total blanks were less than 50 pg and therefore insignificant. For the age determination, zircons were dissolved by the vapour digestion method (Wendt & Todt 1991) The CLC-method (cathodoluminescence controlled) was applied to control compositional heterogeneities (Poller 2000) and only homogeneous grains pulled out of the

locality	Ziarská	Valley		Jalovecká Valley							Jamnická Valley			
sample	**1003**	**1004**	**1006**	**1058**	**1058b**	**1058d**	**1058e**	**1059**	**1060**	**1202**	**1009**	**1013**	**1200**	**1201**
SiO_2	72.5	69.2	57.8	66.0	65.2	64.5	59.7	59.7	59.5	55.2	70.7	71.3	82.8	71.6
TiO_2	0.5	0.7	0.9	0.8	0.8	0.7	0.9	0.9	1.0	0.9	0.4	0.6	0.4	0.6
Al_2O_3	13.3	14.7	20.7	17.2	18.5	17.3	21.0	21.2	21.2	23.9	13.9	14.4	9.3	14.3
Fe_2O_3	3.7	4.8	7.3	6.2	5.4	6.9	6.6	7.8	8.3	9.5	4.9	3.5	2.2	4.0
MnO	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.0	0.0	0.1
MgO	1.4	1.8	2.4	1.9	1.9	1.9	2.3	2.2	2.2	2.7	1.0	1.7	0.9	1.3
CaO	3.0	1.2	1.2	0.4	0.4	0.8	0.3	0.6	1.3	1.0	4.8	0.6	0.4	0.9
Na_2O	1.3	2.6	2.5	2.3	2.2	3.1	1.9	1.2	2.3	1.9	3.2	2.1	1.3	3.0
K_2O	1.9	2.7	3.4	3.2	3.6	2.9	4.6	4.0	2.5	3.4	0.2	3.6	1.9	3.2
P_2O_5	0.1	0.2	0.1	0.0	0.0	0.2	0.0	0.1	0.0	0.0	0.1	0.1	0.1	0.1
LOI	1.5	1.6	3.1	2.1	2.3	1.7	2.7	2.6	1.3	1.8	0.6	1.7	1.2	1.4
total	99.2	99.5	99.4	100.2	100.4	100.1	100.1	100.3	99.8	100.4	99.7	99.6	100.6	100.5
Ba	461	557	788	687	747	499	996	823	480	694	79	599	781	750
Co	52	40	28	55	55	38	34	54	39	43	85	35	51	44
Cr	54	77	94	77	93	77	110	100	102	109	11	54	33	54
Cu	19	16	<3	7	1	19		62	16	16	7	9	9	2
Ga	16	19	26	21	24	22	28	28	26	30	16	18	12	17
Nb	12	15	20	16	17	15	19	16	18	16	2	14	8	14
Ni	22	26	34	31	34	30	46	36	41	51	5	22	12	24
Pb	19	14	15	15	16	25	16	14	24	17	12	10	28	5
Rb	71	98	143	131	134	139	159	179	143	182	9	142	58	138
Sc	9	12	15	12	13	13	15	16	18	16	14	8	5	9
Sr	173	175	199	166	187	231	160	116	248	200	244	148	70	188
Th	10	9	12	14	13	16	17	15	15	8	2	3	1	1
U	2	2	3	2	4	3	3	2	2	2	1	1	n.d.	n.d.
V	57	82	118	77	83	76	114	100	102	125	34	59	38	61
Y	24	27	28	30	23	32	26	25	34	29	14	22	14	24
Zn	45	62	80	61	90	84	61	128	128	120	43	58	40	40
Zr	195	198	180	206	238	373	175	126	140	127	71	203	167	216
La	29.42	25.12	30.68	31.55	33.05	35.67	32.86	36.78	37.55	32.73	8.00	10.49	8.42	16.35
Ce	61.55	57.61	60.95	63.82	70.82	77.35	64.73	77.83	80.61	56.88	18.00	21.56	15.96	24.48
Pr	6.21	5.84	6.45	6.76	8.50	8.94	7.14	8.75	8.98	6.91	n.d.	2.15	1.83	2.63
Nd	14.83	16.62	18.30	25.41	28.65	31.29	22.55	30.87	33.57	21.61	n.d.	8.52	8.11	11.57
Sm	3.14	3.78	4.24	4.62	6.18	6.83	4.42	6.54	6.75	3.75	n.d.	2.22	2.07	2.78
Eu	0.82	0.93	0.86	1.10	1.01	1.13	1.04	1.03	1.11	0.85	n.d.	0.24	0.21	0.34
Gd	2.50	3.81	2.66	3.41	4.67	4.20	4.11	3.52	4.74	3.38	n.d.	2.21	2.13	2.63
Tb	0.42	0.73	0.44	0.61	0.87	0.68	0.75	0.64	0.91	0.62	n.d.	0.33	0.31	0.30
Tm	0.21	0.35	0.23	0.29	0.45	0.32	0.38	0.33	0.47	0.27	n.d.	0.13	0.12	0.09
Yb	1.19	2.10	1.35	1.68	2.91	1.85	2.33	1.75	2.96	1.71	n.d.	0.82	0.78	0.51
Lu	0.22	0.35	0.22	0.31	0.46	0.31	0.37	0.29	0.48	0.27	n.d.	0.12	0.11	0.08

n.d. = not determined

Table 1. Major element (in wt. %), trace element and REE (in ppm) composition for samples of the metasediments of the Lower Unit

mount were used. The zircons were dissolved together with a $^{205}Pb/^{233}U$ spike in teflon bombs with individual holes for each zircon grain. One bomb has holes for 6 single zircons of the same sample; and the middle hole is used for the blank determination. U and Pb measurements were performed using a MAT 261 with SEV in peak hopping mode. All measurements were controlled with NBS 981 and U_{nat} standard analyses. All analyses were corrected using the parallel-detected procedure blank and also for fractionation and spike contribution. The fractionation was 1.45 ± 0.3 ‰ per Δ amu.

Geochemical analyses were performed by XRF and ICP-MS measurements at the Institut für Mineralogie, Johannes-Gutenberg Universität Mainz. The measurements were controlled with respect to international standards.

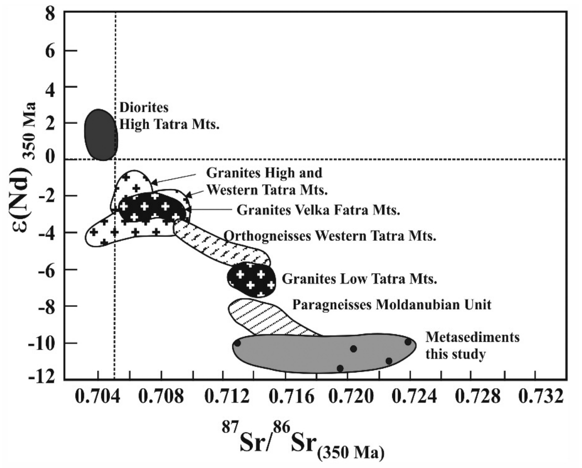

Fig. 3. $\varepsilon_{Nd(350)}$ versus $^{87}Sr/^{86}Sr_{(350)}$ data for the studied metasedimentary rocks in comparison with published data from the Western Carpathians (POLLER & *al.* 2001) and paragneisses from the Bohemian massif (JANOUŠEK & *al.* 1995). All data are recalculated to 350 Ma

GEOCHEMISTRY

The principal differences in chemical composition of the rocks studied (Table 1) reflect the flyschoid character of the Lower Unit from the Western Tatra Mts. in the discrimination diagram of HERRON (1988). It is evident that the protolith of the mica-schists from the Jalovecka Valley was composed mostly of claystones, whereas greywackes and arenites formed the protolith of the quartz-rich metapsammites from the Ziarska and Jamnicka Valley (see Text-fig. 2a). However, the presence of detrital material within the Jalovecka Valley metapelites indicates their semipelitic nature which, together with the prominent flyschoid character, represents hemipelagic background sedimentation.

The geochemical data show that the Jalovecka samples are richer in MgO and Al_2O_3 than all other rocks investigated. Using the classification of THÉLIN (1983), the precursor of the metasediments can be identified as follows: ortho (magmatic) lithologies for the Jalovecka Valley, whereas the metamorphic rocks of the Ziarska and Jamnicka Valleys seem to have a more para (sedimentary) origin. Indeed, it is obvious that the sources of these arenites were former felsic igneous rocks and that differences in chemical composition are attributable to differences in sediment maturity.

Concerning the tectonic environment during sedimentation, it can be inferred that the Jalovecka sediments originated from a continental island arc, whereas the other sediments have more in common with an active continental margin environment. These assumptions are constrained by the geochemical character of the samples according to ROSER & KORSCH (1986). However, based on some immobile elements such as Ti or Zr in combination with La and Sc (Text-fig. 2b), it appears that the differences in chemical compositions are not fundamental, and that all the rocks may have been derived from a continental island arc setting (BHATIA & CROOK 1986). The existence of inherited zircon cores inside the Jalovecka metasediments makes a continental island arc much more probable than an oceanic island arc, which is also sug-

sample	Nd	Sm	^{143}Nd	±2σ	^{147}Sm	ε Nd	T_{DM}	Sr	Rb	^{87}Sr	± 2σ	^{87}Rb	^{87}Sr
	ppm	ppm	^{144}Nd	mean	^{144}Nd	-350	Ma	ppm	ppm	^{86}Sr	mean	^{86}Sr	$^{86}Sr_{(350)}$
UP 1003	7.9	1.8	0.511944	53	0.1383	-10.9	1917	92	9	0.72356	56	0.28738	0.722128
UP 1006	18.3	3.8	0.511972	38	0.12673	-9.9	1834	63	24	0.728718	84	1.08464	0.723314
UP 1058	11.1	2.2	0.511955	38	0.12006	-10.1	1836	34	29	0.732381	63	2.44934	0.720177
UP 1059	17.8	3.5	0.511944	33	0.11869	-9.8	1848	20	35	0.738442	41	5.1385	0.71284
UP 1060	31.9	6.3	0.511876	41	0.11978	-11.4	1956	95	53	0.727283	35	1.62305	0.719196

Table 2.Sm-Nd and Rb-Sr data of some metasediments of the Lower Unit (Western Tatra Mts.). 2σ mean errors refer to mean of the blocks

gested by the major element chemistry (e.g. BHATIA 1983; ROSER & KORSCH 1988).

ISOTOPIC CHARACTERISATION

Five samples from the Jalovecka, Ziarska and Jamnicka Valleys were analysed for their Sr and Nd isotopic compositions (Table 2) and thirteen whole rock samples for their Pb isotope compositions (Table 3).

In order to compare the Sr and Nd isotopic ratios of the metasediments studied with those of neighbouring Variscan granitoids, the ratios were corrected for in-situ decay to 350 Ma, the date of the main Variscan event in the Western and the High Tatra Mountains as well as in the whole European Variscides.

Text-fig. 4 shows the position of the samples in the diagram $\varepsilon_{Nd(350)}$ versus $^{87}Sr/^{86}Sr_{(350)}$. The low $\varepsilon_{Nd(350)}$ values of –9.9 to –11.4, and the radiogenic Sr isotopic ratios ($^{87}Sr/^{86}Sr_{(350)}$ between 0.713 and 0.723, suggest a crustal origin. Compared to other metasediments of the Variscides, the Sr and Nd isotope composition of the Lower unit coincides with the composition of paragneisses from the Moldanubian Unit of the Bohemian Massif (JANOUŠEK & *al.* 1995).

The Pb-Pb data presented refer to measured isotope ratios (Table 3). The whole rock analyses were compared to feldspar and galena analyses (stars in Text-figs 5a and 5b). These mineral analyses show good correspondence with the whole rock data of the Tatra Mts. In Text-fig. 5a the present-day Pb-Pb data from Table 3 (circles) are compared to additional Western Carpathians data published by POLLER & *al.* (2001). Additionally, a comparison of the Western Carpathians basement (WCB) data with available data from various European Variscan realms is presented in Text-fig. 5b.

The uranogenic Pb isotope compositions of the metasediments with $^{206}Pb/^{204}Pb$ ratios between 18.21 and 19.39 and $^{207}Pb/^{204}Pb$ values between 15.62 and 15.77 represent upper crustal material (Text-fig. 5). Most of the samples plot around the upper crust reference line (DOE & ZARTMAN 1979) and between the evolution line of STACEY & KRAMERS (1975). However, the Pb isotopic characteristics of the samples partly overlap with the field of enriched mantle II (EM II) in the ZINDLER & HART (1986) plot, which may reflect a recycled oceanic crust influenced by pelagic sediments, and/or old subcontinental lithosphere. It is generally impossible to distinguish whether, in addition to the continental crust component, there is also a contribution from other sources such as recycled oceanic crust or EM II. In any case, the Pb isotope ratios presented suggest a typical orogenic line (ZARTMAN & HAINES 1988), which is actually a mixture of upper crust, EM II and lower crust characteristics that probably reflect a situation at an eroded continental island arc. Our Pb isotope data are slightly more radiogenic in comparison to those from other Variscan orogenic areas like the Massif Central, Black Forest or Mid German Crystalline Rise (VIDAL & POSTAIRE 1985; REISCHMANN & ANTHES 1996), which can indicate either a lower metamorphic grade or a different protolith source.

U-Pb ZIRCON DATING

The U-Pb single zircon dating was performed for the Jalovecka and the Jamnicka Valley metasediments. The zircons of the metasediments are mainly idiomorphic, prismatic and colourless. Almost all the grains were rounded by transport during sedimentation. No microscopic internal structures are visible. Cathodoluminescence connected to a scanning electron microscope shows that the zircons have magmatic outer zoning and also inherited components and old detrital cores. Diffuse structures due to metamorphic overprint are also visible in the zircons. Text-fig. 6

sample	**$^{206}Pb/^{204}Pb$**	**±2σ**	**$^{207}Pb/^{204}Pb$**	**±2σ**	**$^{208}Pb/^{204}Pb$**	**±2σ**
Whole rock data						
1003-1	18.450	35	15.629	41	38.738	47
1003-2	18.390	27	15.667	24	38.754	58
1004-1	18.442	43	15.625	52	38.805	54
1004-2	18.374	21	15.637	20	38.664	51
1006-1	18.227	13	15.661	13	38.598	57
1006-2	18.218	7	15.629	7	38.519	17
1007-1	18.376	13	15.704	10	38.987	28
1007-2	18.746	4	15.677	9	39.909	24
1013-1	18.428	7	15.634	8	39.172	20
1058-1	18.876	40	15.725	35	39.565	83
1058-2	19.319	26	15.774	20	39.738	52
1060-1	19.398	19	15.739	7	40.991	40
1060-2	18.941	16	15.740	14	39.835	33
Mineral data (F=feldspar, S=staurolite, K=kyanite)						
1058-F	18.881	92	15.713	73	39.686	184
1060-K	22.262	42	15.896	31	46.595	87
1060-K	20.586	778	15.562	617	42.776	160
1060-K	18.657	36	15.756	25	39.556	74
1060-S	18.774	24	15.729	20	39.577	50
1200-F	18.476	172	15.700	189	38.789	466

Table 3. Common Pb data, corrected for fractionation. 2σ mean errors refer to mean of the blocks

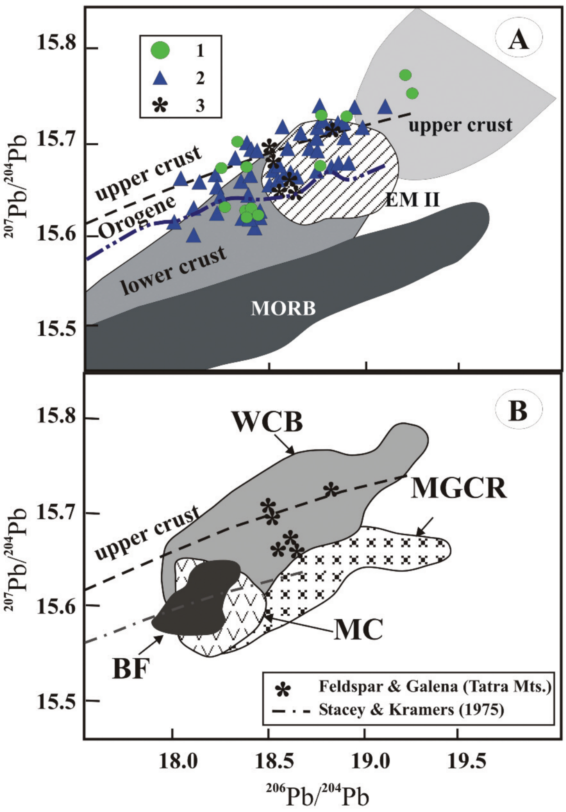

Fig. 4. ^{207}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb diagrams showing the origin (4A), and the relationship between the Western Carpathian rocks and those of typical Variscan regions (4B). The reference line for upper crust and reference fields for upper crust, enriched mantle II and MORB after Doe & Zartman (1979), field for lower crust after Zindler & Hart (1986). Symbols: 1) circle – data this study, 2) triangle – data from Poller & *al.* (2001), 3) star – feldspars and galena from Poller & *al.* (2001). Data for comparison in Fig. 5B are from Reischmann & Anthes (1996) and Vidal & Postaire (1985). WCB – Western Carpathian Basement; MGCR – Mid German Crystalline Ridge; MC – Massif Central; BF – Black Forest

shows some typical CL images of zircons from the Jalovecka (1058) and the Jamnicka (1201) valley. Whereas the grains 1201-1 and 1058-17 are characterised by homogeneous magmatic zoning, the zircons 1201-7 and 1058-22 are rather diffuse and cloudy, with no magmatic growth structures visible.

The U-Pb single zircon dating of seven grains resulted in three concordant ages (490, 503, 510 Ma) for the sample UP 1058 (Text-fig. 7a), which can be combined with core-bearing crystals on a common discordia line. This discordia has an upper intercept age of 2370 ± 140 Ma and a lower intercept age of 491 ± 11 Ma. The older age is interpreted as a protolith age, whereas the younger one gives the last magmatic activity of the precursor rock. For the Jamnicka Valley (Text-fig. 7b), the U-Pb data can also be interpreted by a discordia line with an upper intercept age of 2010 ± 35 Ma and a lower intercept age of 495 ± 4 Ma. The ages of the two samples are in good agreement and a Palaeoproterozoic protolith is most probable for both localities. The late Cambrian age detected in both samples defines a maximum age for the sedimentation of the metasediments.

No evidence for new zircon growth during later metamorphic overprint was found during the U-Pb measurements, indeed possible overgrowth may contribute to the scatter in the near-concordant samples. Dating of the metamorphism by U-Pb method has not been successful so far. Nevertheless, the age of the major protolith and the maximum age of sedimentation could be fixed by the zircon dating.

DISCUSSION

The Carpathians form part of Stille's (1924) Alpine "Neo-Europa", which originated from the Late Jurassic–Tertiary orogenic processes in a mobile belt between the stable North European Plate and Africa-related continental fragments connected with the evolution of the Tethys Ocean. Typical features of this mobile belt are the Mesozoic rifting and extension of the Variscan basement, compression and nappe stacking of attenuated continental crust, subduction of longitudinal oceanic crust and/or general northward migration of pre-orogenic and orogenic processes (Mahel' 1981; Plašienka & *al.* 1997). Indeed, Mesozoic sedimentary rocks predominate in the Western Carpathians, but even the pre-Mesozoic basement rocks form an important component of its structure. The general lack of isotopic dating and/or stratigraphic data in the past was responsible for regarding a major part of the Western Carpathians basement to be either Early Palaeozoic (Zoubek 1936; Andrusov 1968), or Late Proterozoic to Early Palaeozoic (Máška & Zoubek 1960; Kamenický 1968; Kamenický & Kamenický 1983) in age. Stratigraphic determination of palynomorphs, tracheids and phyto-detritus (Čorná & Kamenický 1976) from black schists indicated an Early Palaeozoic (Silurian–Devonian) age of sedimentation for dominant parts of the Carpathian basement. The age relationships of the majority of the igneous rocks (granites) were less problematic as the first K-Ar determinations clearly proved their Variscan–Carboniferous origin (Kantor 1959). Modern isotope data shed more light on this problem (Poller & *al.* 2000, 2001, 2005; Gaab & *al.* 2006) and documented repeated magmatic activity between

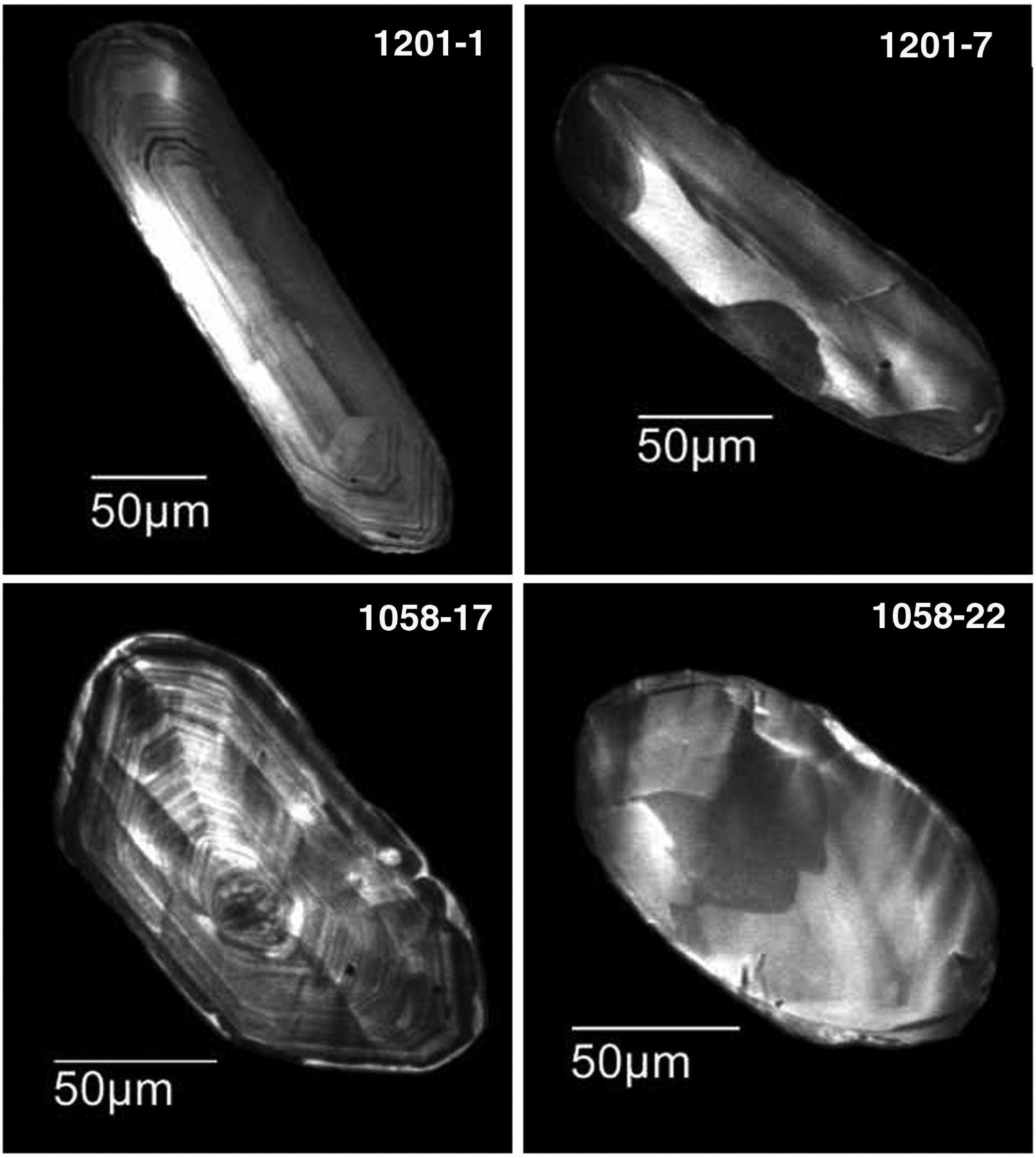

Fig. 5. Cathodoluminescence images of zircons from metasedimentary rocks from Jamnicka (1201) and Jalovecka (1058) valley. 1201-1 and 1058-17 show magmatic features, whereas 1201-7 and 1058-22 show diffuse structures, typical of metamorphic overprinting

465 Ma and 300 Ma. However, recent in-situ U-Pb zircon (SHRIMP) data proved the existence of older (525–470 Ma) metaigneous rocks within the Western Carpathians basement (Putiš & *al*. 2008).

Although our U-Pb zircon study did not reveal a distinctive Variscan metamorphic overprint within the medium-grade rocks of the Lower Unit of the Western Tatra Mts., the results indicate a Late Cambrian magmatic origin of the source rocks from which the metasedimentary rocks were derived. Both lower intercepts ages of around 500 Ma thus represent the maximum age for the sedimentation of the present-day metasediments, and/or the youngest age of their protolith. It is noteworthy that such old igneous rocks were more or less unknown in the Western Carpathians basement (WCB) until now, albeit Lower Carboniferous meta-trondhjemitic orthogneisses (350 Ma) from the Veporic layered amphibolite complex display a comparable upper intercept 514 ± 24 Ma age (Putiš & *al*. 2001). New laser-probe ^{40}Ar/^{39}Ar amphibole ages from tonalitic gneisses (leptino-amphibolite complex) indicate the existence of an older metamorphism episode ca. 750 Ma old, which was overprinted by the 350 Ma metamorphic/magmatic event that is documented by biotite data from identical samples (Kohút & *al*. 2005). Generally, the HT/MP metamorphism,

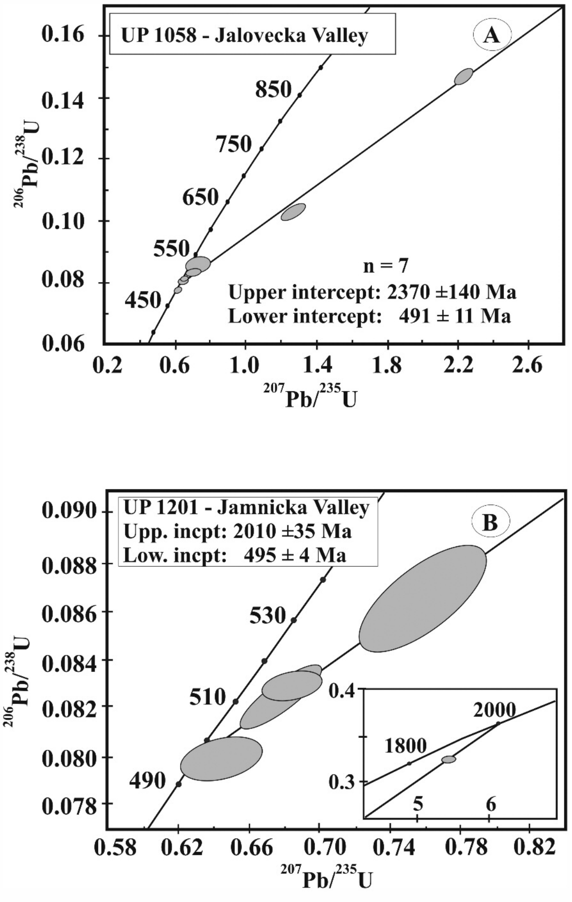

Fig. 6. A – ^{206}Pb/^{238}U vs. ^{207}Pb/^{235}U discordia plot for sample UP 1058, Jalovecka Valley; B – ^{206}Pb/^{238}U vs. ^{207}Pb/^{235}U discordia plot for sample UP 1201, Jamnicka Valley

with concomitant widespread granitic magmatism, heavily overprinted basement precursors and masked the polyorogenic history of the WCB during the Early Carboniferous in the Upper Unit of the Western Carpathians. This is typical for granitic orthogneisses in which the Cambrian–Ordovician proto-magmatic ages are often preserved in cores of zircons and monazites (e.g. Petrík & *al.* 2006; Kohút 2007; Putiš & *al.* in print). However, the metasedimentary rocks of the Lower Unit were not affected by intrusion of Variscan granitic rocks and/or metamorphism, as is shown by the former detrital zircons within these rocks and the general absence of Variscan ones. The age spectrum of the detrital zircons reflects input of sources with ca. 660 – 500 Ma, and ca. 2.0 – 1.8 Ga ages. The younger detrital zircons are common for Avalonian/Cadomian events in northern peri-Gondwana (Nance & Murphy 1996), whereas the older zircons may reflect the Late Palaeoproterozoic evolution within Gondwana (Fernández-Suárez & *al.* 2000; Zeh & *al.* 2001).

The presence of Late Proterozoic–Cambrian basement remnants was not previously known in the Western Carpathians. However, related lithologies are known but rare in the Austroalpine domain of the Alps e.g. Ötztal, Speik and Ritting complex, Silvretta nappe or Greywacke Zone (von Raumer & Neubauer 1993; Poller 1997; Schaltegger & *al.* 1997; Neubauer & *al.* 2002) and such complexes continue sporadically to the Central and Western Alps (Schaltegger & Gebauer 1999; von Raumer & *al.* 2002 and references therein). Pre-Variscan basement relics in the Central European realm are more common for “stable” Variscan “Meso-Europa” sensu Stille (1924) e.g. in the eastern or northern border of the Bohemian Massif in the Moravo-Silesian (Brunovistulian) zone (Finger & *al.* 2000), the Sudetic block (Kröner & *al.* 2000; Kryza & *al.* 2004 and citations therein), or the Saxo-Thuringian zone (Mingram & Rötzler 1999). Ongoing discussions suggest ways for discrimination of Avalonian or Armorican origin within the pre-Variscan basement of the eastern margin of the Bohemian Massif (Pharoah 1999; Finger & *al.* 2000; Winchester 2002), and of Intra-Alpine origin in the framework of the Alpine chain (von Raumer & *al.* 2002) since these microcontinents were all derived from the northern margin of the Gondwana supercontinent. Our study represents only a piece in this puzzle, and further work is needed before all questions of pre-Mesozoic basement evolution of the Western Carpathians and its relationship to the basement of Central Europe can be answered.

CONCLUSIONS

Although we planned to date typical Variscan medium-grade metamorphic rocks from the Lower Unit of the Western Tatra Mts., we actually dated their magmatic precursor which originated in a continental arc before ca 500 Ma. Geochemical data (^{87}Sr/^{86}Sr$_{(350)}$ = 0.713 ~ 0.723; $\varepsilon_{Nd(350)}$ = –9.5 to –11.1; ^{206}Pb/^{204}Pb = 18.21 ~ 19.39 and ^{207}Pb/^{204}Pb = 15.62 ~ 15.77) reflect an upper crustal origin and/or suggest derivation of the protolith – magmatogenic greywackes and claystones – from a recycled continental island arc source. Detrital zircons with homogeneous magmatic zoning have ^{207}Pb/^{206}Pb ages from 660 to 515 Ma, whereas core-bearing zircons with inherited components display ages from ca. 1980 to 1800 Ma. The Nd model ages, with t$_{(DM2st)}$ ca 1960 ~ 1830 Ma, are comparable to the late Palaeoproterozoic detrital zircon ages. U-Pb single zircon dating resulted in two effective discordia lines, with upper intercept ages of 2370 ± 140, and

		measured atomic ratios -a)							corrected ages (Ma) -b)					
sample	method	Utot	^{206}Pb	2σ	^{207}Pb	2σ	^{208}Pb	2σ	^{206}Pb	2σ	^{207}Pb	2σ	^{207}Pb	2σ
		Pb*	^{204}Pb	m	^{206}Pb	m	^{206}Pb	m	^{238}U	m	^{235}U	m	^{206}Pb	m
UP 1058, Jalovecká Valley Micaschist														
1058-9	**CLC**	11.26	117	1	0.17386	64	0.32655	130	517.2	4.6	537.0	21.0	625	112
1058-12	**CLC**	12.07	323	4	0.09811	18	0.12758	45	482.4	3.4	489.9	8.7	525	30
1058-17	**CLC**	11.14	722	20	0.07561	27	0.10908	45	501.4	3.8	503.9	9.3	515	33
1058-22	**CLC**	5.84	163	1	0.18507	59	0.28172	153	884.7	7.1	1189.0	14.0	1794	26
1058-a	**V.D.**	10.59	1094	35	0.07119	19	0.14439	48	503.5	5.0	509.5	9.2	536	28
1058-b	**V.D.**	7.62	1196	135	0.10079	41	0.21901	103	633.0	12	833.0	24.0	1414	42
1058-f	**V.D.**	10.12	674	88	0.08275	52	0.15505	118	528.7	9.4	555.0	33.0	666	131
UP 1201, Jamnická Valley Micaschist														
1201-D	**V.D.**	10.47	546	17	0.08953	20	0.11394	33	535.0	10	573.0	17.0	729	40
1201-F	**V.D.**	11.11	911	22	0.07416	16	0.07618	19	511.0	6.4	525.0	10.0	590	18
1201-J	**V.D.**	9.94	488	7	0.08779	18	0.22895	113	513.6	3.1	529.8	8.5	600	26
1201-M	**V.D.**	10.76	1022	40	0.07157	39	0.14406	31	495.8	4.5	504.7	11.0	545	39
1201-7	**CLC**	2.37	183	1	0.19394	43	0.36712	128	1821.0	7.0	1895.0	13.0	1978	22

a) corrected for fractionation
CLC = cathodoluminescence controlled dating

b) corrected for blank, spike and common Pb
V.D. = vapour digestion single zircon dating

2σ m errors refer to the 2σ deviation of the weighted mean of 2-6 blocks.

Table 4. U-Pb zircon data

2010 ± 35 Ma and a lower intercept ages of 491 ± 11 and 495 ± 4 Ma respectively. Identification of the Upper Proterozoic–Lower Palaeozoic basement relics opened a new horizon in the geology of the Western Carpathians, revealing a similarity to the common pre-Variscan basement of the Central European realm. Detrital zircons from the mica-schists and metaquartzites showed that they were derived from a Pan-African/Cadomian basement precursor of Avalonian or Armorican provenance. We cannot exclude that the source of the studied metasedimentary rocks was a continental island arc as is represented on the eastern border of the Bohemian Massif in the Moravo-Silesian zone or in the Sudetes; indeed the older rocks (≥500 Ma) of such affinity were exactly identified in the Western Carpathians only recently.

Acknowledgement

This work was supported by the Max-Planck-Gesellschaft. We thank J. HUTH for help with cathodoluminescence. The authors wish to thank to Fritz FINGER together with an anonymous reviewer for constructive reviews, and Ewa SŁABY and Ireneusz WALASZCZYK for editorial handling along with suggested improvements to the manuscript. Our thanks go to F. LUCASSEN and B. TRUMBULL for critical comments of an earlier version of manuscript as well. This is contribution to Grant APVV-549-07 and APVT-20-016-104.

REFERENCES

ANDRUSOV, D. 1968. Grundriss der Tektonik der Nördlichen Karpaten, pp. 1-188, *Veda Publishing House* of SAV; Bratislava.

ARNDT, N. & TODT, W. 1994. Formation of 1.9 Ga old Trans-Hudson continental crust: Pb isotopic data. *Chemical Geology*, **118**, 9-26.

BHATIA, M.R. 1983. Plate tectonics and geochemical composition of sandstones. *Journal of Geology*, **91**, 611-627.

BHATIA, M.R. & CROOK, K.A.W. 1986. Trace element characteristics of graywakes and tectonic discrimination of sedimentary basins. *Contribution to Mineralogy and Petrol*ogy, **92**, 181-193.

BURDA, J. & GAWĘDA, A. 1999. Petrogeneza migmatytów z górnej części Doliny Kościeliska w Tatrach Zachodních. *Archiwum Mineralogiczne*, **52**, 163-194.

ČORNÁ, O. & KAMENICKÝ, L. 1976. Ein Beitrag zur Stratigraphie des Kristallinikum der West Karpaten auf Grund der Palynologie. *Geologický zborník Geologica Carpathica*, **27**, 117-132.

DE PAOLO, D.J. & WASSERBURG, G.J. 1976. Nd isotope variations and petrogenetic models. *Geophysical Research Letters*, **3**, 249-252.

DOE, B.R. & ZARTMAN, R.E. 1979. Plumbotectonics, the Phanerozoic. *In*: H.L. BARNES, (*Ed.*), Geochemistry of hydrothermal ore deposits, pp. 22-70, *Wiley Interscience Publication;* New York.

FERNÁNDEZ-SUÁREZ, J., GUTÍERREZ-ALONSO, G., JENNER, G.A. & TUBRETT, M.N. 2000. New ideas on the Proterozoic – Early Palaeozoic evolution of NW Iberia: insights from U– Pb detrital zircon ages. *Precambrian Research*, **102**, 185-206.

FINGER, F., HANSEL, P., PIN., C., VON QUADT, A. & STEYRER, H.P. 2000. The Brunovistulian: Avalonian Precambrian sequence at the eastern end of the Central European Variscides? *In*: W. FRANKE, V. HAAK, O. ONCKEN, D. TANNER (*Eds*), Orogenic Processes: Quantification and Modeling in the Variscan Belt. *Geological Society of London, Special Publication*, **179**, 103-112.

FRIEND, C.R.L., STRACHAN R.A., KINNY, P.D. & WATT, G.R. 2003. Provenance of the Moine Supergroup of NW Scotland: Evidence from geochronology of detrital and inherited zircons from (meta)sedimentary rocks, and migmatites. *Journal of the Geological Society, London*, **160**, 247-257.

FRITZ, H., NEUBAUER, F., JANÁK, M. & PUTIŠ, M. 1992. Variscan mid-crustal thrusting in the Carpathians II: Kinematics and fabric evolution of the Western Tatra basement. Terra Abstracts, Supplement 2 to *Terra Nova*, **4**, 24.

GAAB, A., POLLER, U., TODT, W. & JANÁK, M. 2006. Alpine reworking of Ordovician protoliths in the Western Carpathians: Geochronological and geochemical data on the Muráň Gneiss Complex, Slovakia. *Lithos*, **87**, 261-275.

GAWĘDA, A. & KOZŁOWSKI, K. 1996. Pressure-temperature-time evolution of metamorphic complex in the Polish part of the Western Tatra Mts. *Polskie Towarzystwo Mineralogiczne – Prace specjalne*, **7**, 20-22.

GAWĘDA, A., WINCHESTER, J., KOZŁOWSKI, K., NAREBSKI, W. & HOLLAND, G. 2000. Geochemistry and paleotectonic setting of the amphibolites from the Western Tatra Mountains, *Geological Journal*, **35**, 69-85.

GAWĘDA, A. & BURDA, J. 2005. Partial melting processes in the Western Tatras Mts.: geochronological and geochemical study. *Mineralogical Society of Poland – Special Papers*, **26***,* 162-166.

GEBAUER, D., WILLIAMS I.S., COMPSTON, W. & GRÜNENFELDER, M. 1989. The development of the Central European continental crust since the Early Archaean based on conventional and ion-microprobe dating of up to 3.84 b.y. old detrital zircons. *Tectonophysics*, **157**, 81-96.

GURK, Ch. 1999. Petrographie, Geochemie und Geochronologie der Unteren Einheit, Tatricum, Westliche Tatra (Slowakei). Unpubl. Diploma thesis Johannes Gutenberg Universität Mainz, 124 p.

HERRON, M.M. 1988. Geochemical classification of terrigeneous sands and shales from core or log data: *Journal of sedimentary petrology*, **58**, 820-829.

HROUDA, F. & KAHAN, S. 1991. The magnetic fabric relationship between sedimentary and basement nappes in the High Tatra Mountains, N. Slovakia. *Journal of Structural Geology*, **13**, 431-442.

JACOBSEN, S.B. & WASSERBURG, G.J. 1980. Sm-Nd evolution of chondrites. *Earth and Planetary Science Letters*, **50**, 139-155.

JANÁK, M. 1994. Variscan Uplift of the Crystalline Basement Tatra Mts., Central Western Carpathians: Evidence from ^{40}Ar/^{39}Ar Laser Probe Dating of Biotite and P-T-t Paths. *Geologica Carpathica*, **45**, 293-300.

JANÁK, M., KAHAN, S. & JANČULA, D. 1988. Metamorphism of pelitic rocks and metamorphic zones in SW part of Western Tatra Mts. crystalline complexes. *Geologický Zborník Geologica Carpathica*, **39**, 455-488.

JANÁK, M., O´BRIEN, P. J., HURAI, V. & REUTEL, C. 1996. Metamorphic evolution and fluid composition of garnet-clinopyroxene amphibolites from the Tatra Mountains, Western Carpathians. *Lithos*, **39**, 57-79.

JANÁK, M., HURAI, V., LUDHOVÁ, L., O´BRIEN, P.J. & HORN, E.E. 1999. Dehydration melting and devolatilization of high-grade metapelites: the Tatra Mountains, Western Carpathians. *Journal of Metamorphic Geology,* **17**, 379-396.

JANOUŠEK, V., ROGERS, G. & BOWES, D.R. 1995. Sr-Nd isotopic constraints on the petrogenesis of the Central Bohemian Pluton, Czech Republic. *Geologische Rundschau* **84**, 520-534.

JUREWICZ, E. 2005. Geodynamic evolution of the Tatra Mts. and the Pieniny Klippen Belt (Western Carpathians): problems and comments, *Acta Geologica Polonica*, **55**, 295-338.

JUREWICZ, E. & BAGIŃSKI, B. 2005. Deformation phases in the selected shear zones within the Tatra Mts. granitoid core. *Geologica Carpathica*, **56**, 17-28.

KAHAN, S. 1969. Eine neue Ansicht über den geologischen Aufbau des Kristallinikums der West Tatra. *Acta Geologica et Geographica Universitatis Comenianae*, **12**, 115-122.

KANTOR, J. 1959. Contribution to knowledge of the age of some Western Carpathians granites and related ore deposits. *Acta Geologica et Geographica Universitatis Comenianae*, **2**, 63-73.

KAMENICKÝ, J. 1968. Some problems of the West Carpathian Crystalline complex. *Geologický zborník Geologica Carpathica*, **19**, 7-20.

KAMENICKÝ, L. & KAMENICKÝ, J. 1983. Precambrian in the West Carpathian. *Mineralia Slovaca*, **15**, 289-302.

KOHÚT, M. 2007. Orogenic Granitic Magmatism in the Western Carpathians – 500 Ma History: A Review. *Mineralogia Polonica, Special Papers,* **31**, 30-39.

KOHÚT, M. & JANÁK, M. 1994. Granitoids of the Tatra Mts., Western Carpathians: Field relations and petrogenetic implications. *Geologica Carpathica*, **45**, 301-311.

KOHÚT, M. & SHERLOCK, S.C. 2003. Laser microprobe ^{40}Ar-^{39}Ar analysis of pseudotachylyte and host rocks from the

Tatra Mountains, Slovakia: Evidence for Late Paleogene seismic/tectonic activity. *Terra Nova*, **15**, 417-424.

KOHÚT, M., SHERLOCK, S.C. & POLLER, U. 2005. Do we know the oldest rock from the Western Carpathians at all? *Geolines*, **19**, 63-64.

KOVÁC, M., KRÁL, J., MÁRTON, E., PLASIENKA, D. & UHER P. 1994. Alpine uplift history of the Central Western Carpathians: geochronological, paleomagnetic, sedimentary and structural data. *Geologica Carpathica*, **45**, 83-96.

KRÖNER, A., STÍPSKA, P., SCHULMANN, K. & JAECKEL, P. 2000. Chronological constrains on the pre-Variscan evolution of the northeastern margin of the Bohemian Massif, Czech Republic. *In*: W. FRANKE, V. HAAK, O. ONCKEN & D. TANNER (*Eds*), Orogenic Processes: Quantification and Modeling in the Variscan Belt. *Geological Society of London, Special publication*, **179**, 175-197.

KRYZA, R., MAZUR, S. & OBERC-DZIEDZIC, T. 2004. The Sudetic geological mosaic: Insights into the root of the Variscan orogen. *Przeglad Geologiczny*, **52**, 8/2, 761-773.

MAHEĽ, M. 1981. Island character of Klippen Belt; Vahicum – continuation of Southern Penninicum in West Carpathians. *Geologický Zborník Geologica Carpathica*, **32**, 293-305.

MALUSKI, H., RAJLICH, P. & MATTE, P. 1993. ^{40}Ar/^{39}Ar dating of the Inner Carpathians Variscan basement and Alpine mylonitic overprinting. *Tectonophysics*, **223**, 313-337.

MÁŠKA, M. & ZOUBEK, V. 1960. The tectonic development of the West-Carpathian system. *In*: T. BUDAY, (*Ed*.), The Tectonic development of Czechoslovakia, pp. 152-166, *Academia Publication House of ČSAV*; Praha.

MINGRAM, B. & RÖTZLER, K. 1999. Geochemische petrologische und geochronologische Untersuchungen im Erzgebirgskristallin – Rekonstruktion eines Krustenstapels. *Schriftreihe für Geowissenschaften*, **9**, 1-80.

NANCE, R.D. & MURPHY, J.B. 1996. Basement isotopic signatures and Neoproterozoic palaeogeography of Avalonian–Cadomian and related terranes in the circum-North Atlantic. *In*: R.D. NANCE & M.D. THOMPSON (*Eds*), Avalonian and Related Peri-Gondwanan Terranes of the Circum-North Atlantic. *Geological Society of America, Special Papers*, **304**, 333-346.

NEUBAUER, F., FRISCH & HANSEN, B.T. 2002. Early Paleozoic tectonothermal events in basement complexes of eastern Greywacke Zone (Eastern Alps): evidence from U-Pb zircon data. *International Journal of Earth Sciences*, **91**, 775-786.

PETRÍK, I., KONEČNÝ, P., KOVÁČIK, M. & HOLICKÝ, I. 2006. Electron microprobe dating of monazite from the Nízke Tatry Mts. orthogneisses (Western Carpathians, Slovakia). *Geologica Carpathica*, **57**, 227-242.

PHARAOH, T.C. 1999. Paleozoic terranes and their lithospheric boundaries within the Trans-European Suture Zone (TESZ): a review. *Tectonophysics*, **314**, 17-41.

PLAŠIENKA, D., GRECULA, P., PUTIŠ, M., HOVORKA, D. & KOVÁC, M. 1997. Evolution and structure of the Western Carpathians: an overview. *In*: P. GRECULA, D. HOVORKA, M. PUTIŠ (*Eds*) Geological Evolution of the Western Carpathians, pp. 1-24. *Mineralia Slovaca* – Monograph, Bratislava.

POLLER, U. 1997. U-Pb single zircon study of gabbroic and granitoid rocks of Val Barlasch (Sivretta nappe, Schwitzerland). *Schweizerische Mineralogische Petrographische Mitteilungen*, **77**, 351-359.

POLLER, U. 2000. A combination of single zircon dating by TIMS and cathodoluminescence investigations on the same grain: The CLC method ± U-Pb geochronology for metamorphic rocks. *In*: M. PAGEL, V. BARBIN, P. BLANC, D. OHNENSTETTER (*Eds*) Cathodoluminescence in Geosciences, pp. 401-414. *Springer*; Heidelberg.

POLLER, U., JANÁK, M., KOHÚT, M. & TODT, W. 2000. Early Variscan magmatism in the Western Carpathians: U-Pb zircon data from granitoids and orthogneisses of the Tatra Mountains (Slovakia). *International Journal of Earth Sciences*, **89**, 336-349.

POLLER, U., KOHÚT, M., ANDERS, B. & TODT, W. 2005. Multistage geochronological evolution of the Velká Fatra Mountains – a combined TIMS and ion-microprobe study on zircons. *Lithos*, **82**, 113-124.

POLLER, U., TODT, W., KOHÚT, M. & JANÁK, M. 2001. Nd, Sr, Pb isotope study of the Western Carpathians: implications for Palaeozoic evolution. *Schweitzerische Mineralogische Pertrographische Mitteilungen,* **81**, 159-174.

POLLER, U. & TODT, W. 2000. U-Pb single zircon data of granitoids from the High Tatra Mountains (Slovakia): implications for the geodynamic evolution. *Transactions Royal Society of Edinburgh: Earth Sciences*, **91**, 235-243.

PUTIŠ, M., KOTOV, A.B., KORIKOVSKY, S.P., SALNIKOVA, E.B., YAKOVLEVA, S.Z., BEREZHNAYA, N.G., KOVACH, V.P. & PLOTKINA, J.V. 2001. U-Pb zircon ages of dioritic and trondhjemitic rocks from a layered amphibolitic complex crosscut by granite vein (Veporic basement, Western Carpathians). *Geologica Carpathica,* **52***,* 49-60.

PUTIŠ, M., SERGEEV, S., ONDREJKA, M., LARIONOV, A., SIMAN, P., SPIŠIAK, J., UHER, P. & PADERIN, I. 2008. Cambrian-Ordovician metaigneous rocks associated with Cadomian fragments in the West-Carpathian basement dated by SHRIMP on zircons: a record from the Gondwana active margin setting. *Geologica Carpathica*, **59**, 3-18.

PUTIŠ, M., IVAN, P., KOHÚT, M., SPIŠIAK, J., SIMAN, P., RADVANEC, M., UHER, P., SERGEEV, S., LARIONOV, A., MÉRES, Š., DEMKO, R. & ONDREJKA, M. (in print). Metaigneous rocks of the West-Carpathians basement as an indicator of Early Paleozoic extension-rifting/breakup events. *Bulletin de la Société Géologique de France*.

RAINBIRD, R.H., HAMILTON, M.A. & YOUNG, G.M. 2001. Detrital zircon geochronology and provenance of the Torridonian, NW Scotland. *Journal of the Geological Society, London*, **158**, 15-27.

RAUMER, J.F. VON & NEUBAUER, F. 1993. Late Precambrian and Paleozoic evolution of the Alpine Basement: an overview. *In*: J. VON RAUMER & F. NEUBAUER (*Eds*), The pre-Mesozoic geology in the Alps, pp. 625-639. *Springer*; Berlin – Heidelberg – New York.

RAUMER, J.F. VON, STAMPFLI, G.M., BOREL, G.D. & BUSSY, F. 2002. Organization of pre-Variscan basement areas at the north-Gondwanan margin. *International Journal of Earth Sciences*, **91**, 35-52.

REISCHMAN, T. & ANTHES, G. 1996. Geochronology of the mid-German crystalline rise west of the River Rhine. *Geologische Rundschau*, **85**, 761-774.

ROSER, B. P. & KORSCH, R. J. 1986. Determination of tectonic setting of sandstone-mudstone suites using SiO_2 content and K_2O/Na_2O ratio. *Journal of Geology*, **94**, 635-650.

ROSER, B.P. & KORSCH, R.J. 1988. Provenance signatures of sandstone-mudstone suites determined using discriminant function analysis of major-element data. *Chemical Geology*, **67**, 119-139.

SCHALTEGGER, U. & GEBAUER, D. 1999. Pre-Alpine geochronology of the Central, Western and Southern Alps. *Schweizerische Mineralogische Petrographische Mitteilungen*, **79**, 79-87.

SCHALTEGGER, U., NÄGLER, T.N., CORFU, F., MAGGETTI, M., GALETTI, G. & STOSCH, H. 1997. A Cambrian island arc in the Silvretta nappe: constraints from geochemistry and geochronology. *Schweizerische Mineralogische Petrographische Mitteilungen*, **77**, 337-350.

STACEY, J.S. & KRAMERS, J.D. 1975. Approximation of terrestrial lead isotope evolution by two stage-model. *Earth and Planetary Science Letters*, **26**, 207-221.

STAMPFLI, G.M. & BOREL, G.D. 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. *Earth and Planetary Science Letters*, **196**, 17-33.

STILLE, H. 1924. Grundfragen der vergleichenden Tektonik, 443 pp. *Borntraeger*; Berlin.

THÉLIN, P. 1983. Les gneiss oeillés de la Nappe du Grand Saint-Bernard, essai d'évaluation des critères susceptibles d'en préciser l'hérédité pré-métamorphique (Alpes valaisannes, Suisse). PhD Thesis, University of Lausanne.

VALVERDE-VAQUERO, P., DÖRR, W., BELKA, Z., FRANKE, W., WISZNIEWSKA, J. & SCHASTOK, J. 2000. U-Pb single-grain dating of detrital zircon in the Cambrian of central Poland: implications for Gondwana versus Baltica provenance studies. *Earth and Planetary Science Letters*, **184**, 225-240.

VIDAL, P. & POSTAIRE, B. 1985. Etude par la méthode Pb–Pb de roches de haut grade métamorphique impliquées dans la chaine Hercynienne. *Chemical Geology*, **49**, 429-449.

WENDT, J. & TODT, W. 1991. A vapor digestion method for dating single zircons by direct measurement of U and Pb without chemical separation. *Terra Abstracs*, **3**, 507-508.

WHITE, W.M. & PATCHETT, J. 1984. Hf-Nd-Sr isotopes and incompatible element abundances in island arcs: implications for magma origins and crust-mantle evolution. *Earth and Planetary Science Letters*, **67**, 167-185.

WINCHESTER, J.A. 2002. Paleozoic amalgamation of Central Europe: new results from recent geological and geophysical investigations. *Tectonophysics*, **360**, 5-21.

ZARTMAN, R. E. & HAINES, S. M. 1988. The plumbotectonic model for Pb isotopic systematics among major terrestrial reservoirs – a case for bidirectional transport. *Geochimica Cosmochimica Acta*, **52**, 1327-1339.

ZEH, A., BRÄTZ, H., MILLAR, I.L. & WILLIAMS, I.S. 2001. A combined zircon SHRIMP and Sm–Nd isotope study of high-grade paragneisses from the Mid-German Crystalline Rise: evidence for northern Gondwana and Grenvillian provenance. *Journal of the Geological Society, London*, **158**, 983-994.

ZINDLER, A. & HART, S. 1986. Chemical Geodynamics. *Annual Review Earth Planet Sciences*, **14**, 493-571.

ZOUBEK, V. 1936. Bemerkungen űber das Kristallin der Westkarpathen. *Vestník Státiho geologického Ústavu ČSR*, **12,** 6, 207-239.

Manuscript submitted: 20th June 2008
Revised version accepted: 15th September 2008