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The emplacement age of the Muntele Mare Variscan granite (Apuseni Mountains, Romania)

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Abstract: Like the Alps and Western Carpathians, the Apuseni Mountains represent a fragment of the Variscan orogen involved in the Alpine crustal shortenings. Thus the more extensive Alpine tectonic unit in the Apuseni Mountains, the Bihor Autochthonous Unit is overlain by several nappe systems. During the Variscan orogeny, the Bihor Unit was a part of the Someş terrane involved as the upper plate in subduction, continental collision and finally in the orogen collapse and exhumation. The Variscan thermotectonic events were marked in the future Bihor Unit by the large Muntele Mare granitoid intrusion, an S-type anatectic body. Zircon U-Pb laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) dating yielded a weighted mean age of 290.9 ± 3.0 Ma and a concordia age of 291.1 ± 1.1 Ma. U-Pb isotope dilution zircon analyses yielded a lower intercept crystallization age of 296.6 + 5.7/–6.2 Ma. These two ages coincide in the error limits. Thus, the Muntele Mare granitoid pluton is a sign of the last stage in the Variscan history of the Apuseni Mountains. Many zircon grains show inheritance and/or Pb loss, typical for anatectic granitoid, overprinted by later thermotectonic events.

Key words: U/Pb geochronology, Variscan orogeny, Apuseni Mountains, Muntele Mare granitoid pluton.

Introduction

The present architecture of the Romanian Carpathians has been achieved during the Alpine tectonism (e.g. Săndulescu 1984; Balintoni 1997; Iancu et al. 2005). An overview of the pre-Alpine basement components and of reliable isotopic ages in the Romanian Carpathians was recently published by Balintoni et al. (2009). According to these authors, the main part of the Carpathian basement consists of Gondwanan terranes containing Ordovician orthogneisses intensely reworked during the Variscan orogeny. For example, Variscan nappes were described in the Eastern Carpathians (e.g. Balintoni et al. 1983), the Variscan thermotectonic events reached the eclogite facies in the Southern Carpathians (e.g. Medaris et al. 2003) and Variscan granitoid bodies intruded successively the basement of the Apuseni Mountains (e.g. Pană 1998; Pană et al. 2002b; Balintoni et al. 2007). The succession of the Variscan thermotectonic events, their significance and their correlation among the three Carpathians segments (i.e. Eastern Carpathians, Southern Carpathians and Apuseni Mountains, Fig. 1 inset) are not well established. Moreover, because a great part of Central and Western Europe was amalgamated during the Variscan orogeny (e.g. von Raumer & Stampfli 2008), a good knowledge of the Variscan orogen in its entirety is vital for understanding the Pangea assemblage and its subsequent history. Due to successive granitoid intrusions, the basement of the Apuseni Mountains offers a good opportunity to distinguish between different Variscan thermotectonic events.

Some of the existing Paleozoic ages in the Apuseni Mountains were well constrained, whereas others had a preliminary character, deduced from a limited number of analyses and in the absence of in situ dating. Regarding the Muntele Mare pluton, we mention the isotope dilution U-Pb age of 295 ± 1 Ma reported by Pană (1998) and of 278.4 ± 2.1 Ma reported by Pană et al. (2002b). In an attempt to better constrain the age of the Muntele Mare granitoid, we performed in situ zircon U-Pb laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) dating, avoiding in this way the mixed results that might happen in the case of complex zoned grains with inherited cores, new magmatic overgrowth and/or recrystallized margins. We also used these data as a reference frame for new U-Pb isotope dilution age data. A brief discussion of the tectonic significance of the emplacement age of the Muntele Mare pluton was also included. The pluton was re-sampled in two locations, 22 km apart (Fig. 2).

Geological setting and samples

The Apuseni Mountains represent an isolated mountain range in the interior of the Carpathian orocline (Fig. 1 inset). They consist of Alpine tectonic units, which include in geometric succession from bottom to top: a) the Bihor Unit in an autochthonous position, b) the Codru Nappe System, c) the Biharia Nappe System and d) the Mureş Zone units at top (e.g. Ianovici et al. 1976; Bleahu et al. 1981). The Bihor Unit is made predominantly of crystalline rocks overlain by Permian-Mesozoic sedimentary and volcanic cover. The Codru Nappe System comprises a single tectonic unit consisting of a metamorphic basement and a sedimentary cover, with the rest of

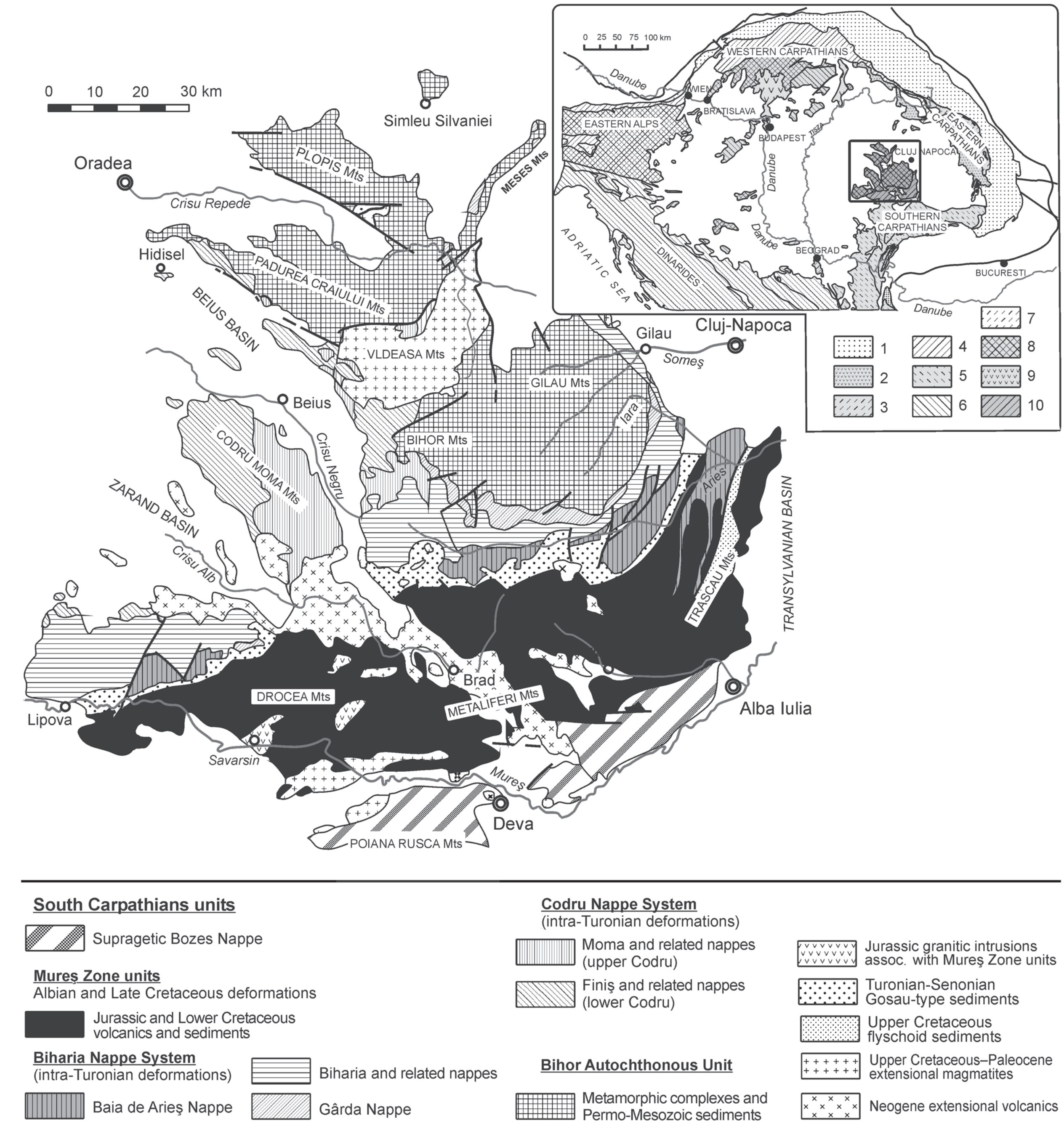

Fig. 1. A sketch of the main Alpine tectonic units in the Apuseni Mountains (compiled according to Bleahu et al. 1981; Săndulescu 1984; Kräutner 1997; Balintoni & Puşte 2002). The inset shows the position of the Apuseni Mountains within the Central-East European Alpine orogenic frame: **1** — Flysch units; **2** — Neogene volcanics; **3** — Basement units in the Eastern Carpathians; **4** — Magura and Trans-Carpathian flysch units and sedimentary units in the Tauern window; **5** — Basement units in the Southern Carpathians; **6** — Dinarides, Vardarides and similar units in Hungary and Slovakia; **7** — Basement units in Tauern window; **8** — Apuseni Mts, Mecsek, Western Carpathians and Austroalpine basement units; **9** — Neogene and Paleogene volcanics; **10** — Mureş Zone units.

the units including exclusively Permian and Mesozoic sequences. The Biharia Nappe System is formed entirely by metaigneous and metasedimentary rocks, ranging in age from lattermost Cambrian to Triassic (e.g. Dimitrescu in Ianovici et al. 1976; Pană 1998; Pană & Balintoni 2000). These sequences are variously overprinted by early Cretaceous shearing and low grade metamorphism (Pană 1998; Dallmeyer et al. 1999). The tectonic units of the Mureş Zone are made up of Jurassic-Cretaceous mafic and felsic igneous rocks (e.g. Pană et al. 2002a) and associated sediments deposited in a rift-like setting (e.g. Bleahu 1974), as well as a tectonic slice of metamorphosed rocks (Balintoni & Iancu 1986).

The Apuseni Mountains basement (Fig. 2) is built up from three pre-Alpine Gondwanan terranes, named Someş, Biharia

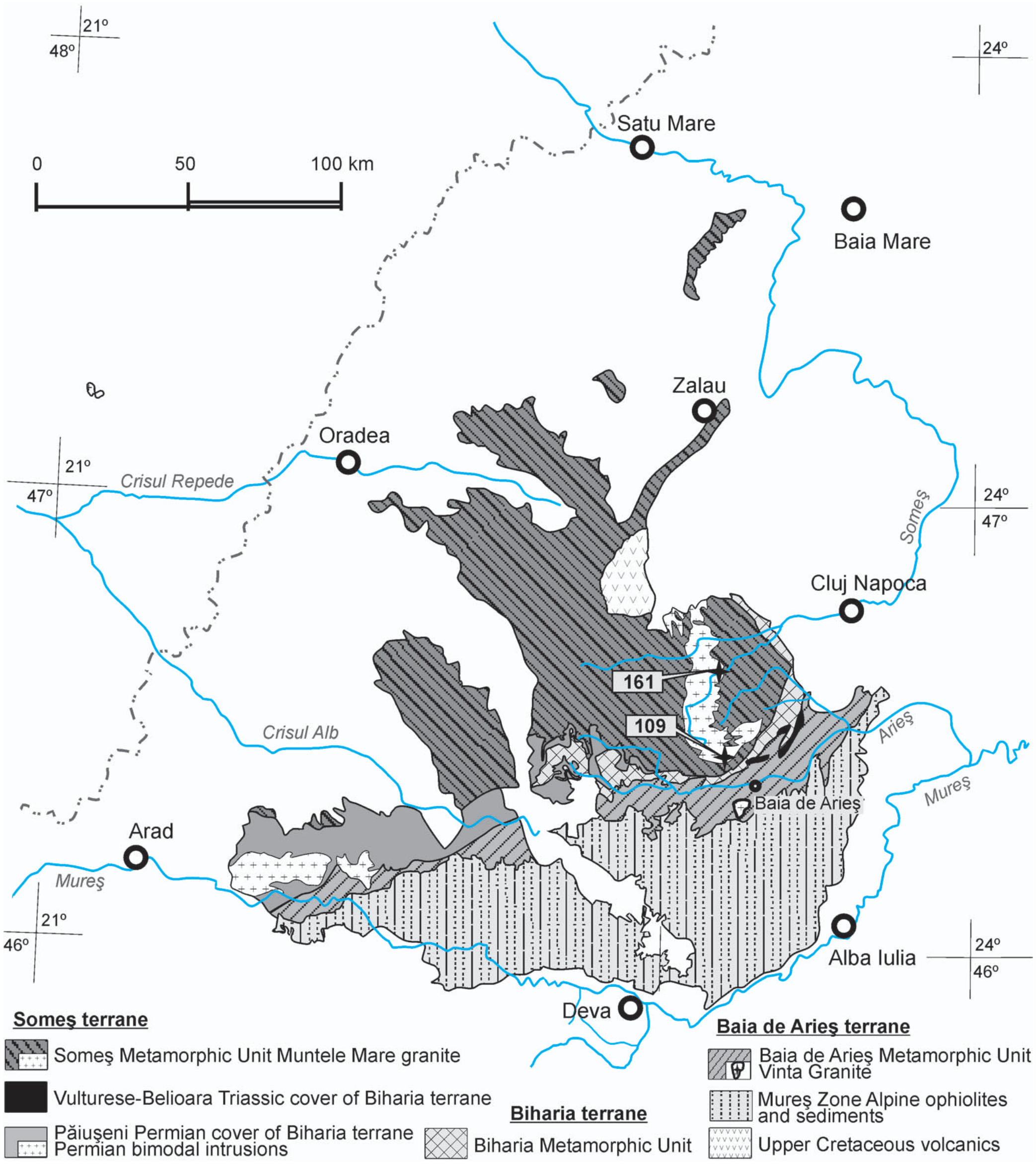

Fig. 2. A sketch of the main metamorphic units and pre-Alpine terranes in the Apuseni Mts (compiled from Ianovici et al. 1976; Balintoni 1997; Pană 1998; Dallmeyer et al. 1999).

and Baia de Arieş (e.g. Balintoni et al. 2009). They were probably parts of some larger terranes that constituted the basement of all the Carpathian branches (e.g. Pană et al. 2002b). According to the Romanian literature (e.g. Ianovici et al. 1976; Balintoni 1997), the Someş terrane is composed of the Someş metamorphic sequence, the Biharia terrane of the Biharia metamorphic sequence and the Baia de Arieş terrane of the Baia de Arieş metamorphic sequence. The above structural and metamorphic entities are shown in Fig. 2 and in Table 1 where a synopsis of the Alpine and pre-Alpine tectonic and metamorphic units of the Apuseni Mountains is presented.

The Muntele Mare granitoid is a northerly trending elongated pluton (Fig. 2), that covers approximately 300 km^2 in the lower Bihor Unit. The thermal contact aureole is expressed by andalusite hornfels and in the roof pendants is characterized by the sillimanite+cordierite mineral assemblage (e.g. Dimitrescu 1966; Mârza 1969).

The main rock type of the pluton is a biotite granodiorite consisting of plagioclase, quartz, K-feldspar, biotite and muscovite as rock-forming minerals and tourmaline, apatite, zircon, monazite and allanite as accessory minerals (e.g. Anton 2000). It intrudes and includes roof pendants of the Someş sequence (e.g. Dimitrescu 1966; Anton 2000). It has a porphyritic texture due to K-feldspar megacrysts and can locally be pegmatoid or microgranular. The Muntele Mare granodiorite is a strongly peraluminous S-type granitoid, it plots in the late-post-collisional field of the Hf-Rb-Ta diagram and zircon and monazite thermometers indicate a crystallization temperature range of 780–830 °C consistent with decompression melting in the granulite stability field (Anton 2000). Such temperatures suggest the upper limit of granulite facies typical for de-

Table 1: North Apuseni Mountains Structure. **P** — Permian, **Tr** — Triassic, **J** — Jurassic, **K** — Cretaceous.

<table>
<tr><th>Pre-Alpine terranes and their basement</th><th colspan="2">Alpine metamorphosed cover of the pre-Alpine terranes</th><th colspan="3">Alpine tectonic units</th></tr>
<tr><td rowspan="2">Baia de Arieş terrane
Baia de Arieş metamorphic sequence</td><td colspan="2" rowspan="2">No metamorphic cover</td><td colspan="2">Highiş-Muncel Nappe
Păiuşeni sequence</td><td rowspan="9">Biharia Nappe System</td></tr>
<tr><td colspan="2">Baia de Arieş Nappe
Baia de Arieş sequence</td></tr>
<tr><td rowspan="5">Biharia terrane
Biharia metamorphic sequence</td><td rowspan="5">Păiuşeni Permian sequence</td><td rowspan="5">Vulturese-Belioara Triassic marbles</td><td colspan="2">Biharia Nappe
Păiuşeni sequence Vulturese-Belioara marbles
Biharia sequence</td></tr>
<tr><td colspan="2">Poiana Nappe
Păiuşeni sequence</td></tr>
<tr><td rowspan="3">Arieşeni Nappe</td><td>P–Tr</td></tr>
<tr><td>Păiuşeni sequence</td></tr>
<tr><td>Biharia sequence</td></tr>
<tr><td rowspan="11">Someş terrane
Someş metamorphic sequence</td><td colspan="2" rowspan="11">No metamorphic cover</td><td rowspan="2">Gârda Nappe</td><td>P–Tr</td></tr>
<tr><td>Someş sequence</td></tr>
<tr><td>Coleşti Nappe</td><td>Tr–J</td><td rowspan="7">Codru Nappe System</td></tr>
<tr><td>Vaşcău Nappe</td><td>Tr–J</td></tr>
<tr><td>Moma Nappe</td><td>P–Tr</td></tr>
<tr><td>Dieva Nappe</td><td>P–K_1</td></tr>
<tr><td rowspan="2">Finiş Nappe</td><td>P–K_1</td></tr>
<tr><td>Someş sequence</td></tr>
<tr><td>Vălani Nappe</td><td>Tr–K_1</td></tr>
<tr><td rowspan="2">Bihor Unit</td><td>P–K_1</td><td rowspan="2">Bihor Autochthonous Unit</td></tr>
<tr><td>Someş sequence</td></tr>
</table>

hydration melting. Consequently, Muntele Mare granitoid crystallized from an anatectic melt. Yet the zircon thermometer temperature can be a little overestimated due to its significant inheritance in the anatectic melts.

The emplacement age of the Muntele Mare pluton was uncertain. Ten biotite and muscovite K-Ar ages reported by Soroiu et al. (1969) and Pavelescu et al. (1975) range between 85 and 237 Ma and have problematic geological significance: the oldest two dates of 232 and 237 Ma could be interpreted as minimum emplacement ages, whereas the cluster of four dates between 85 and 119 Ma suggest an "Austrian" phase tectonic overprint. An $^{40}Ar/^{39}Ar$ muscovite analysis (Dallmeyer et al. 1999) yielded an age of 191 Ma, which may record the uplift and cooling of the Muntele Mare Batholith above the ca. 350 °C isotherm during the Early Jurassic. This age could be influenced by the secondary muscovite (sericite) developed on plagioclase, possibly partially due to the Alpine hydrothermal fluids (see the Alpine reset ages in the Table 2). Anton (2000) reported Rb-Sr ages ranging between 88 and 267 Ma. Pană (1998) proposed an emplacement age of at least 295 ± 1 Ma

Table 2: Zircon U-Pb isotope dilution data for the Muntele Mare granite.

Sample	Atomic ratios									Apparent Ages (Ma)			
	$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	2σ %	$^{207}Pb/^{235}U$	2σ %	rho	$^{207}Pb/^{206}Pb$	2σ %	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	Sample on diagram
109-II	430	0.1221	0.05043	1.09	0.3727	1.45	0.78	0.0874	0.19	317.2	321.6	354.1	3
	50	0.8840	0.05735	0.76	0.7177	2.22	0.57	0.3694	0.09	259.3	549.3	1442	8
	65	0.7080	0.07346	0.88	0.9075	2.71	0.57	0.3043	0.13	457.0	655.7	1417	9
	377	0.1870	0.03757	2.04	0.2850	3.05	0.72	0.0935	0.38	237.8	254.7	413.4	1
	71	0.6204	0.05486	1.47	0.5946	1.47	0.70	0.2783	0.13	344.3	473.8	1162	7
109-I	191	3.4354	0.04040	2.15	0.3214	2.27	0.95	0.1335	0.11	255.3	283.02	518.7	2
	104	2.1833	0.05628	0.95	0.5230	1.88	0.60	0.2053	0.14	353.0	427.16	850.1	5
	34	0.8289	0.05767	0.87	0.5746	3.63	0.52	0.4961	0.08	361.4	460.99	993.4	6
	129	2.8023	0.05332	0.70	0.4133	2.04	0.48	0.1691	0.18	334.9	351.24	461.0	4
161-I	88	0.3854	0.04655	2.14	0.3352	4.88	0.53	0.1985	0.22	293.3	293.5	2814	12
	318	0.1276	0.03949	2.37	0.2793	3.12	0.79	0.0899	0.34	249.7	250.1	1424	11
	131	0.2863	0.06527	2.10	0.5066	2.86	0.77	0.1554	0.13	407.7	416.1	2407	16
	1531	0.2227	0.09397	2.33	0.7718	2.81	0.85	0.1328	0.14	579.1	580.8	2136	17
161-II	179	0.2331	0.04868	2.21	0.3665	2.69	0.84	0.1263	0.16	306.5	317.1	2047	14
	79	0.4434	0.03499	2.17	0.2446	4.48	0.56	0.2191	0.14	221.7	222.1	2974	10
	191	0.2069	0.05548	2.08	0.3849	2.47	0.86	0.1179	0.14	348.2	330.6	1924	15
	94	0.3730	0.04457	2.13	0.3513	3.71	0.63	0.1961	0.18	281.1	305.6	2794	13

based on the concordia upper intercept with a regression line forced through origin and two multigrain U-Pb zircon analyses with small discordance (2.7 % and 3.5 %, respectively). A later attempt to date the Muntele Mare pluton, based on more analyses yielded a concordia lower intercept age of 278.4 ± 2.1 Ma (Pană et al. 2002b). The data variation was likely caused by Alpine thermotectonic events overprinting and the employed dating methods. For complex zircons, i.e. inherited zircons or affected by lead loss or recrystallization, only the in situ dating methods can offer accurate data. In order to get more reliable ages we performed some new U-Pb datings on zircon by isotope dilution and LA-ICP-MS methods.

For this study, we have used zircon grains extracted from two samples collected from the southern part (Sample 109: E 23°11′12″/N 46°25′53″) and from the central part (Sample 161: E 23°10′48″/N 46°37′40″) of the Muntele Mare granitoid pluton (Fig. 2).

In the two samples, the Muntele Mare granitoid contains plagioclase (15–20 % An), K-feldspar, quartz, biotite and muscovite as rock-forming minerals and sericite, epidote, zoisite, apatite, sometimes tourmaline, allanite and zircon as accessory minerals.

The plagioclase is clouded and filled with sericite. The epidote and zoisite also formed at the expense of plagioclase. We do not exclude the possibility that at least partially, sericite and epidote might have formed during the Alpine evolution of the Muntele Mare granite, as suggested by the Alpine reset of the U-Pb ages (Table 2). A sign in this sense is the secondary replacement of albite by microcline. Megablasts of microcline often appear (1–2 cm thick and 4–5 cm long). This megablastic microcline probably crystallized in the final stage of granite cooling from strongly differentiated fluids when the plagioclase was altered, too (Dimitrescu 1966). Zircon, allanite and apatite can be included in biotite. Biotite dominates over muscovite and is frequently chloritized, with sagenitic rutile included, again a possible Alpine alteration. A clear distinction between the mineral alterations due to the residual fluids accumulated during granite cooling and those due to the subsequent Alpine hydrothermal events is difficult to do. No mineralogical differences between the two samples are observable, and nothing pleads for a genetic difference between them.

In both samples the zircon grains show two populations. One population consists of thick, relatively short square prisms, with pyramidal tips; their colour is honey yellow without transparency and with rare inclusions. The other population is formed of elongated, thin, flattened prisms, completely transparent and colourless (Fig. 3).

Zircon U-Pb analytical methods

In order to extract zircon grains, 10 to 15 kg of fresh material have been subjected to the classical crushing, milling, sifting, gravitational separation, heavy liquids treatment and magnetic separation procedures. The best crystals were selected using a stereomicroscope. For conventional U-Pb isotopic dilution analyses, isotopic ratios were measured in the Laboratory of Radiogenic Isotope Geochemistry, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, using an IsoProbe-T thermal ionization mass spectrometer manufactured by the GV company and equipped with 9 F 97 Faraday cups, 1 Daly receiver and 7 ion counters. A single zircon grain was shortly washed in warm 7 N HNO_3 and warm 6 N HCl, respectively, prior to dissolution, to remove surface contamination after air abrasion. A mixed $^{205}Pb/^{235}U$-tracer solution was added to the grain. Dissolution was performed in PTFE (polytetrafluorethylene) vessels in a Parr acid digestion bomb (Parrish 1987) using the vapour digestion method. The bomb was placed in an oven at 210 °C for one week in 22 N HF and for one day in 6 N HCl to dissolve fluorides into chloride salts and avoid U-Pb fractionation. No separation of U and Pb was carried out by the ion exchange chromography method. Pb isotopic ratios were measured statically using combination of Daly receiver and Faraday cups. U isotopic ratios were measured in UO_2 + using the Daly receiver in dynamic mode. Total procedural blanks were < 10 pg for Pb and U. A factor of 1 ‰ per atomic mass unit for instrumental mass fractionation was applied to all Pb analyses, using NBS 981 as reference material.

Common Pb contribution remaining after correction for tracer and blank was corrected using the values of Stacey & Kramers (1975). U-Pb analytical data were evaluated with 2σ standard error using the Pbdat program (Ludwig 1988). Regression of the U-P data in concordia diagrams was done using the Isoplot program (Ludwig 2001). More details on analytical techniques are given in Chen et al. (2000).

For in situ dating the zircon grains were mounted in 25 mm epoxy and polished. After C-L imaging (Fig. 3), LA-ICP-MS measurements were conducted at LaserChron facility, Department of Geosciences, University of Arizona using an ISOPROBE MC-ICP-MS. The ISOPROBE MC-ICP-MS was equipped with a New Wave DUV193 nm Excimer laser-probe with a spot diameter of 35 and 50 micrometers, depending on grain size. Each grain analysis consisted of a single 20-second integration on isotope peaks without laser-firing to obtain on-peak background levels, 20 one-second integrations with the laser firing, followed finally by a 30-second purge with no laser firing in order to deliver out the remaining sample (e.g.

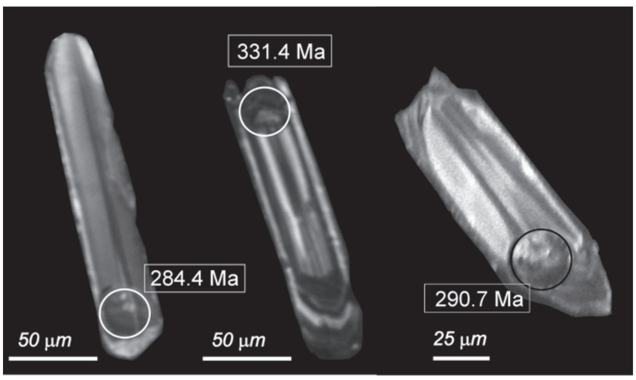

Fig. 3. CL Images of typical zircon grains from sample 161. Most of the grains exhibit elongate habit with weak or no zonation expressed as flat CL signal. Some of the grains show typical magmatic zonation. Circles on images emphasize the ablation pits. Ages in boxes represent $^{206}Pb/^{238}Pb$ apparent ages (see Table 3).

Table 3: Zircon U-Pb LA-ICP-MS Analytical data for sample 161.

Analysis	U (ppm)	$^{206}Pb/^{204}Pb$	U/Th	Isotope ratios $^{206}Pb^{*}/^{207}Pb^{*}$	± (%)	$^{207}Pb^{*}/^{235}U^{*}$	± (%)	$^{206}Pb^{*}/^{238}U$	± (%)	rho	Apparent ages (Ma) $^{206}Pb^{*}/^{238}U^{*}$	± (Ma)	$^{207}Pb^{*}/^{235}U$	± (Ma)	$^{206}Pb^{*}/^{207}Pb^{*}$	± (Ma)	Best age (Ma)	± (Ma)
161-1	711	25515	4.1	17.4895	5.2	0.3556	5.6	0.0451	2.2	0.39	284.4	6.1	309.0	14.9	498.4	113.9	284.4	6.1
161-3	1123	71300	5.5	18.8951	1.7	0.3850	2.3	0.0528	1.6	0.68	331.4	5.0	330.7	6.5	325.5	38.4	331.4	5.0
161-4	1137	87815	6.4	18.5652	1.6	0.4184	2.3	0.0563	1.7	0.73	353.3	5.8	354.9	7.0	365.4	36.1	353.3	5.8
161-5	210	16295	3.0	18.4970	4.9	0.3736	5.3	0.0501	2.2	0.41	315.3	6.7	322.3	14.8	373.6	110.0	315.3	6.7
161-6	345	19070	1.9	18.7350	2.5	0.3365	2.7	0.0457	1.0	0.37	288.2	2.8	294.5	6.9	344.8	56.8	288.2	2.8
161-7	1239	46275	4.8	18.4780	2.5	0.3442	3.8	0.0461	2.9	0.76	290.7	8.2	300.3	9.9	376.0	55.9	290.7	8.2
161-8	1333	76675	4.3	18.7886	2.1	0.3288	3.2	0.0448	2.4	0.76	282.5	6.7	288.6	8.1	338.3	47.4	282.5	6.7
161-9	525	23345	1.9	18.2833	4.1	0.3566	4.3	0.0473	1.4	0.32	297.8	4.0	309.7	11.6	399.7	92.2	297.8	4.0
161-10	1521	105400	8.6	19.1435	2.2	0.3329	2.5	0.0462	1.2	0.49	291.3	3.5	291.8	6.4	295.8	50.2	291.3	3.5
161-11	602	41435	2.4	18.8026	3.2	0.3332	3.3	0.0454	1.0	0.30	286.5	2.8	292.0	8.5	336.6	72.1	286.5	2.8
161-12	208	18040	3.9	19.0796	4.6	0.3464	5.2	0.0479	2.3	0.45	301.8	6.8	302.0	13.5	303.4	105.3	301.8	6.8
161-13	654	47030	4.6	18.9512	1.4	0.3260	2.8	0.0448	2.4	0.87	282.6	6.7	286.5	7.0	318.8	31.6	282.6	6.7
161-14	1610	88295	7.7	18.7197	5.1	0.3385	5.2	0.0460	1.2	0.23	289.7	3.4	296.1	13.3	346.6	114.3	289.7	3.4
161-15	266	24460	5.6	18.3689	4.0	0.3540	4.1	0.0472	1.0	0.24	297.1	2.9	307.7	11.0	389.3	90.1	297.1	2.9
161-16	390	35835	4.7	18.2597	3.5	0.4335	3.9	0.0574	1.7	0.42	359.8	5.8	365.7	12.0	402.6	79.3	359.8	5.8
161-17	1924	50290	11.6	18.2852	2.4	0.3534	4.2	0.0469	3.5	0.82	295.2	10.0	307.3	11.1	399.5	53.6	295.2	10.0
161-18	1415	96460	6.2	19.2822	3.7	0.3316	3.9	0.0464	1.4	0.35	292.2	3.9	290.8	9.9	279.3	84.3	292.2	3.9
161-19	937	54515	3.8	18.9932	2.2	0.3510	2.4	0.0484	1.0	0.41	304.4	3.0	305.5	6.4	313.7	50.5	304.4	3.0
161-20	636	45650	3.5	19.1379	1.8	0.3457	2.2	0.0480	1.2	0.56	302.1	3.5	301.5	5.6	296.4	40.9	302.1	3.5

Dickinson & Gehrels 2003). Hg contributions to ^{204}Pb were removed by taking on-peak backgrounds. Each excavation pit is ~20 μm in depth. The ablated material was carried via argon gas into the IsoProbe, equipped with a sufficiently wide flight tube allowing U, Th and Pb isotopes to be measured simultaneously. Measurements were done in static mode, using Faraday detectors for ^{238}U, ^{232}Th, ^{208}Pb, ^{207}Pb, ^{206}Pb, and an ion-counting channel for ^{204}Pb. Common Pb corrections were made using the measured ^{204}Pb and assuming initial Pb compositions from Stacey & Kramers (1975). Analyses of zircon standards of known isotopic and U-Pb composition were conducted in most cases after each set of five unknown measurements to correct for elemental isotopic fractionation. The samples were analysed in hard extraction mode, which yielded higher and more variable Pb/U fractionation. The $^{206}Pb^{*}/^{238}U$ values for the standards were corrected for an average of 15.3 % (±2.6 %) and 27.2 % (±3.0 %) fractionation (uncertainties at 2σ standard deviation of ~20 analyses), respectively. The U/Pb measurements, ratios, ages and errors are shown in the Table 3. Using the ISOPLOT program of Ludwig (2001), the data were plotted in weight averaged $^{206}Pb/^{238}U$ age diagrams, with data point error symbols at 1σ (Fig. 5). Analyses that have greater than 10 % uncertainty or are more than 30 % discordant or 5 % reverse discordant are excluded from further consideration.

Results

Isotope dilution data

A number of 17 single zircon grains (Fig. 4) separated from the two rock samples (8 and 9 grains, respectively) where analysed by the dilution method. The analytical data for the U-Pb ages are presented in Table 2. Both samples analysed by the isotope dilution method were divided in two populations based on grain size and shape (short and thick prisms and thin and long prisms, respectively). For sample #161, five zircons out of eight plot on the concordia curve at approximately 580 Ma, 410 Ma, 295 Ma, 250 Ma and 222 Ma. Of the remaining three analyses, one shows a small reverse discordance and the other two are located near the concordia (Fig. 4a). Out of them, the numbers 10, 13, 14 and 15 represent short and thick prisms. For sample #109, five zircon analyses out of nine are strongly discordant, three have relatively small discordances and one falls very close to the concordia line at approximately 318 Ma (Fig. 4b). From these grains the numbers 1, 3, 7, 8 and 9 represent short and thick prisms. All the data were plotted together in Fig. 4c. The relatively large age scattering offers the possibility to trace several regression lines and it is not easy to choose the most accurate one representing the crystallization age of the Muntele Mare granite. The LA-ICP-MS results were used in order to solve this problem (see further), as a suggestion for tracing the most reliable regression line. As a starting point we have considered the concordant ID-TIMS (isotope dilution-thermal ionization mass spectrometry) analysis # 12, the closest one to the LA-ICP-MS age (Table 2). Using this analysis

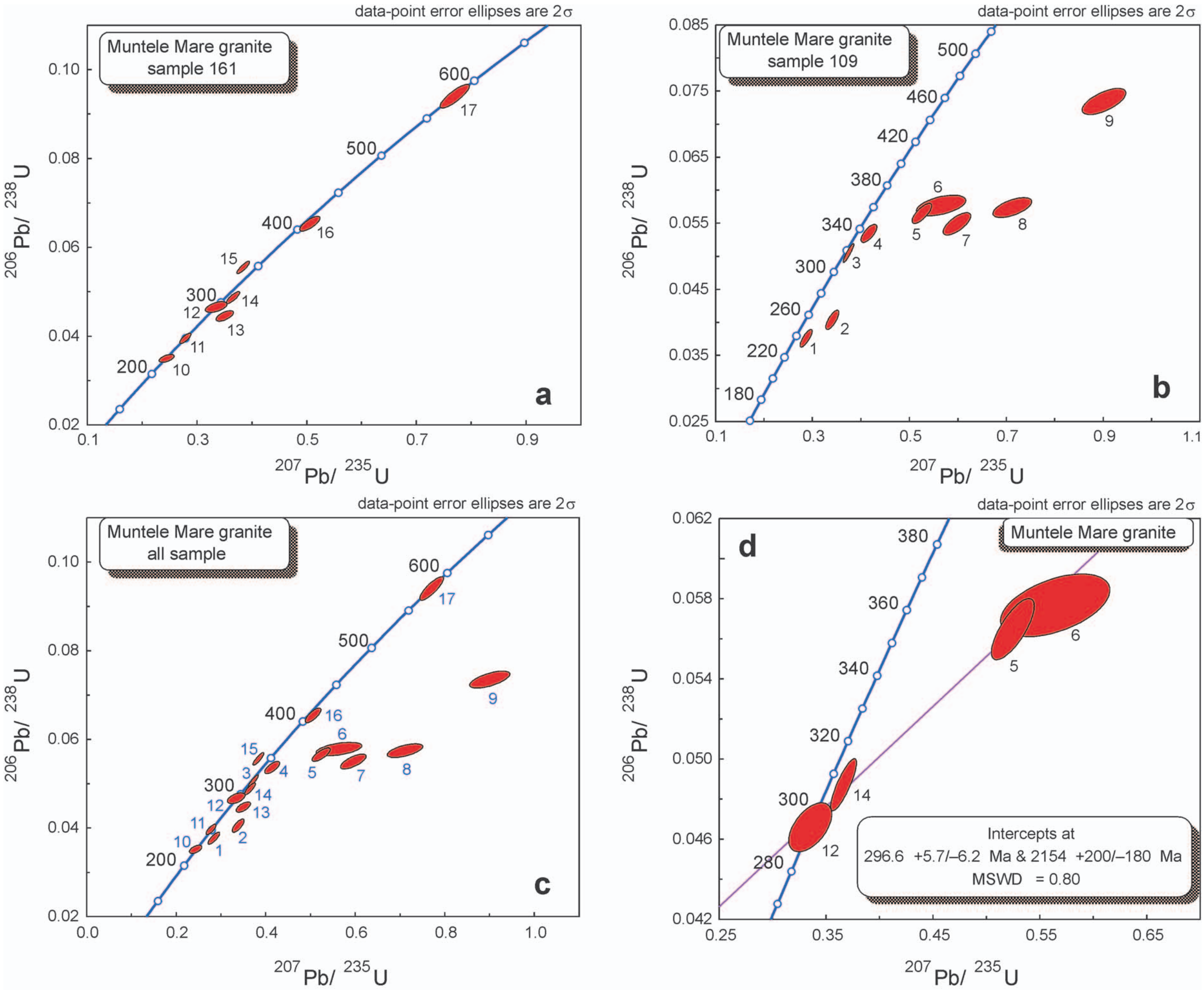

Fig. 4. Concordia projections of U-Pb isotopic ratios for: **a** — sample 161, and **b** — sample 109. **c** — Concordia projections of all isotopic ratios corresponding to the samples 161 and 109. **d** — Concordia/discordia solution through points #5, 6, 12 and 14. Numbers shown on diagrams represents analyses identifiers (see Table 2).

and the ID-TIMS analyses no. 5, 6 and 14 we got a lower intercept age of 296.6+5.7/–6.2 Ma with a robust MSWD of 0.80. This age is within the error limits of the LA-ICP-MS weighted mean age, interpreted as the crystallization age. Fig. 4c indicates a complex zircon crystallization history with many inherited grains and partially or totally reset crystals, characteristic of anatectic melts.

LA-ICP-MS data

The LA-ICP-MS analytical data presented in Table 3 represent nineteen point analyses obtained from nineteen different zircon grains of sample 161. All analyses are plotted in Fig. 5a. Thirteen ^{206}Pb/^{238}U apparent ages between 282.5 ± 6.7 Ma and 301.8 ± 6.8 Ma yielded a weighted mean age of 290.9 ± 3.0 Ma and a concordia age of 291.1 ± 1.1 Ma (Fig. 5b). These ages correspond to early Permian and are interpreted as crystallization ages of the Muntele Mare granitoid parental magma. Six other analyses yielded ages ranging between 302.1 and 359.8 Ma. The in situ data facilitated the interpretation of the ID-TIMS data and confirmed the age of ca. 295 Ma proposed by Pană (1998) for the emplacement of the Muntele Mare granitoid.

Discussion

Muntele Mare crystallization age. The new age data presented in this study indicate that the magma of anatectic source was generated, emplaced and cooled in the Someş terrane basement during the 297–291 Ma interval. We interpret the Muntele Mare pluton as a late Variscan intrusion in a post-collisional setting, following the Variscan subduction and magmatic arc development on the upper Someş plate at ca. 350 Ma (e.g. Balintoni et al. 2007). The age spectra between 302.1 and 359.8 Ma suggests early Variscan inherited zircon more or less reset in the Muntele Mare magma.

Similar granitoid intrusions in the European Variscides. In the larger picture of the Carpathian-Balkan region, late

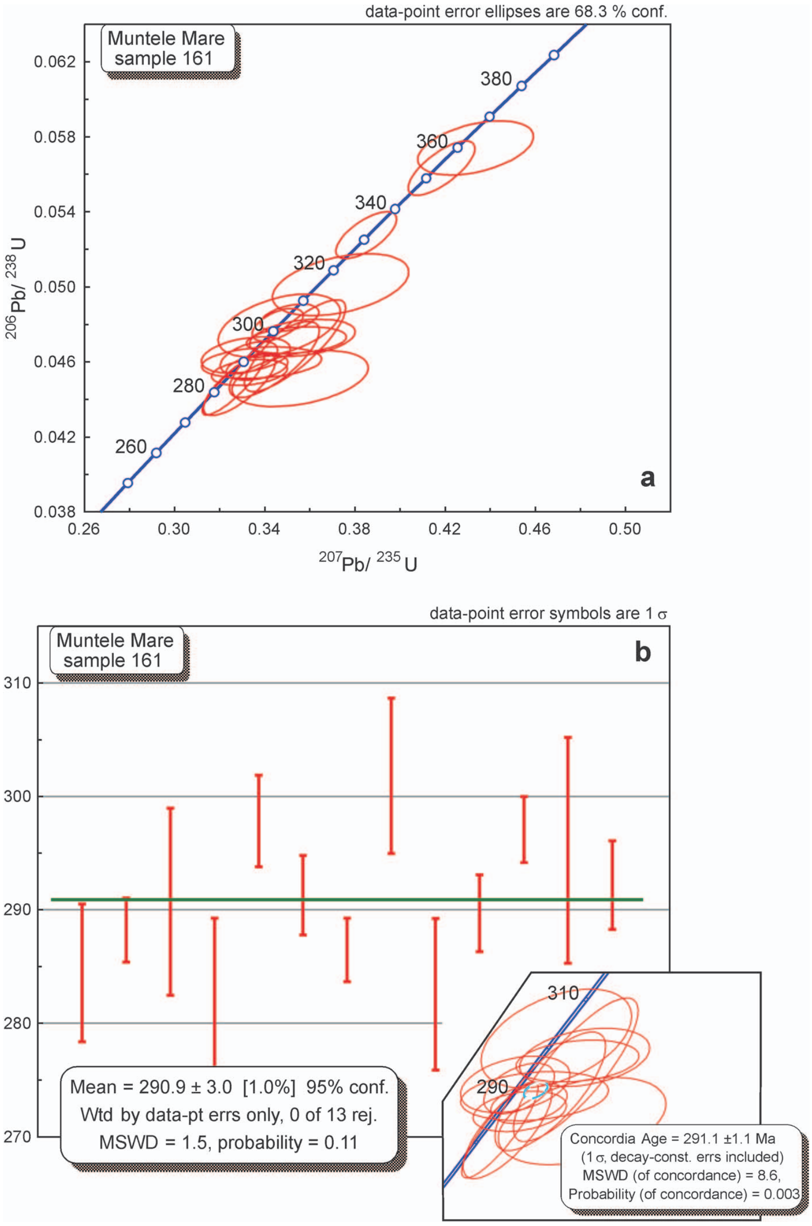

Fig. 5. Concordia plot of LA-ICP-MS zircon U-Pb data (**a**), and weighted average plot of relevant $^{206}Pb/^{238}U$ apparent ages for sample 161 (**b**) (see Table 3). Inset: Concordia plot of respective U/Pb isotope ratios.

Within the Alpine realm, Schaltegger & Corfu (1992), von Quadt et al. (1994), Eichhorn et al. (2000) reported U-Pb zircon ages around 300 Ma from igneous rocks. In the Veľká Fatra Mountains many samples yielded zircon ages ~310 Ma (Poller et al. 2005). Carrigan et al. (2005) considered nearly all these intrusions as post-collisional and generated after the main compresional and high grade metamorphic events of the Variscan orogeny. For the Sicheviţa-Poneasca pluton in Southern Carpathians, Duchèsne et al. (2007) proposed thermal relaxation and heat transfer along a lithospheric discontinuity, following a linear lithospheric delamination connected with a shear zone.

In our opinion, the Muntele Mare anatectic pluton represents a late Variscan intrusion generated due to lithospheric delamination of the Someş upper plate and mantle rise after continental collision cessation and concomitant to withdrawal and exhumation of the lower plate (Baia de Arieş terrane).

Post Variscan overprinting. The tectonic significance of our data in the 250 to 220 Ma range is still unclear. Based on well-constrained emplacement ages of diorite (ca. 267 Ma) and granite (ca. 264 Ma) plutons in the Păiuşeni metamorphic sequence (Table 1), Pană (1998) suggested a Permian rift-like setting as a precursor to the widespread Triassic extension. Our Middle to Early Triassic data could record zircon resetting triggered by thermal and hydrothermal events related to continued extensions that finally created the Alpine rift systems. This interpretation is consistent with the previously reported K-Ar and Rb/Sr data. Thus, Anton (2000) recorded Rb/Sr ages of 233 and 243 Ma from muscovite and of 267 Ma from K-feldspar samples collected from the Muntele Mare pluton. The same author obtained a Rb/Sr whole-rock isochron of 244.2 ± 16 Ma from pegmatite samples hosted by the Someş sequence, but geochemically unrelated to the Muntele Mare intrusion. In the Carpathian region, records of the Triassic extensions are known in the Eastern Carpathians, where the Ditrău Alkaline Massif was emplaced at 229.1 Ma (e.g. Pană et al. 2000), and where at least some of the mafic rocks interpreted as "ophiolites" are associated with Triassic limestone (e.g. Hoeck et al. 2009). A Triassic rift has also been identified in the North Dobrogea orogen (e.g. Savu 1980). The age resetting was favoured by the relatively high U content of the Muntele Mare granitoid zircons (i.e. 883 ppm average).

Inherited and discordant ages. The 580 Ma age is an inherited Neoproterozoic age, well represented in the detrital zircons from the metasedimentary rocks of the Someş se-

Variscan intrusions are also known in the Southern Carpathians (i.e. Sicheviţa-Poniasca pluton, 311 ± 2 Ma; Duchèsne et al. 2007), in Serbia (e.g. Brnjica, Neresnica, Beljanica, southern extensions of the Sicheviţa-Poniasca pluton and Gornjani pluton, 304 Ma; Kräutner & Krstić 2003) and in Bulgaria (e.g. San Nikola — 311.9 ± 4.1 Ma; Petrohan — 304.6 ± 4.0 Ma; Smilovene — 304.1 ± 5.5 Ma; Hisara — 303.5 ± 3.3 Ma; Koprivshtitza — 312.0 ± 5.4 Ma and Strelcha — 289.5 ± 7.8 Ma, plutons, respectively; Carrigan et al. 2005). Such late Variscan granitoid intrusions are also mentioned from other European Variscan massifs like the Harz Massif (Baumann et al. 1991) and Iberian Massif (Dias et al. 1998; Bea et al. 1999; Fernándes-Suárez et al. 2000; Azevedo et al. 2003).

quence of maximum mid-Cambrian age (Balintoni et al. 2009). The 411 Ma age may record an inherited grain that partially lost its radiogenic Pb in the younger magma. The group of discordant ages visible in Fig. 4 probably represents mixed ages in zoned zircon.

Conclusions

The S-type Muntele Mare granitoid pluton is late Variscan in age. It may be related to late Variscan delaminations as proposed elsewhere by Stampfli & Mosar (1999). The anatectic origin of the Muntele Mare granite resulted in a complex structure of its zircons, with much inheritance from the previous hosts. The emplacement of the Muntele Mare pluton in the Apuseni Mountains was contemporaneous with a group of young late Variscan plutons identified throughout the Balkan Peninsula.

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