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Age and provenance of mica-schist pebbles from the Eocene conglomerates of the Tylicz and Krynica Zone (Magura Nappe, Outer Flysch Carpathians)

NESTOR OSZCZYPKO[1], DOROTA SALATA[1] and PATRIK KONEČNÝ[2]

[1]Jagiellonian University, Institute of Geological Sciences, Oleandry 2a, 30-063 Kraków, Poland; nestor.oszczypko@uj.edu.pl; dorota.salata@uj.edu.pl
[2]State Geological Institute of Dionýz Štúr, Mlynská dolina 1, 817 04 Bratislava, Slovakia; patrik.konecny@geology.sk

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Abstract: During the Late Cretaceous to Palaeogene, the Magura Basin was supplied by clastic material from source areas situated on the northern and southern margins of the basin, which do not outcrop on the surface at present. The northern source area is traditionally connected with the Silesian Ridge, whereas the position of the southern one is still under discussion. A source area situated SE of the Magura Basin supplied the Eocene pebbly para-conglomerates containing partly exotic material. The studied clastic material contains fragments of crystalline rocks, and frequent clasts of Mesozoic to Palaeogene deep and shallow-water limestones. Numerous mica schists, scarce volcanites and granitoids as well as gneisses, quartzites and cataclasites were found in the group of crystalline exotic pebbles. Monazite ages of "exotic" mica-schist pebbles from the Tylicz, Zarzecze and Piwniczna-Mniszek sections document the Variscan 310±10 Ma age of metamorphic processes. The provenance of these exotic rocks could be connected with a remote source area located SE of the Magura Basin, which could be the NW part of the Dacia Mega Unit. The idea is strongly supported by palaeotransport directions from the SE, the absence of material derived from the Pieniny Klippen Belt, the presence of shallow water limestones, typical facies of the Median Dacides belt and metamorphic age distribution proved by monazite dating.

Key words: Magura Basin, palaeogeography, source areas, monazite age, mica-schist pebbles.

Introduction

The Outer Carpathian flysch basins were supplied with clastic material derived both from external as well as internal source areas, so-called "cordilleras" (Książkiewicz 1962; Unrug 1968). Our palaeogeographical reconstructions of the source areas are based on the investigations of "exotic" pebbles that were transported into sedimentary basins by submarine gravity flows (see Książkiewicz 1962). The Eocene/Oligocene deposits of the Tylicz and Krynica facies zone of the Magura Basin contain fragments of sedimentary, igneous and metamorphic rocks, derived from a continental type of crust. The location of the source area in the present-day tectonic configuration is unknown. Mišík et al. (1991) suggested that carbonate material was derived from "the basement of the Magura Basin", that was exhumed during the Early/Middle Eocene. This material is fundamentally different from the carbonates of the Czorsztyn/Oravicum of the Pieniny Klippen Belt (PKB) which are currently located along the southern boundary of the Magura Nappe. Alternatively, this clastic material may have been derived from a Central Carpathian source area type, located on the SE margin of the basin (e.g., tip of the ALCAPA Block, see Plašienka 2000). The aim of this paper is to present results of the monazite dating of metamorphic pebbles from the Tylicz, Mniszek-Piwniczna and Zarzecze sections of the Krynica subunit of the Magura Nappe and to identify possible sources for the pebbles.

Outline of geology and stratigraphy

Previous studies on the exotic pebbles

The "exotic" conglomerates in the Tylicz and Krynica zones of the Magura Nappe (Fig. 1), have been studied for many years (Jaksa-Bykowski 1925; Mochnacka & Węcławik 1967; Wieser 1970; Oszczypko 1975; Oszczypko et al. 2006, Olszewska & Oszczypko 2010). The first detailed description of exotic pebbles from the Eocene deposits of the Beskid Sądecki Range (Krynica zone) was given by Oszczypko (1975). This author described granitoids, gneisses, phyllites and quartzites, with a relatively small amount of basic volcanic rocks and Mesozoic carbonates. The exotic carbonate material of the Strihovce Sandstone, an equivalent of the Piwniczna Sandstone Member of the Magura Formation in Poland, has been studied by Mišík et al. (1991). Recently Olszewska and Oszczypko (2010) studied the carbonate pebble population of the Tylicz Conglomerate, which is dominated by deep-water Jurassic–Lower Cretaceous sediments as well as fragments of shallow-water limestones of Triassic, Upper Jurassic, Lower and Upper Cretaceous, Palaeocene and Lutetian age.

Geological setting

The studied area is located in the south-eastern part of the Magura Nappe, south of the boundary between the Bystrica

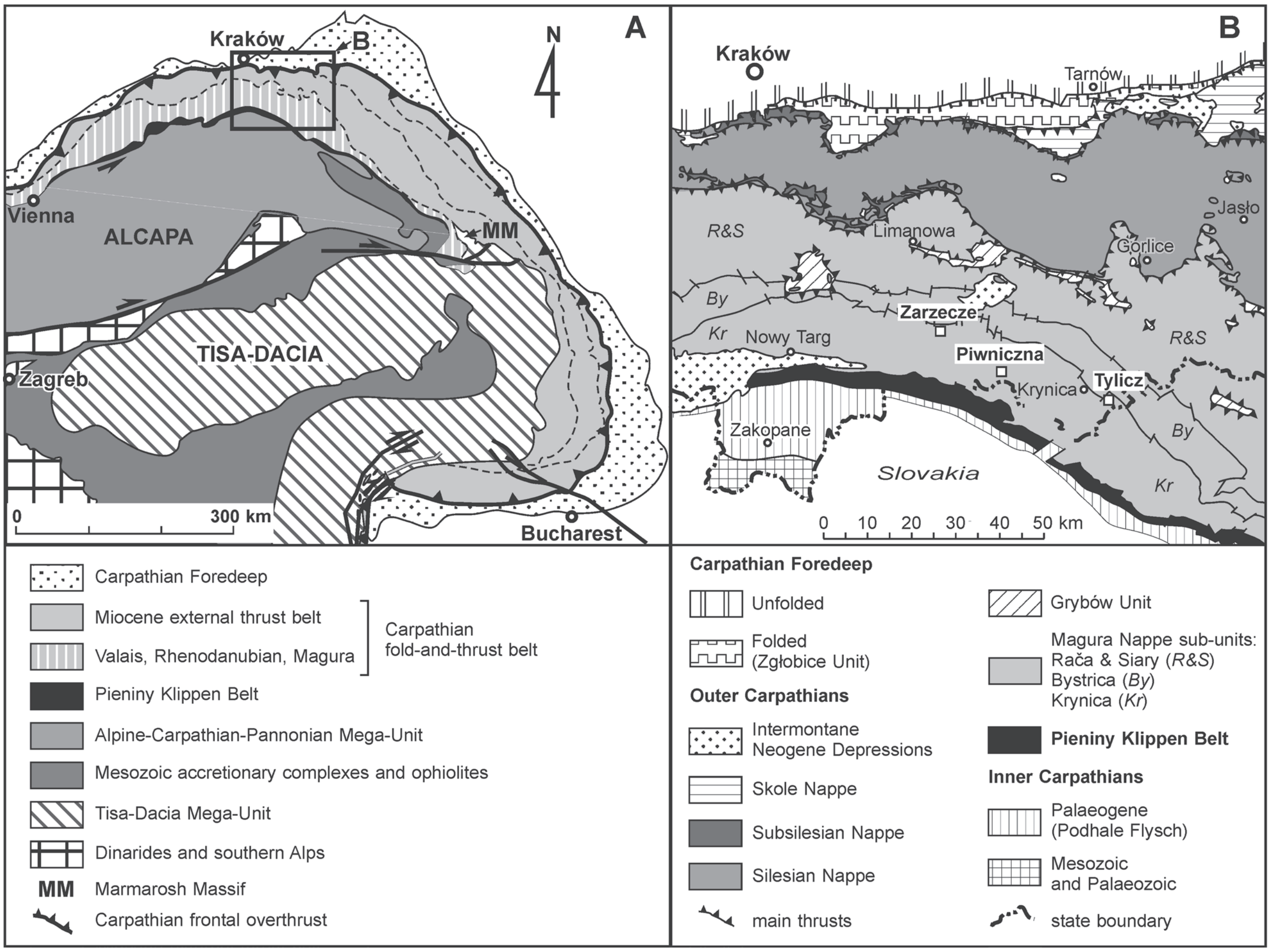


Fig. 1. Location of the studied area in: **A** — the Alpine-Carpathian Pannonian realm and **B** — within the Magura Nappe in Poland (based on Żytko et al. 1989).

and Krynica subunits (Fig. 1). The Krynica facies-tectonic zone is composed of the Upper Cretaceous to Oligocene deposits (Birkenmajer & Oszczypko 1989; Oszczypko & Oszczypko-Clowes 2010). The oldest deposits are known from the Muszyna-Złockie area, 5 km west of Krynica. They consist of the Turonian-Maastrichtian, deep-water variegated shales (Malinowa Fm.) with sporadic intercalations of thin-bedded sandstones (Oszczypko et al. 1990). That formation passes upwards into strongly tectonized, medium to thin-bedded turbidites of the Maastrichtian/Palaeocene to Lower Eocene (Ropianka Fm.), which are rich in calcite veins. Higher up in the succession, thin-bedded turbidites occur (Zarzecze Fm.), with intercalations of thick-bedded Krynica sandstones and conglomerates of the Lower–Middle Eocene. The youngest deposits of the Krynica facies zone in the Krynica area belong to thick-bedded sandstones of the Magura Fm. (Middle Eocene to Oligocene; see Oszczypko & Oszczypko-Clowes 2010) and the recently discovered Lower Miocene Kremna Fm. (Oszczypko et al. 2005; Oszczypko-Clowes et al. 2013).

The stratigraphic thickness of the Magura Nappe reaches at least 2.6 km. During overthrust movements and tectonic repetitions, the total thickness of the flysch deposits in the Krynica subunit increased up to 5.5–7.5 km, as shown by magnetotelluric investigations (Oszczypko & Zuber 2002). The Bystrica and Krynica subunits contact along the sub-vertical thrust fault, which dips to the NE.

The Late Cretaceous to Oligocene flysch formations of the Krynica succession were deposited in a deep-water basin (Oszczypko 1992). Starting from the Early Eocene, the sedimentary processes in the southern part of the Magura Basin were accompanied by growth of the accretionary wedge (Oszczypko & Oszczypko-Clowes 2009). It is manifested by shallowing of the basin and development of sub-marine coarse-clastic fan sedimentation of the Magura Sandstone Formation. At the turn of the Middle/Late Eocene this deposition was followed by a short-lasting episode of the basin deepening (beneath the CCD level) and deposition of variegated shales of the Mniszek Sh. Mb. (Sh.=Shale; Mb.=Member) (Oszczypko-Clowes 2001; Oszczypko & Oszczypko-Clowes 2006). The Late Eocene gradual shallowing of the basin again enabled the coarse-clastic sedimentation of the Poprad Sandstone Mb. (Fig. 2). This was followed by folding and uplifting of the basin after the Late Oligocene/Early Miocene and prior to the Middle Miocene (Oszczypko et al. 2005; Oszczypko & Oszczypko-Clowes 2009).

Bodies of exotic conglomerates in the Krynica zone are rare. Such conglomerates are related to thick-bedded turbidites of the Zarzecze and Magura formations (Oszczypko 1975; Oszczypko et al. 2006). The exotic conglomerates of the Jarmuta-Proč Formation of the Grajcarek Unit, occurring along the contact zone between the Magura Nappe and Pieniny Klippen Belt, occupy a separate position (Birkenmajer 1977; Birkenmajer & Wieser 1990).

Studied sections

Piwniczna-Mniszek section

The Piwniczna-Mniszek section belongs to the Krynica facies zone and is located on the left slope of the Dunajec Valley (Fig. 1). This profile belongs to the top part of the Piwniczna Member of the Magura Formation. The Middle Eocene variegated shales of the Mniszek Shale Member appear directly above (Fig. 2).

The exotic rocks occur in the submarine slump bed, up to 2 m thick, which developed at the top of the thick-bedded sandstones of the Magura type. The slump layer is composed of folded exotic conglomerates with detached blocks of shales and armed claystones, as well as of sandstones, mudstones and claystones (Oszczypko et al. 2006). The studied metamorphic pebbles usually reach 7 cm across, while sedimentary pebbles (sandstones and limestones) are bigger, up to 10 cm. The material of conglomerates (Oszczypko et al. 2006) is represented by: vein-quartz of metamorphic origin (37 %), sandstones (35 %), igneous rocks (14 %), metamorphic rocks (11 %) and carbonates (3 %).

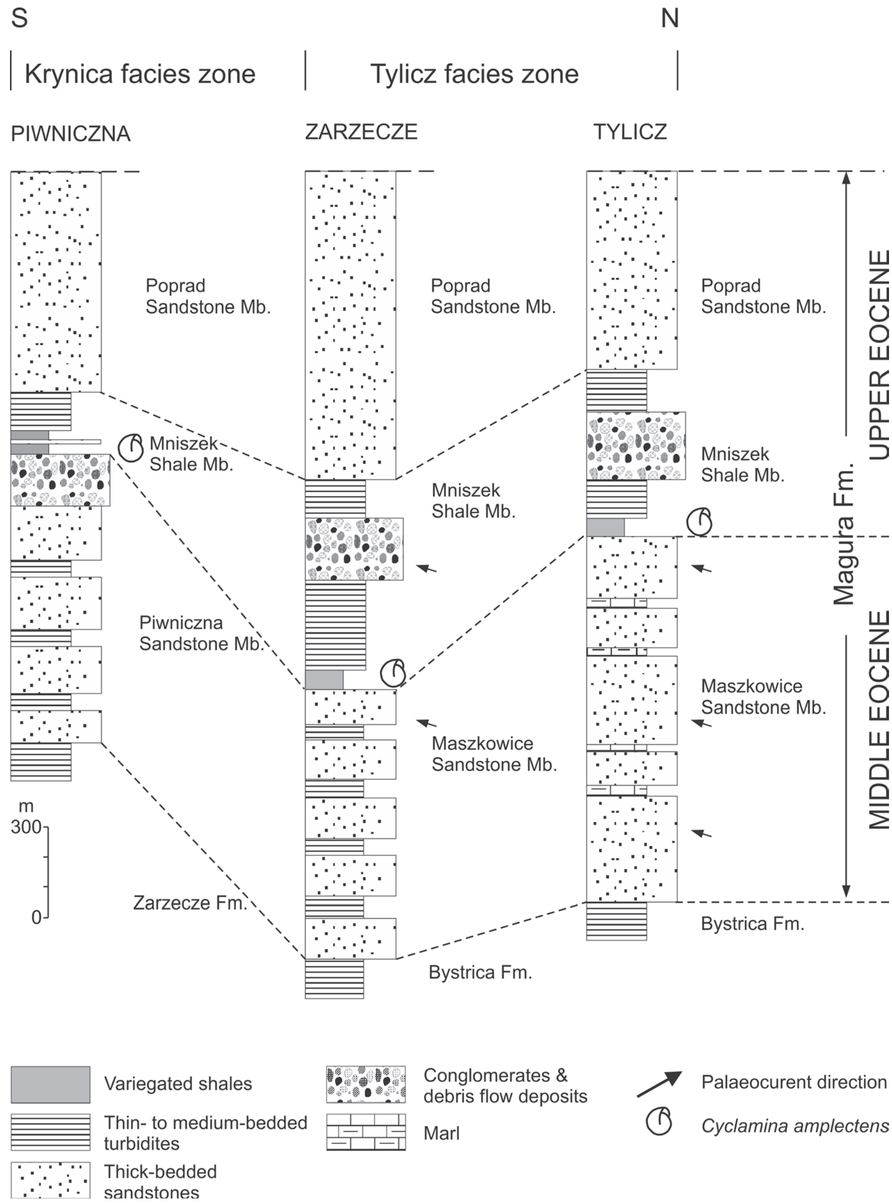


Fig. 2. Lithology and stratigraphy of the sampled sections.

Zarzecze section

The Zarzecze section, located on the right slope of the Dunajec River (Fig. 1B), belongs to the Tylicz transitional facies zone. The exotic beds are displayed at the top of a 170 metres thick packet of thick-bedded turbidite sadstones and conglomerates of the Mniszek Shale Member of the Magura Formation (Fig. 2; Oszczypko 1975; Oszczypko et al. 2006; Oszczypko & Oszczypko-Clowes 2010). The exotic pebbles are dominated by crystalline rocks (32 %), vine quartz of metamorphic origin (26 %), flysch sandstones (24 %) and Mesozoic carbonate rocks (18 %). Among the exotics sedimentary rocks representing the following microfacies were diagnosed (Oszczypko 1975; Oszczypko et al. 2006): the Tithonian–Berriasian — organodetritc *Calpionella* limestones, *Globocheta* and charty limestones, *Radiolarian-Nannoconus* (Valanginian–Hauterivian) and Urgonian limestones (Barremian–Aptian), Spiculla limestones (Albian–Cenomanian), marls (Maastrichtian–Palaeocene), and Lithotamnium Palaeocene sandstone (Oszczypko 1975).

Tylicz section

The exposures at Tylicz are situated in the transitional position (see Tylicz zone after Węcławik 1969; Figs. 1, 2) between the Bystrica and Krynica facies zones (Mochnacka & Węcławik 1967). The lower part of this succession is typical for the Bystrica zone, whereas the upper part belongs to the Krynica type of facies (Oszczypko & Oszczypko-Clowes

2010). The Tylicz exotic conglomerates, belonging to the Mniszek Shale Member of the Magura Formation (Fig. 2), are exposed on the left bank of the Muszynka River, partly in the bed rock of the river. The base and the top of the conglomerate boundaries are well exposed. The conglomerates are underlain and overlain by thin-bedded turbidites represented by grey and dark grey marly mudstone and marly shales (Fig. 2; see also Olszewska & Oszczypko 2010). The marly-shaly deposits are intercalated by thin- to medium-bedded fine-grained sandstones with muddy/marly cement. The sandstones display the Bouma Tc and conv. divisions. The conglomerates and thick-bedded sandstones form two bodies of 150 m and 50 m thick, separated by a 50 m packet of thin-bedded flysch (Fig. 2). These conglomerates represent channel infill incised in thin-bedded turbidites. In general, these coarse-clastic deposits display a fining and thinning-upward sequence. The basal packet of the conglomerates begins with 2 m thick layer of coarse conglomerates and boulders, which passes upwards into a 75 m thick layer of paraconglomerate packet, composed of pebbly mudstones. This part of the section was deposited by cohesive debris flow. Higher up in the section the conglomerates pass upwards into a 75 m packet of thick-bedded coarse- to very coarse-grained sandstones, deposited by high-concentrated density flow. The palaeocurrent measurements suggest palaeotransport from the SE. The conglomerates are composed of pebbles of 2 do 16 cm in diameter. The biggest pebbles are represented by sandstones and limestones. The material of conglomerates (Olszewska & Oszczypko 2010) is represented by: carbonates (44 %), igneous and metamorphic rocks (26 %), sandstones (26 %) and other (4 %). The biggest pebbles are spindle-shaped and ellipsoidal, while smaller ones are dominated by spheroidal and discoidal shapes. The carbonate pebble population contains fragments of shallow-water limestones of the Triassic (Anisian), Kimmeridgian, deep water Upper Tithonian limestones, as well as the Lower Cretaceous (Urgonian), Upper Cretaceous, Lower and Upper Palaeocene, and Lower Lutetian (Olszewska & Oszczypko 2010).

Analytical methods

The chemical composition of rock-forming minerals and monazites from the mica-schist pebbles was studied in polished carbon-coated thin sections. In total 243 monazite analyses in 4 samples were made (sample Tyl14-116 analyses in 30 grains; sample Tyl2-48 analyses in 9 grains; sample Mn1-63 analyses in 23 grains; sample Zar 3-16 analyses in 8 grains). Several spot analyses were made per single monazite grain if possible. The monazites analysed were located most of all in the matrix and only single grains within biotite flakes. Minerals were analysed by electron microprobe using a Cameca SX100 electron microprobe housed at the Dionýz Štúr State Geological Institute, Bratislava (Slovak Republic). The microprobe was calibrated with synthetic and natural standards: P — apatite, Si — wollastonite, Al — Al_2O_3, Pb — cerusite, Th — ThO_2, U — UO_2, Ca — wollastonite, Fe — forsterite, S — barite, As — GaAs and REE plus Y were calibrated on phosphates $REEPO_4$ and YPO_4, respectively. The microprobe is equipped with large (parabolic) analysing crystals LLIF and LPET that ensure a few times higher sensitivity then conventional (planar) ones. Monazite dating strongly depends on the precise measurement of the Pb, which reaches only low to trace concentrations in monazites. The measurement method was therefore adjusted for getting maximum counts especially for Pb. An accelerating voltage of 15 kV and beam current of 120 nA were applied. The beam diameter of 3 to7 mm was preferred. The counting time was 100 s for Pb, 75 s for U and 45 s for both Y and Th. Pb was measured at Pb$M\alpha$ line, U at U$M\beta_1$, and Th at Th$M\alpha$. An overlap of Pb$M\alpha$ with Y$L\gamma_1$ and U$M\beta$ with Th$M\beta$ was resolved via empirical correction (Åmli and Griffin 1975).

Before measurement of monazites of unknown age a set of so-called age standards were measured. A collection of monazite standards include monazites of various ages and compositions which were dated using SHRIMP: pegmatite from Madagascar (495 Ma), granite form Veikkola (1825 Ma), granite from Aalfang, Austria (327 Ma), gneiss-migmatite from Dürstein/Wachau, Austria (341 Ma), monzogranite from Nakae, Japan (77 Ma). Age standards provide additional tests for accuracy of microprobe calibration and measurement conditions. Some more details on the monazite dating method are given by Konečný et al. (2004). A statistical approach following Montel et al. (1996) was used to obtain resulting ages from spot microprobe analyses.

Results

Mineral composition of pebbles

The rock pebbles analysed in all localities studied are represented by mica-schists. The texture and mineral composition is alike in all samples. The texture of the schists representing the Tylicz (Tyl2, Tyl14) and Piwniczna-Mniszek sections (Mn1) is typical monotonous schistose texture characterized by parallel alignment of fine- to medium-grained mica flakes (mainly biotite, muscovite) intercalated with quartz, plagioclase feldspar (albite and oligoclase), orthoclase and accompanying minerals like garnet, apatite, monazite, zircon, TiO_2 polymorph (Fig. 3A–C and E–H), pyrite and xenotime. Muscovite is more abundant than biotite in the Tyl2 sample, whereas biotite flakes dominate among micas in the Tyl14 and Mn1 samples. Garnet grains are scarce in all the mentioned schist pebbles. Garnet grains follow schistose fabric forming fine anhedral grains of about 50–100 µm across rarely reaching 250 µm (Fig. 3A–C, F). Apatite occurs as relatively large subhedral or anhedral grains (up to 200 µm across) occurring mainly in the matrix and less frequently within biotite flakes (Fig. 3A–B, E–F, H) or as inclusions in feldspars. Monazite is a typical constituent of the pebbles from the Tylicz and Piwniczna-Mniszek sections. It occurs in the form of subhedral or anhedral crystals up to 150 µm long prevailingly in the matrix, rarely hosted by biotite or feldspar (Fig. 3E, G). Zircon, similarly to monazite, occurs in between quartz or feldspar

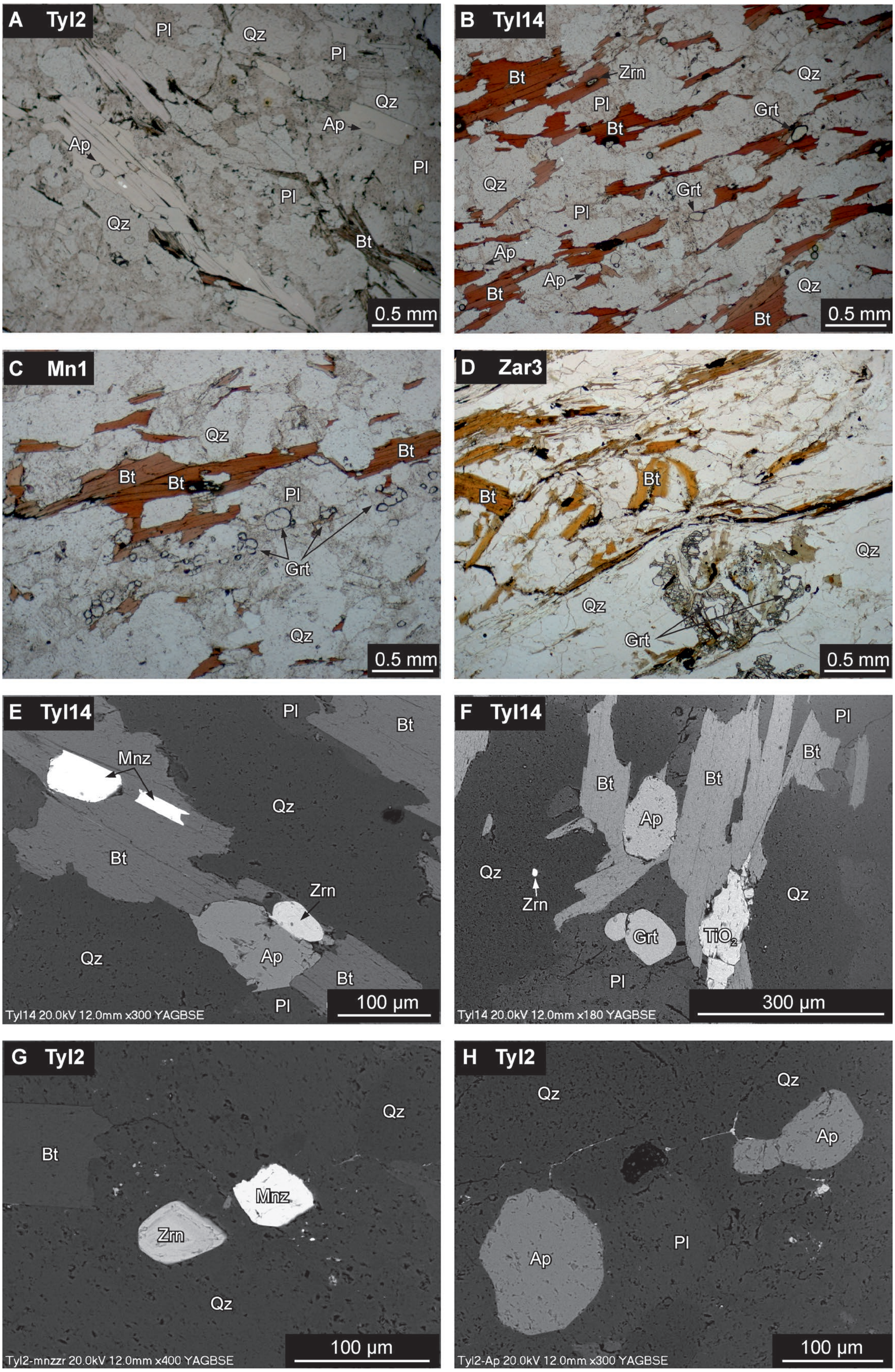


Fig. 3. Microphotographs of the studied mica-schist pebbles. Pictures **A–D** — plane polarized light; pictures **E–H** — YAGBSE. Abbreviations: **Ap** — apatite; **Bt** — biotite; **Grt** — garnet; **Mnz** — monazite ; **Pl** — plagioclase feldspar; **Qz** — quartz; $\mathbf{TiO_2}$ — TiO_2 polymorph; **Zrn** — zircon.

grains or as inclusions in biotite (Fig. 3B, E, G). The schist from the Zarzecze section (Zar3) is composed of similar minerals to the pebbles from the other localities studied. Biotite dominates among micas, accompanied by quartz and feldspars. Garnet grains are much bigger than those from the Tylicz and Piwniczna-Mniszek pebbles forming porphyroclasts reaching up to 1mm across. Mica and garnet yield features of deformation showing a N-S alignment (Fig. 3D). Garnet grains are partly broken down and fragmented. Monazite and apatite are less frequent than in the Tylicz and Piwniczna-Mniszek schist pebbles.

Table 1: Representative analyses of garnet from the pebbles studied. Oxides in [wt. %], molecular garnet end-members in [mol %].

Element/analysis	Zar3 core	Zar3 rim	Mn1 core	Mn1 rim	Tyl2	Tyl2	Tyl14	Tyl14
SiO_2 [wt%]	37.51	37.62	37.85	37.76	39.86	39.10	38.95	39.38
TiO_2	0.08	0.22	0.01	0.00	0.14	0.00	0.00	0.00
Al_2O_3	20.78	20.85	21.32	21.28	19.02	19.47	19.62	19.46
Cr_2O_3	0.02	0.00	0.01	0.05	0.00	0.12	0.00	0.19
Fe_2O_3	0.25	0.00	0.49	0.46	0.00	0.00	0.03	0.00
FeO	28.44	36.20	31.20	30.34	32.43	32.55	27.21	27.84
MnO	4.08	0.32	5.42	6.89	6.63	7.09	10.71	9.72
MgO	0.84	2.40	3.36	2.90	0.99	0.72	2.50	2.50
CaO	8.48	3.17	2.01	2.08	0.93	0.95	0.81	0.91
Total	100.48	100.79	101.68	101.75	100.00	100.00	99.82	100.00
Numbers of cations calculated on the basis of 12 oxygen atoms								
Si [apfu]	3.005	3.009	2.993	2.993	3.215	3.168	3.136	3.159
Ti	0.005	0.013	0.001	0.000	0.008	0.000	0.000	0.000
Al	1.962	1.966	1.988	1.988	1.808	1.860	1.862	1.840
Cr	0.001	0.000	0.001	0.003	0.000	0.008	0.000	0.012
Fe^{3+}	0.015	0.000	0.029	0.027	0.000	0.000	0.000	0.000
Fe^{2+}	1.906	2.425	2.063	2.010	2.188	2.206	1.834	1.868
Mn	0.276	0.022	0.363	0.462	0.453	0.487	0.730	0.660
Mg	0.101	0.286	0.396	0.342	0.119	0.087	0.300	0.299
Ca	0.728	0.272	0.170	0.177	0.080	0.082	0.070	0.078
Total	7.997	7.990	8.005	8.005	7.872	7.898	7.933	7.915
End-members [mol %]								
Almandine	62.9	80.4	68.9	67.2	75.9	76.6	60.6	62.6
Andradite	1.1	0.5	0.7	0.7	0.0	0.0	0.0	0.0
Grossular	23.2	8.7	4.9	5.1	3.0	2.5	2.5	2.2
Pyrope	3.4	9.7	13.2	11.4	4.4	3.1	10.7	10.8
Spessartine	9.3	0.7	12.1	15.4	16.7	17.4	26.1	23.8
Uvarovite	0.1	0.0	0.0	0.1	0.0	0.4	0.0	0.7

Garnet from pebbles from the Tylicz and Piwniczna-Mniszek sections is not zonal in terms of main elements. Almandine molecule prevails in the garnet in all mica-schists studied reaching up to 80 mol %. They are accompanied by lesser amounts of pyrope and spessartine. Pyrope and spessartine in mica schists from Tylicz (Tyl2) and Piwniczna-Mniszek (Mn1) usually do not exceed 15 mol % each. The spessartine molecule amount in sample Tyl14 is slightly elevated in respect to Mn1 and Ty2 samples reaching up to 26 mol %. The grossular content in the mica-schists from Tylicz and Piwniczna-Mniszek is very low, usually not exceeding 5 mol %. The garnet population from a mica-schist pebble from the Zarzecze section (sample Zar3) differs in composition compared to other samples studied. The garnet from the Zarzecze section displays zonality expressed in elevated grossular and spessartine molecule amounts in the core (up to 23 mol % and 9 % respectively) at the expense of pyrope and almandine molecules (Table 1). Garnet chemistry from the mica-schists of Tylicz and Piwniczna-Mniszek suggests that it was formed in low P/T metamorphic environment, while the composition of garnet from Zarzecze implies higher P/T metamorphic conditions of its formation (Fig. 4).

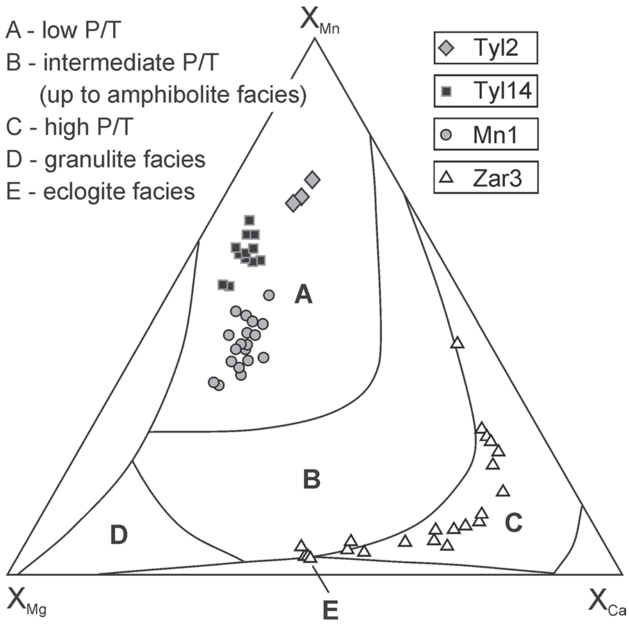


Fig. 4. Garnet composition in the mica-schists studied and its P/T conditions of forming (diagram adapted from Win et al. 2007).

Monazite composition and age

The contents of Th and U and LREE like La, Ce and Nd show restricted ranges in all the samples analysed. The Th content changes in the range of 0.03–0.09 (cations/4oxygens) and U content from 0.004 to 0.010 (cations/4 oxygens). However, the Th and U amounts concentrate mostly around 0.05±0.02 and 0.007±0.02 cations/4 oxygens respectively (Fig. 5A, B). The La amount oscillates in the range of 0.18–0.23, Ce in the range of 0.38-0.45 and Nd content concentrates around 0.17 cations/4 oxygens (Fig. 5C–E). The REE curve slightly slopes down towards HREE with Eu negative anomaly visible in most of the monazites analysed

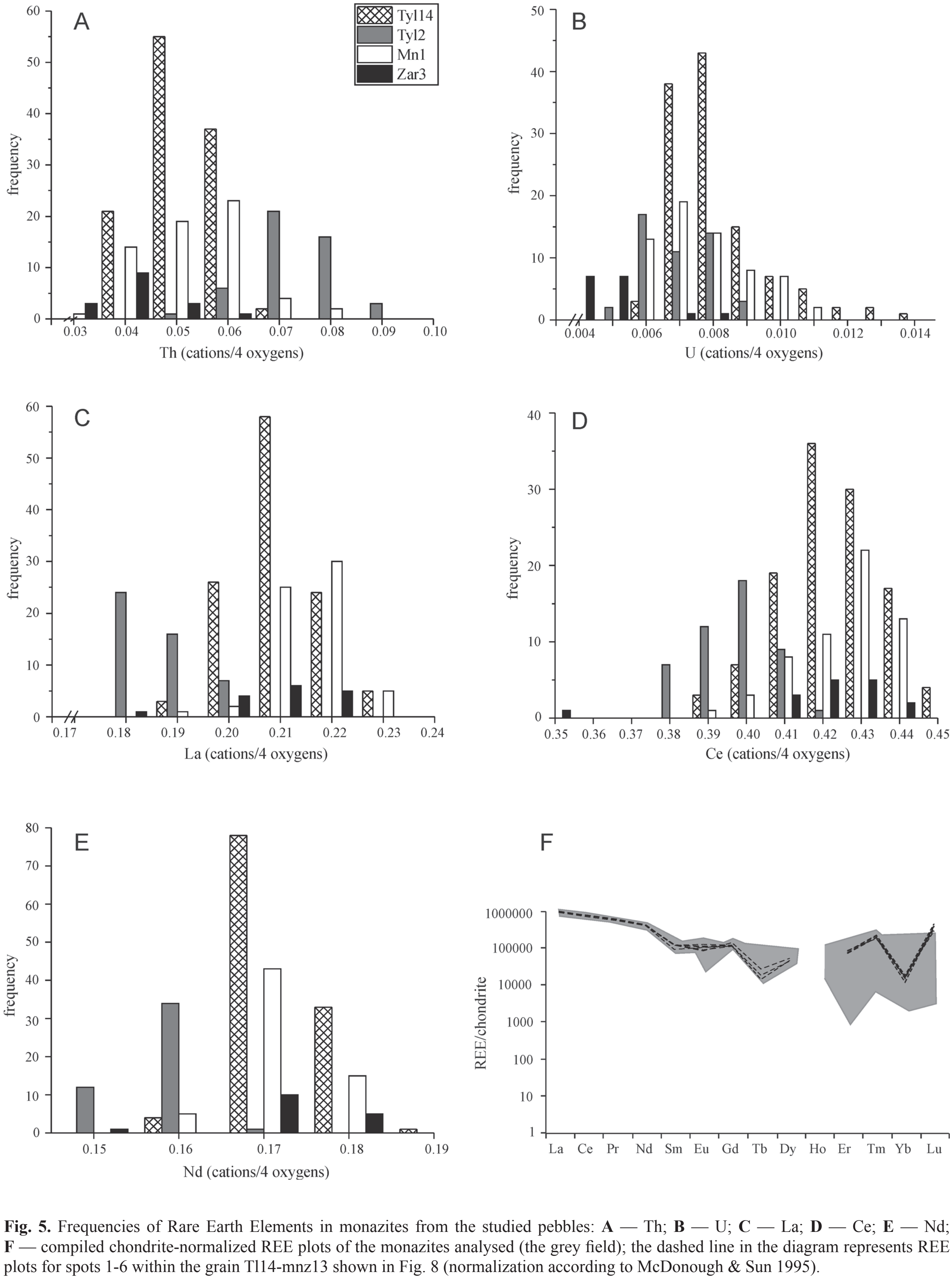


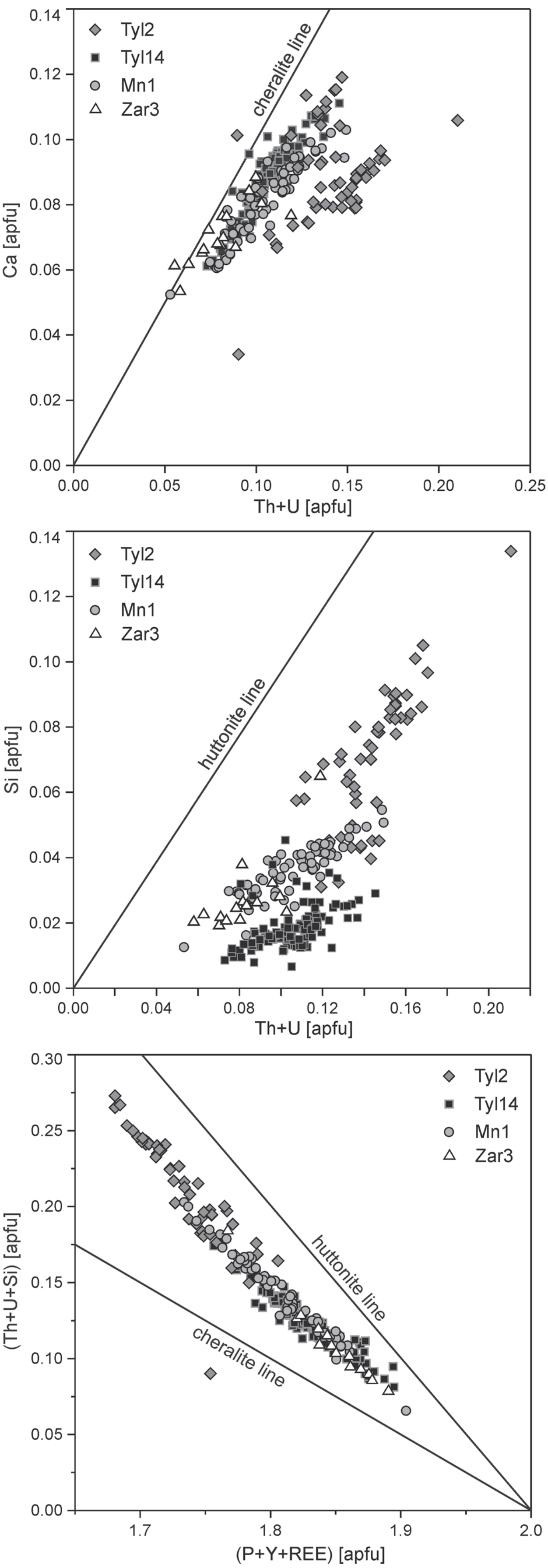
Fig. 5. Frequencies of Rare Earth Elements in monazites from the studied pebbles: **A** — Th; **B** — U; **C** — La; **D** — Ce; **E** — Nd; **F** — compiled chondrite-normalized REE plots of the monazites analysed (the grey field); the dashed line in the diagram represents REE plots for spots 1-6 within the grain Tl14-mnz13 shown in Fig. 8 (normalization according to McDonough & Sun 1995).

(Fig. 5F). Some monazites in sample Tyl2 show enrichment in Si (up to 1.16 wt. % of SiO_2) (Table 2). This may be the effect of cation substitution in monazite structure or of quartz micro-inclusions present in monazite grains (Pyle et al. 2001). All of the monazites analysed (Fig. 6) represent huttonite-cheralite solid solutions (e.g. Spear & Pyle 2002 and references therein). The monazites analysed are generally compositionally alike. The difference in the ThO_2 content within all monazite populations studied does not exceed 3.5 wt. % for each sample studied, while the difference in the UO_2 concentration does not exceed 0.8 wt. %. The difference in the UO_2 content, considering various spots within a single monazite grain, is mostly lower than 0.1 wt. %, rarely reaching about 0.2 wt. %, while variation of ThO_2 within singular grains may reach up to 2 wt. % (Table 2). Changes in chemical composition within single grains are irregular or patchy, but there is no difference between the chondrite normalized REE plots representing various spots in a grain (e.g., grain Tyl14-mnz13 in Fig. 5F).

There is no significant difference in the composition and age of monazites occurring in the matrix or as inclusions within biotite. The calculated spot ages for the analysed monazites indicate Variscan Devonian/Carboniferous to Permian time-span. The average ages are very similar for mona-

Table 2: Selected microprobe analyses of monazites from the samples studied. Monazite number (=Mnz No.) refers to monazite grain analysed; spot number (=spot No.) refers to analytical spot within a grain. Representative analyses within a grain are marked. The data refer to monazite grains shown in Fig. 8.

Sample label	**Tyl2**				**Tyl14**				**Mn1**			**Zar3**		
Mnz No.	**Mnz 2**		**Mnz 4**		**Mnz 1**		**Mnz 13**		**Mnz 2**		**Mnz 20**	**Mnz 3**	**Mnz 4**	**Mnz 8**
Spot No.	**3**	**4**	**1**	**2**	**1**	**2**	**1**	**4**	**1**	**2**	**4**	**5**	**8**	**15**
P_2O_5	27.79	27.92	27.45	27.52	29.24	27.93	27.42	27.68	28.77	29.18	28.53	29.22	29.11	29.19
SiO_2	0.74	0.75	1.16	0.98	0.22	0.17	0.21	0.38	0.44	0.39	0.50	0.26	0.31	0.27
Al_2O_3	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.00
La_2O_3	12.06	12.81	12.01	12.04	12.90	13.41	13.37	13.28	14.27	15.03	13.99	14.51	13.53	14.51
Ce_2O_3	26.44	27.27	26.23	26.45	26.76	27.76	28.02	26.04	29.20	29.89	27.60	29.68	28.26	29.49
Pr_2O_3	3.28	3.24	3.16	3.16	3.24	3.35	3.36	3.11	3.19	3.31	3.08	3.28	3.15	3.27
Nd_2O_3	10.60	10.80	10.34	10.46	11.08	11.31	11.52	11.16	11.72	11.85	11.39	12.16	11.86	11.93
Sm_2O_3	1.18	1.22	1.22	1.21	1.05	1.03	1.11	1.07	1.95	1.83	2.00	2.26	2.10	1.97
Eu_2O_3	0.28	0.27	0.26	0.33	0.43	0.32	0.30	0.28		0.11	0.01	0.26	0.24	0.23
Gd_2O_3	1.53	1.64	1.58	1.62	1.40	1.29	1.33	1.67	1.68	1.68	1.78	1.94	1.83	1.71
Tb_2O_3	0.08	0.11	0.17	0.17	0.03	0.02	0.00	0.06	0.10	0.06	0.13	0.15	0.12	0.08
Dy_2O_3	0.95	0.99	1.04	1.04	0.77	0.73	0.68	0.78	0.44	0.50	0.63	0.54	0.65	0.57
Er_2O_3	0.84	0.85	0.81	0.79	0.78	0.81	0.68	0.82	0.10	0.06		0.09	0.06	0.13
Tm_2O_3	0.33	0.31	0.36	0.35	0.29	0.37	0.28	0.27		0.04			0.03	0.01
Yb_2O_3	0.23	0.15	0.22	0.20	0.16	0.17	0.11	0.17	0.02	0.08	0.07	0.06	0.05	0.05
Lu_2O_3	0.35	0.34	0.39	0.41	0.36	0.44	0.60	0.42						
PbO	0.13	0.10	0.16	0.14	0.14	0.12	0.12	0.15	0.11	0.09	0.12	0.06	0.09	0.10
ThO_2	7.11	5.78	8.34	7.55	6.00	5.36	4.92	6.87	4.90	3.91	5.56	2.89	5.50	3.85
UO_2	0.66	0.53	0.66	0.62	0.90	0.75	0.81	1.41	0.87	0.63	1.07	0.45	0.48	0.41
PbO	0.11	0.09	0.14	0.12	0.13	0.11	0.11	0.14	0.10	0.08	0.11	0.05	0.08	0.09
Y_2O_3	2.61	2.77	2.89	2.91	2.34	2.03	1.69	2.00	1.41	1.28	1.65	1.74	1.97	1.56
CaO	1.14	0.83	1.00	0.98	1.27	1.11	1.01	1.35	0.98	0.74	1.03	0.65	0.99	0.88
Total	**98.45**	**98.74**	**99.58**	**99.03**	**99.50**	**98.61**	**97.66**	*99.12*	**100.24**	**100.74**	**99.26**	**100.23**	**100.43**	**100.28**
Oxygen base	16	16	16	16	16	16	16	16	16	16	16	16	16	16
P	3.803	3.805	3.735	3.760	3.913	3.842	3.817	3.800	3.869	3.890	3.865	3.905	3.892	3.899
Si	0.120	0.121	0.187	0.158	0.036	0.028	0.035	0.061	0.070	0.061	0.081	0.042	0.049	0.043
Al	0.000	0.000	0.000	0.000	0.001	0.003	0.001	0.002	0.000	0.000	0.000	0.001	0.001	0.000
La	0.719	0.761	0.712	0.716	0.752	0.803	0.811	0.794	0.836	0.873	0.826	0.845	0.788	0.844
Ce	1.565	1.607	1.544	1.562	1.549	1.651	1.687	1.546	1.698	1.723	1.617	1.715	1.634	1.703
Pr	0.193	0.190	0.185	0.186	0.187	0.198	0.201	0.184	0.184	0.190	0.180	0.188	0.181	0.188
Nd	0.612	0.621	0.593	0.603	0.625	0.656	0.677	0.647	0.665	0.666	0.651	0.686	0.669	0.672
Sm	0.066	0.068	0.068	0.067	0.057	0.058	0.063	0.060	0.107	0.100	0.111	0.123	0.115	0.107
Eu	0.016	0.015	0.014	0.018	0.023	0.018	0.017	0.016	0.000	0.006	0.001	0.014	0.013	0.012
Gd	0.082	0.087	0.084	0.087	0.073	0.070	0.073	0.090	0.089	0.087	0.094	0.101	0.096	0.089
Tb	0.004	0.006	0.009	0.009	0.002	0.001	0.000	0.003	0.005	0.003	0.007	0.008	0.006	0.004
Dy	0.050	0.051	0.054	0.054	0.039	0.038	0.036	0.040	0.022	0.025	0.033	0.027	0.033	0.029
Er	0.043	0.043	0.041	0.040	0.039	0.041	0.035	0.042	0.005	0.003	0.000	0.004	0.003	0.006
Tm	0.017	0.016	0.018	0.018	0.014	0.018	0.014	0.013	0.000	0.002	0.000	0.000	0.002	0.000
Yb	0.011	0.008	0.011	0.010	0.008	0.009	0.006	0.008	0.001	0.004	0.004	0.003	0.002	0.002
Lu	0.017	0.016	0.019	0.020	0.017	0.022	0.030	0.021	0.000	0.000	0.000	0.000	0.000	0.000
Pb	0.006	0.004	0.007	0.006	0.006	0.005	0.005	0.007	0.005	0.004	0.005	0.003	0.004	0.004
Th	0.262	0.212	0.305	0.277	0.216	0.198	0.184	0.253	0.177	0.140	0.202	0.104	0.198	0.138
U	0.024	0.019	0.024	0.022	0.032	0.027	0.030	0.051	0.031	0.022	0.038	0.016	0.017	0.014
Pb	0.005	0.004	0.006	0.005	0.005	0.005	0.005	0.006	0.004	0.004	0.005	0.002	0.003	0.004
Y	0.224	0.237	0.247	0.250	0.197	0.176	0.148	0.173	0.119	0.107	0.141	0.146	0.166	0.131
Ca	0.197	0.143	0.173	0.169	0.215	0.193	0.178	0.235	0.166	0.125	0.177	0.110	0.167	0.149
Total cath.	**8.053**	**8.050**	**8.054**	**8.055**	**8.032**	**8.084**	**8.084**	**8.052**	**8.053**	**8.043**	**8.045**	**8.048**	**8.042**	**8.054**
Th	6.252	5.078	7.326	6.636	5.275	4.711	4.325	6.037	4.302	3.434	4.885	2.539	4.835	3.385
U	0.578	0.463	0.580	0.545	0.790	0.657	0.711	1.241	0.766	0.558	0.939	0.396	0.421	0.357
Pb	0.106	0.080	0.130	0.112	0.118	0.099	0.101	0.128	0.092	0.077	0.106	0.045	0.073	0.082
Y	2.054	2.178	2.278	2.291	1.842	1.601	1.334	1.576	1.110	1.009	1.299	1.366	1.553	1.226
Th*	8.125	6.577	9.210	8.403	7.844	6.847	6.639	10.059	6.788	5.248	7.931	3.819	6.198	4.552
Age (Ma)	**292**	**273**	**317**	**299**	**339**	**325**	**341**	**286**	**303**	**331**	**301**	**266**	**265**	**405**



zites from all the mica-schists studied oscillating around 300 Ma: 303±4.2 Ma (Tyl2) and 313±3.8 Ma (Tyl14) in Tylicz, 314±4.5 Ma in Piwniczna-Mniszek and 320±11.8 Ma in Zarzecze (Table 2; Figs. 7, 8). The differences in age calculated for spots within single grains do not exceed 50 Ma still oscillating around 300 Ma. Age distribution within single monazite grains is irregular, showing a patchy pattern (Table 2; Fig. 8).

Discussion and conclusions

The set of pebbles

The exotic pebbles in the Eocene deposits of the southern part of the Magura Nappe (Tylicz and Krynica zones) have been recognized in two stratigraphic positions: 1) in the Mniszek Shale Member (Middle-Upper Eocene) of the Magura Formation (Tylicz and Zarzecze sections); 2) in the Piwniczna-Mniszek section belonging to the Piwniczna Member of the Magura Fm. (Lower-Middle Eocene).

The thick-bedded sandstones and conglomerates of the Mniszek Shale Member, uppermost part of the Piwniczna Member of the Magura Formation are located above the Middle-Upper Eocene variegated shales of *Cyclammina amplectens* Grzybowski. These are deposits of channel facies with relatively high contents of the Mesozoic carbonate pebbles from 18 % in the Zarzecze section (in the west) to 44 % at Tylicz (in the east) and similar content pebbles of flysch sandstones (about 26 %). The content of crystalline rocks ranges from ca 26 % to 32 % in the Tylicz and Zarzecze sections respectively. The population of pebbles at Tylicz is rich in medium grade metamorphic rocks such as fine-grained gneisses and schists and very poor in igneous rocks, while a striking feature of the conglomerates at Zarzecze is the high content of vein quartz. The composition of carbonate material and microfossil assemblages of the Tylicz and Zarzecze conglomerates (Middle–Late Eocene) indicates similarity to both the Jarmuta/Proč and Strihovce exotic pebbles (Oszczypko & Olszewska 2010).

The exotic conglomerates of the Piwniczna-Mniszek section belonging to the Piwniczna Member of the Magura Fm. are located beneath the horizon of variegated shales with *Cyclammina amplectens* Grzybowski. These conglomerates are rich in vein quartz (37 %), flysch clasts (35 %), crystalline clasts (25 %) and poor in carbonate clasts (3 %). The exotic conglomerates of the Piwniczna Sandstone Mb. (Middle/Lower Eocene) of the Magura Fm. are an equivalent of conglomerates of the lower part of the Strihovce Sandstone (see Nemčok 1990a,b; Mišík et al. 1991). These conglomerates are rich in granitoids, medium-grade metamorphic gneisses and schists, phyllites and quartzites, with a relatively small amount of felsic volcanic rocks and Mesozoic carbonates (Oszczypko 1975; Mišík et al. 1991; Oszczypko et al. 2006).

Metamorphic rocks found in all sampled conglomerates are similar to each other and correspond to medium grade

Fig. 6. Substitution diagrams for the monazites analysed.

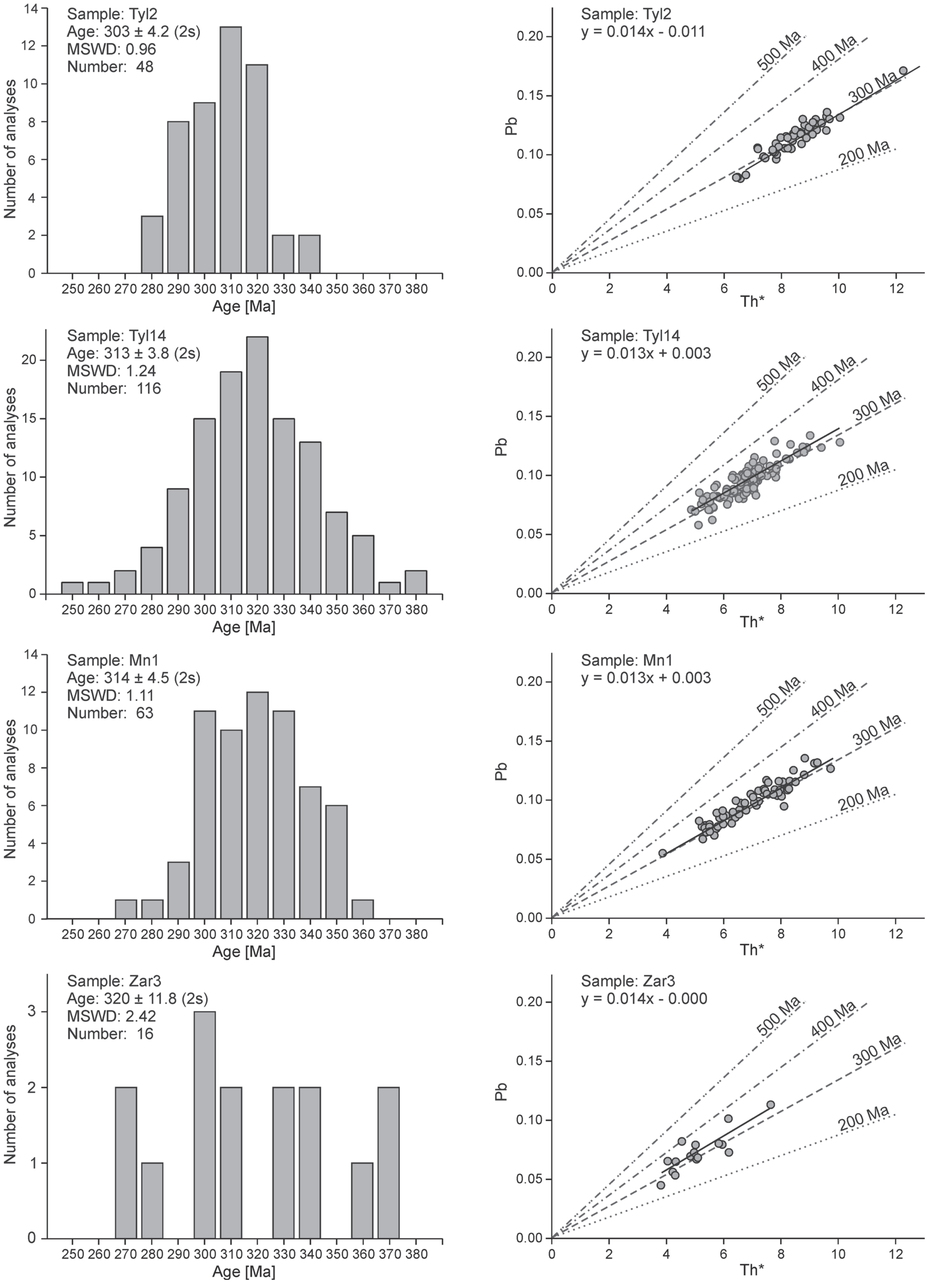


Fig. 7. Monazite age histograms and Pb vs. Th* (wt. %) monazite isochrone diagrams.

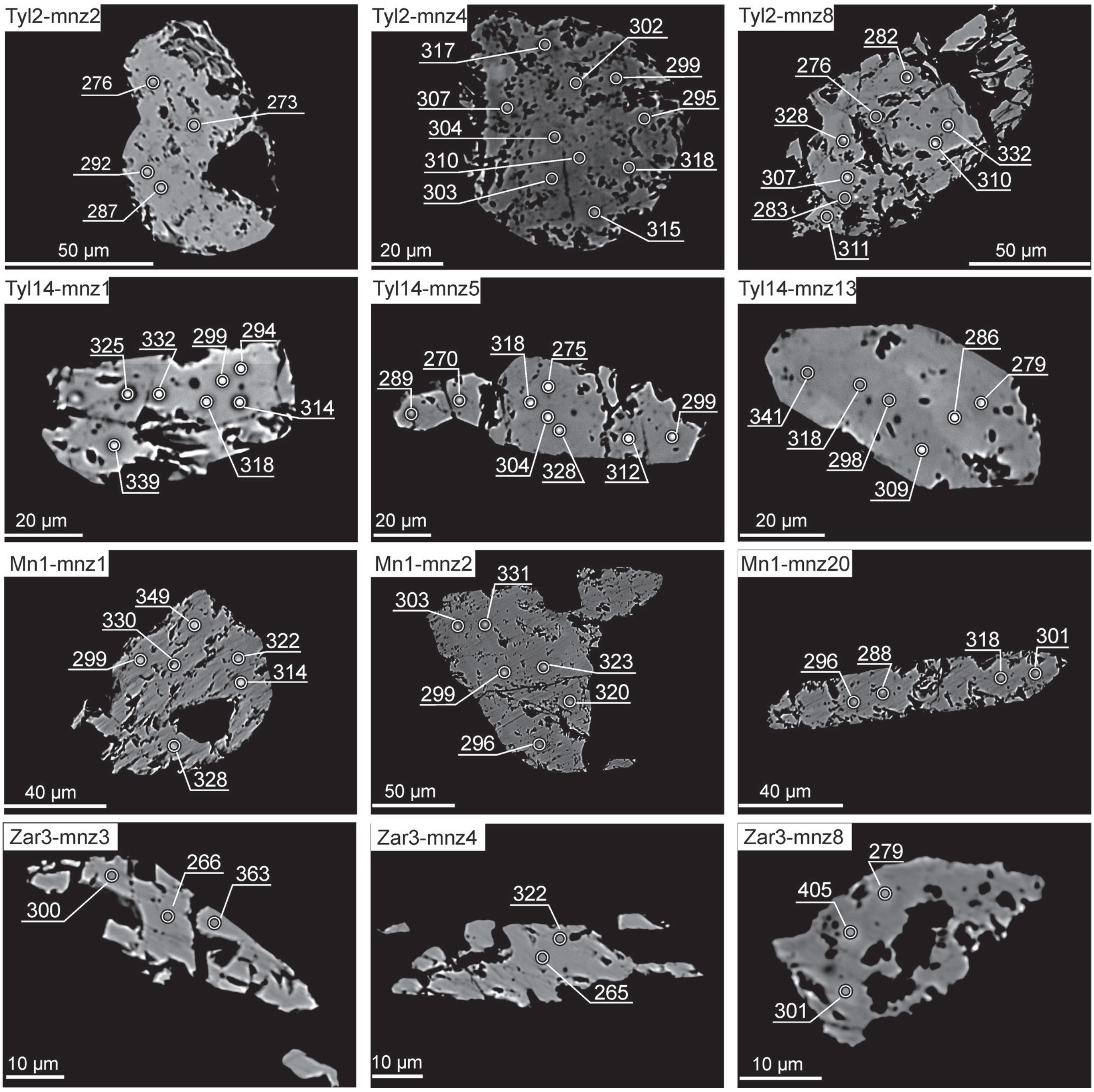


Fig. 8. Microphotographs showing representative monazites analysed with distribution of calculated ages. SEM BSE.

metamorphic conditions of epidote-amphibolite or amphibolite facies. Similar results as for garnet composition and metamorphic conditions of its forming were obtained on the basis of numerous analyses of detrital garnets found in the Jarmuta (Maastrichtian-Palaeocene) and Szczawnica (Palaeocene-Lower Eocene) Formations (Salata 2004; Oszczypko & Salata 2005).

Monazite age remarks

According to Spear & Pyle (2002 and references therein) a low and restricted range of Th content oscillating around 0.05, U content up to 0.01 and also La, Ce and Nd averaging around 0.20, 0.43 and 0.17 cations/4 oxygens respectively are typical for monazites formed in metamorphic conditions. Additionally, the REE patterns of metamorphic monazites slope down towards HREE (e.g. Catlos et al. 2002; Spear & Pyle 2000 and references therein). Therefore, the Variscan ages of the monazites analysed are interpreted as documenting metamorphic processes in the source area. There is no evidence of a rejuvenation younger then the Variscan orogeny reflected in the calculated ages. The irregular age distribution within single grains may reflect different phases of metamorphic processes influencing trace element composition in the monazites analysed. The compositional patchy pattern could be caused by several processes that include overgrowth, regrowth, intergrowth, replacement and recrystallization during metamorphic events (e.g. Zhu & O'Nions

1999). The currently obtained ages correspond well to earlier radiometric ages obtained from mica dating and CHIME dating of monazite in a metamorphic rock pebble from Tylicz (Poprawa et al. 2004, 2005).

Possible sources

The plutonic rocks in the Tylicz conglomerate represent volcanic-arc granites and syn-collisional granites of S-type, which are well known from the Western Carpathians (e.g., Petrík et al. 1994; Broska & Uher 2001; Broska & Petrík 2015). Such granites were also described as protoliths for Carpathian orthogneisses found as pebbles in Palaeocene flysch in the Dukla Nappe (Bąk & Wolska 2005). According to Pitcher (1982) and Broska and Uher (2001) S-type granites are orogenic granites connected with continental collision. They can be accompanied by regional metamorphic rocks (Pitcher 1982). The Western Carpathian I- and S-type granitoids display monazite ages of ~350 Ma and ~340 Ma (Broska & Petrík 2015 and references therein). Unfortunately, the very small (up to 2 cm across maximum) granitic pebbles found in the studied sections did not contain monazites to compare the dating. Variscan metamorphism, although documented in the Tatric (~310 Ma) and Veporic (~340–350 Ma) metamorphic units, is not widespread in the Western Carpathian domains as mainly Alpine recrystallization events are recorded in the area (e.g., Janák 1994; Dallmeyer et al. 1996; Janák & Plašienka 1999; Janák et al. 2001 and references therein). The dates established for the Western Carpathian igneous and metamorphic rocks suit the timespan established for the dated mica-schist pebbles studied here. However, there are some facts that exclude Western Carpathian crystalline massifs from the possible source areas for the studied conglomerates. They are: i) the total lack of sedimentary rocks, derived from the PKB and instead the presence of shallow-water limestone of the Urgonian facies, typical for the Median Dacides of the Dacia Mega Unit; ii) the palaeotransport directions measured in the sampled deposits indicate location of the source massif(s) in the south-east termination of the Magura Basin, while the small dimensions of the mica-schist pebbles suggest a rather distal source in relation to their deposition place in the Magura Basin and/or their re-deposition. The similar mineral composition and consistent monazite age distribution and palaeocurrent directions of deposits suggest provenance of the mica-schists studied from the same source area. The different garnet composition between schists from Tylicz, Piwniczna-Mniszek (low- to medium grade) and Zarzecze (high-grade) may reflect the origin of the pebbles from various parts of an inhomogeneous metamorphic body of the source area.

Both crystalline and sedimentary rock pebbles are characterized by good roundness, typical for river channel sand and marine coastal abrasion. These pebbles could be re-deposited in coastal embankments or as channel facies of submarine cones.

The exotic conglomerates are located directly below (Piwniczna/Mniszek section) and above (Tylicz and Zarzecze sections) the variegated shales of the Mniszek Sh. Mb, manifesting vertical movements of the Magura Basin basement. These movements were accompanied by seismic shocks, which triggered gravity-driven debris flows and submarine slumps moving forward into the deepest parts of the basin (Einsele 2002).

The exact position of the source area for the investigated exotic pebbles is speculative. However, the obtained data suggest recycling and erosion during the Middle Late Eocene to Oligocene an older accretionary wedge and deposition of detritus from the SE prolongation of the Marmarosh Massif located at the south-eastern boundary of the Magura Basin (Lashkievitsch et al. 1995). The supply of carbonate and siliciclastic material from a SE source area (part of the Dacia Mega Unit) was suggested by Oszczypko and Oszczypko-Clowes (2009) as well as by Oszczypko et al. (2005, 2015). The latter solution can be also deduced from the Oligocene?/Early Miocene (Fig. 9) pre-orogenic palaeogeographic restoration of the Alpine-Carpathian-Panonian realms (Ustaszewski et al. 2008).

Currently, the eastern termination of the Magura Nappe is situated in the Eastern Carpathians, along the boundary between Ukraine and Romania (Fig. 1). In this place the Magura Nappe (Monastyrets and Pertrova subunits) is a few km wide, and it is limited to the north by the Median Dacides and its sedimentary cover and from the south by the Pieniny Klippen Belt, Neogene volcanic belt and the Miocene deposits of the Pannonian Basin (Aroldi 2001; Schmid et al. 2008; Oszczypko et al. 2005, 2015).

The possible supply to the Magura Basin from the Marmarosh Massif is indicated by palaeotransport measurements. There are also the similarities between the Jurassic and Lower Cretaceous carbonate microfacies of the Marmarosh Massif and Marmarosh Klippens with the Eocene microfacies exotic pebbles from the Krynica Zone of the Magura Nappe and Pieniny Klippen Belt in Poland and Eastern Slovakia

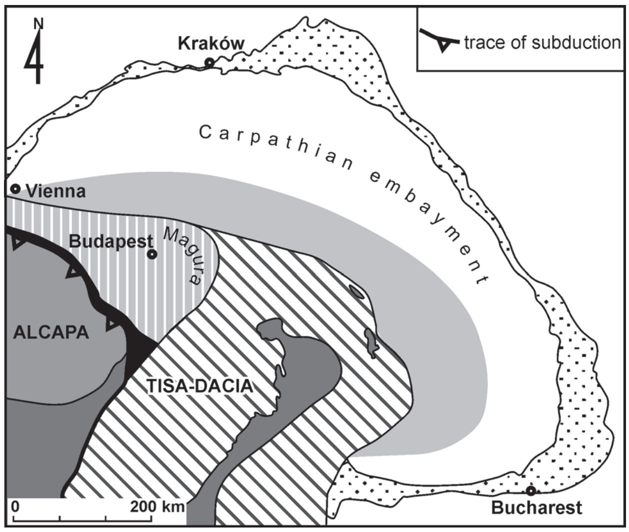


Fig. 9. Reconstruction of the geotectonic situation in the Alps, Carpathians and Dinarides domains in the Early Miocene (based on Ustaszewski et al. 2008 and references therein).

(Mochnacka & Węcławik 1967; Oszczypko 1975; Mišík et al. 1991a, b; Olszewska & Oszczypko 2010).

The Crystalline Mesozoic Zone of the East Carpathians belongs to Median Dacides (Săndulescu 1984) and is composed of the Bucovinian nappe stack, which is of Cretaceous age. In the Ukrainian sector the Marmarosh crystalline massif is an eastern prolongation of the Median Dacide (Ślaczka et al. 2006). This massif displays a nappe structure and is overthrust upon the Black Flysch or Rachiv units. The Marmarosh Massif is composed of Pre-Cambrian gneisses, Palaeozoic metamorphic schists, Carboniferous/Permian coal shales, conglomerates, tuffs, lavas, as well as Mesozoic limestones and breccias (Kruglov & Cypko 1988).

The set of Variscan metamorphic rocks within Eastern (Romanian) Carpathian basement includes very low to low- and medium-grade metamorphic mica-schists, quartz biotite paragneisses, amphibolites metamorphosed under greenschist to almandine-amphibolite facies (see Balintoni 2010 in Miclăuş et al. 2010). Variscan ages are the most common in basement rocks of the Eastern Carpathians and Apuseni Mountains. The ages are well established on the basis of radiometric K-Ar and Ar-Ar dating of muscovite and biotite concentrates as well as monazite (e.g. Dallmeyer et al. 1999; Strutinski et al. 2006; Gröger et al. 2013; Săbău & Negulescu 2014 and references therein). The established Variscan time span of the metamorphic events encloses within 370–251 Ma (see e.g. Strutinski et al. 2006) with a distinct plateau of ages grouping around 300±20 Ma. It is worth noting that the area of the East Carpathians is situated outside the Alpine metamorphic zone, thus Alpine metamorphic rejuvenation is not strongly developed there. However, the rejuvenation overprints Alpine ages in the rocks of the Apuseni Mountains (see e.g. Dallmeyer et al. 1999; Strutinski et al. 2006). The Variscan time-span established for the metamorphic micas in the east Carpathians closely agrees with the currently obtained data for the Magura Nappe mica-schist pebbles. Moreover, since the monazites dated do not show Alpine ages it may be supposed that the pebbles studied derive mainly from the East Carpathian domain of the Dacia Mega Unit rather than from the more southern parts of it. The idea is supported by the garnet composition indicating a mainly low grade of metamorphism of the pebbles studied (Fig. 4).

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