

RAPID COMMUNICATION

An Early Ordovician tonalitic–granodioritic belt along the Schistose-Greywacke Domain of the Central Iberian Zone (Iberian Massif, Variscan Belt)

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Abstract

The Zarza la Mayor and Zarza de Montánchez tonalites and Arroyo de la Luz granodiorite are part of a tonalitic–granodioritic belt located along the Schistose-Greywacke Domain of the Central Iberian Zone. These intrusions are also part of the Central Extremadura Batholith, a set of plutons ranging from tonalite to leucogranite that have been considered a prime example of Variscan syn-kinematic plutonism. New LA-ICP-MS and CA-ID-TIMS U–Pb dating reveals that the Zarza la Mayor tonalite–granodiorite is an Early Ordovician intrusion. The LA-ICP-MS data show that there is an absence of inherited cores, despite some complex internal zoning with obvious resorption features in some of the zircon crystals. Dating of monazite and zircon by CA-ID-TIMS provides a concordant age of 478.1 ± 0.8 Ma. This age coincides with electron microprobe analysis (EMPA) monazite chemical ages for the Zarza de Montánchez (482 ± 10 Ma) and Arroyo de la Luz (470 ± 15 Ma) intrusions. These new data indicate the presence of an Early Ordovician belt of calc-alkaline tonalite–granodiorite in the Schistose-Greywacke Domain – the Beira Baixa–Central Extremadura tonalite–granodiorite belt – which resembles a continental magmatic arc. This belt is contemporaneous with the Ollo de Sapo magmatic event further north in the Central Iberian Zone.

Keywords: Early Ordovician, tonalite–granodiorite, U–Pb geochronology, Iberian Massif, LA-ICP-MS, ID-TIMS, EMPA.

1. Introduction

Early Ordovician magmatism is widespread in many parts of the southern Variscides (e.g. von Raumer *et al.* 2002; Mattauer, 2004 and reference therein). It is particularly well known in the northern Ollo de Sapo Domain of the

Central Iberian Zone, where it has been extensively dated (e.g. Valverde-Vaquero & Dunning, 2000; Montero *et al.* 2009; Díez Montes, Martínez Catalán & Mulas, 2010). Until recently, there was little evidence for magmatism of this age in the southern Schistose-Greywacke Domain of the Central Iberian Zone (Díez Balda, Vegas & González Lodeiro, 1990). New U–Pb ages across the border in Portugal (Antunes *et al.* 2009; Neiva *et al.* 2009) indicated that some tonalite–granodiorite-dominated igneous bodies are not Variscan syn-kinematic intrusions, but Early Ordovician in age. These bodies belong to a tonalite–granodiorite suite, along the Beira Baixa–Zarza la Mayor sector of the Schistose-Greywacke Domain, which had already been recognized by Portugal Ferreira (1982). The correlation of the Oledo pluton (Antunes *et al.* 2009) with the Zarza la Mayor tonalite in Spain prompted our interest in testing the Variscan age of the undated Zarza la Mayor tonalite.

Our study was initially focused on the Zarza la Mayor tonalite (Corretgé-Castañón, 1969; García de Figuerola, Corretgé & Suárez, 1971). This is a composite body located in the northwestern end of the Central Extremadura Batholith of Castro (1986). It belongs to the group of early syn-kinematic calc-alkaline granitoids with tonalitic affinities in the batholith (Castro, 1986; Fernández & Castro, 1999). Combined U–Pb laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) and chemical abrasion isotope dilution thermal ionization mass spectrometry (CA-ID-TIMS) dating revealed an Early Ordovician age and the absence of inherited zircons. In light of these results, we carried out U–Th–Pb electron microprobe analysis (EMPA) chemical dating of monazite from two separate plutons, Arroyo de la Luz granodiorite and Zarza de Montánchez tonalite, to test the extension of the Ordovician tonalitic–granodioritic suite. Our data show that these granodiorites/tonalites of the Central Extremadura Batholith (Castro, 1986) are Early Ordovician bodies contemporaneous with the Ollo de Sapo magmatic event further north, instead of early syn-kinematic Variscan intrusions (Fernández & Castro, 1999). The broad distribution of this tonalite–granodiorite

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belt reveals that magmatism of Early Ordovician age was widespread throughout the Central Iberian Zone.

These epizonal plutons contain abundant mafic enclaves and gabbroic end-members, and they preserve their contact aureoles and many primary igneous features. The fact that these plutons have escaped major Variscan reworking makes them quite unique among the Early Ordovician intrusions in the southern Variscides, most of which are transformed into orthogneisses (see Mattauer, 2004). These features make them key in testing the different tectonic models invoked to explain this magmatic event.

2. Geological setting

The Zarza la Mayor pluton is situated in the Schistose-Greywacke Domain of the Central Iberian Zone (Diez Balda, Vegas & González Lodeiro, 1990) in the western end of the province of Cáceres, near the Portuguese border. It belongs to a group of partially deformed tonalite-dominated intrusions, which also include the Arroyo de la Luz, Zarza de Montánchez and Santa Cruz intrusions. These tonalites occur close to the large late-kinematic bodies of the Central Extremadura Batholith, such as the Cabeza de Araya granite (Fig. 1; Castro, 1986). The tonalites have a classic major-element calc-alkaline geochemical signature (Corretgé, Bea & Suárez, 1985) and juvenile Sr and Nd isotopic signatures (Castro *et al.* 1999). They intruded the Upper Precambrian rocks of the Schistose-Greywacke Group producing hornfels contact metamorphism. In the case of the Zarza la Mayor tonalite the contact aureole is 0.5 to 1.5 km wide and reaches hornblende-hornfels conditions (> 2 kb; García de Figuerola, Corretgé & Suárez, 1971; Bascones, Martín Herrero & Corretgé, 1987). The Arroyo de la Luz and Zarza de Montánchez tonalites belong to the group of early-deformed intrusions of the Central Extremadura Batholith of Castro (1986); whereas the Zarza la Mayor tonalite, owing to its partial overprint, has been considered as an intermediate type between the early, deformed and the late, undeformed plutons.

Across the border in Portugal, the Zarza la Mayor tonalite was correlated by Portugal Ferreira (1982) with the tonalites/granodiorites of Oledo, Zebreiro and Fundão, which are spatially associated with a lineament of mafic dyke swarms. These mafic dykes have a calc-alkaline petrographic character. Similar dykes are also found associated with the Zarza la Mayor intrusion (García de Figuerola, Corretgé & Suárez, 1971; García de Figuerola, Corretgé & Bea, 1974) and the Arroyo de la Luz granodiorite (Bascones, Martín Herrero & Corretgé, 1987).

2.a. Field relationships and petrography

The Zarza la Mayor pluton consists of three main facies: biotite tonalite, coarse-grained muscovite \pm biotite granite and aplitic leucogranite (Corretgé, 1971). The muscovite \pm biotite granite is an elongated body, approximately 3 to 4 km wide and 10 km long, located along the southern border of the tonalite. It belongs to group B of the alkali-feldspar granites of Castro (1986). It is locally overprinted by a mylonitic foliation producing gneissic and cataclastic textures. The aplitic leucogranite intrudes the tonalite forming a ring-dyke complex with dykes feeding sills on the cupola of the stock (Rubio-Ordóñez, Corretgé & Cuesta, 2007). Biotite-rich tonalite, quartz diorite to granodiorite constitutes the largest unit of the pluton. It belongs to group A of the quartz dioritic granitoids of Castro (1986). The Zarza la Mayor tonalite has a medium-grained hypidiomorphic texture with

quartz, plagioclase and biotite as the main minerals and K-feldspar, apatite, oxides, zircon, titanite, anatase and rutile as minor and accessory minerals. The plagioclase crystals are anhedral to subhedral and locally partially oriented defining magmatic flow structures. They show a strong zonation with cores with An₅₀₋₆₀ and rims with An₆₋₁₀, which is evidence of strong changes in magma composition. Despite the lack of penetrative foliation in most of the intrusion, the quartz shows evidence of tectonic overprint such as undulose extinction, formation of subgrains and recrystallization. Other local facies of the intrusion are granodiorite with K-feldspar forming an accumulative texture, K-feldspar-rich syenite formed by the hydrothermal alteration of monzonite-monzodiorite, minor amphibole-bearing dioritic porphyry and hornblende (García de Figuerola, Corretgé & Suárez, 1971; Rubio, 1982; Bascones, Martín Herrero & Corretgé, 1987). In addition, the tonalite contains mafic dykes, as well as microgranular enclaves and country rock xenoliths (Fig. 2).

The Zarza de Montánchez intrusion is very similar to the Zarza la Mayor tonalite. It is dominated by quartz diorite and biotite granodiorite with subordinate muscovite leucogranite and aplitic granite (Gil Serrano, Pérez Rojas & Pineda Velasco, 1982). The Arroyo de la Luz intrusion is slightly more felsic with prevailing biotite granite to granodiorite (Bascones, Martín Herrero & Corretgé, 1987). These two bodies also contain abundant enclaves of country rock xenoliths and mafic enclaves.

2.b. Previous geochronology

Prior to the current work, geochronological data for the tonalites of the Central Extremadura Batholith consisted of Rb–Sr whole-rock isochron ages for rocks from several plutons that gave an age of 326 Ma (Castro *et al.* 1999). In the rest of the Central Extremadura Batholith, geochronological data are scarce. The neighbouring Cabeza de Araya granite has a reported Rb–Sr age of 303 ± 7 Ma (Bea, Montero & Zinger, 2003) coincident with a monazite U–Th–Pb EMP chemical age of 302 ± 7 Ma (Carracedo *et al.* 2005). Across the border in Portugal, the Oledo intrusion is very similar to Zarza la Mayor. It also includes tonalite/granodiorite and a muscovite \pm biotite granite. It has been recently dated by U–Pb ID-TIMS with ages of 480.5 ± 1 Ma (zircon) and 478.3 ± 1.1 Ma (monazite) for the biotite granodiorite; 479 ± 4 Ma for the biotite + muscovite granodiorite; and the 479 ± 4 Ma for the muscovite + biotite granite (Antunes *et al.* 2009). The Oledo pluton is intruded by the 310 ± 1 Ma Castelo Branco granite (U–Pb ID-TIMS; Antunes *et al.* 2008), which is a late-kinematic Variscan intrusion similar to Cabeza de Araya.

3. Geochronology

Our initial purpose was to obtain the intrusion age and the age of the inherited zircon of the Zarza la Mayor tonalite. For this reason, we combined the advantage of the spatial resolution of the LA-ICP-MS technique with the high precision of the U–Pb ID-TIMS. In light of the U–Pb results, monazite EMPA dating using polished petrographic thin-sections was used, as a reconnaissance tool, to check if the Zarza de Montánchez and the Arroyo de la Luz intrusions belonged to the same age group. The U–Pb LA-ICP-MS dating was carried out at the University of Frankfurt am Main (Germany), the U–Pb ID-TIMS at IGME laboratories (Tres Cantos, Spain) and the monazite EMPA dating at the University of Oviedo (Spain). Details of the analytical techniques are given in the Appendix.

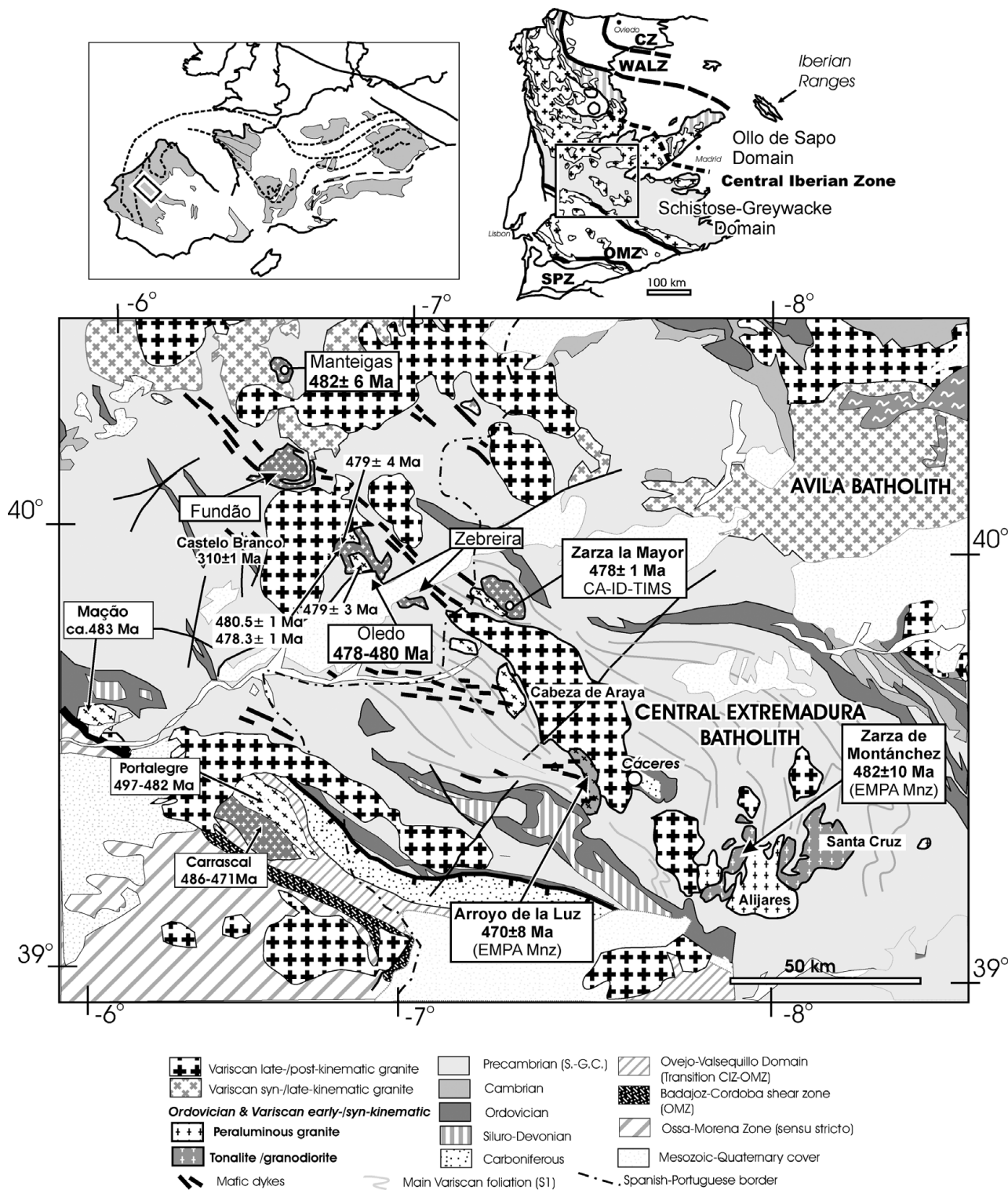


Figure 1. Simplified geological map of the Central Extremadura portion of the Schistose-Greywacke Domain of the Central Iberian Zone showing the location of the different plutons of the Beira Baixa–Central Extremadura tonalite belt (after IGME-LNEG 1:1 000 000 scale map, unpub. data). U–Pb ages, see references in text. Mafic dyke swarms in the Central Iberian Zone after Portugal Ferreira (1982) and García de Figuerola, Corretgé & Bea (1974). Variscan schistosity and elements of the Central Extremadura Batholith after Castro (1986). CZ – Cantabrian Zone, WALZ – West Asturian Leonese Zone, CIZ – Central Iberian Zone, OMZ – Ossa Morena Zone, SPZ – South Portuguese Zone, S-G.C. – Schistose-Greywacke Complex.

3.a. U–Pb LA-ICP-MS and ID-TIMS: Zarza la Mayor tonalite

The zircons from the tonalite and the leucogranitic facies of the Zarza la Mayor intrusion were studied following the method of Pupin & Turco (1972). Zircon is more abundant

in the tonalitic facies, but both rocks have zircon with similar typologies, dominated by {110} prismatic faces and {211} pyramidal forms (Rubio-Ordóñez, Corretgé & Cuesta, 2007). The zircons from the leucogranite fall into the S6 and Q2 morphologies, while those from the tonalite are mainly S1–L1 and Q1 types (Fig. 3). In general, the length/width

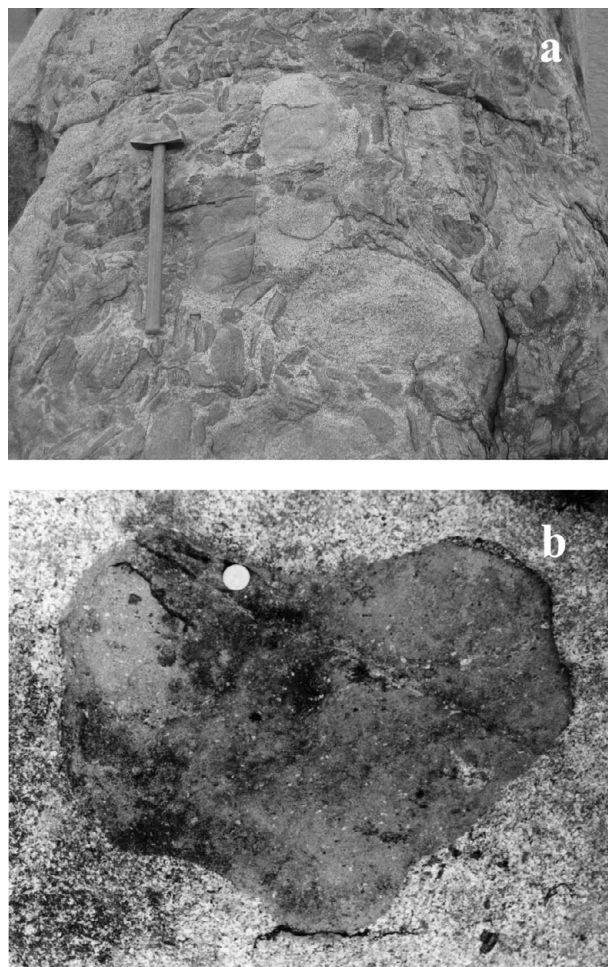


Figure 2. Zarza la Mayor tonalite: (a) enclaves of metasediments from the country rock Schistose-Greywacke complex and blobs of tonalite; (b) undeformed mafic microgranular enclave.

ratio ranges from 3:1 to 5:1. The back-scattered electron (BSE) images show crystals either with complex cores and resorption features, indicating separate stages of zircon

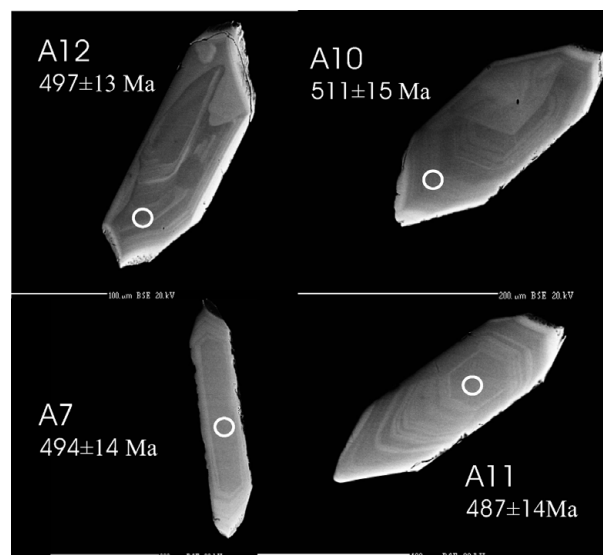


Figure 3. Back-scattered electron images of the zircons dated by LA-ICP-MS. Top, zircons with complex cores and resorption features; bottom, zircons with a simple concentric zoning.

growth and corrosion, or well-defined concentric growth zoning (Fig. 3).

3.a.1. U–Pb LA-ICP-MS: Zarza la Mayor tonalite

Nineteen crystals were dated by U–Pb LA-ICP-MS, including zircons with complex cores as well as zircons with concentric zoning. Four points were rejected, the remaining 15 analyses providing ^{206}Pb – ^{238}U ages between 475 and 512 (± 10 – 20) Ma (Table 1) and a ‘concordia age’ of 495.8 ± 5.6 Ma (MSWD of 2.4), which is in agreement with the weighted average age of 497 ± 6 Ma (MSWD of 1.8) derived from the ^{206}Pb – ^{238}U ages (Fig. 4).

3.a.2. U–Pb ID-TIMS: Zarza la Mayor tonalite

Six fractions were analysed by U–Pb ID-TIMS, two of monazite and four of zircon (Table 2). Each zircon fraction

Table 1. U–Pb LA-ICP-MS data, Zarza la Mayor tonalite

Sample	Isotopic ratios*						Ages (Ma)								
	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{235}\text{U}$	2 σ %	$^{206}\text{Pb}/^{238}\text{U}$	2 σ %	<i>Rho</i>	$^{207}\text{Pb}/^{206}\text{Pb}$	2 σ %	^{207}Pb – ^{235}U	2 σ	^{206}Pb – ^{238}U	2 σ	^{207}Pb – ^{206}Pb	2 σ	<i>Conc</i> %
A27 <i>rz.r.</i>	2970	0.6058	5.2	0.07747	4.7	0.91	0.0567	2.2	481	20	481	22	481	48	100
A28 <i>cz.c.</i>	6720	0.6172	5.4	0.07730	4.8	0.87	0.0579	2.6	488	21	480	22	526	58	91
A29 <i>cz.c.</i>	8179	0.6204	5.1	0.07779	4.8	0.93	0.0578	1.9	490	20	483	22	524	42	92
A30 <i>cz.r.</i>	13908	0.6071	4.9	0.07879	4.8	0.96	0.0559	1.3	482	19	489	22	448	30	109
A31 <i>cz.c.</i>	4565	0.6048	5.1	0.07645	4.7	0.93	0.0574	1.8	480	20	475	22	506	40	94
A32 <i>cz.r.</i>	13240	0.6109	5.1	0.07764	4.7	0.94	0.0571	1.8	484	20	482	22	494	39	98
A1 <i>rz.c.</i>	3019	0.6658	3.5	0.08187	2.8	0.79	0.0590	2.1	518	14	507	14	567	47	90
A2 <i>core</i>	2945	0.6537	3.6	0.08210	2.7	0.75	0.0578	2.4	511	15	509	13	520	53	98
A3 <i>cz.r.</i>	8095	0.6259	3.7	0.08025	2.8	0.76	0.0566	2.4	494	15	498	14	475	54	105
A4 <i>cz.c.</i>	8720	0.6187	3.6	0.08001	2.8	0.79	0.0561	2.2	489	14	496	13	456	49	109
A7 <i>cz.c.</i>	10329	0.6261	3.5	0.08062	2.8	0.82	0.0563	2.0	494	14	500	14	465	44	107
A9 <i>rz.c.</i>	12503	0.6195	4.9	0.08013	2.8	0.57	0.0561	4.1	490	19	497	13	455	90	109
A10 <i>rz.c.</i>	8514	0.6535	3.8	0.08270	2.9	0.78	0.0573	2.4	511	15	512	14	504	52	102
A11 <i>cz.c.</i>	8756	0.6152	3.7	0.07884	2.8	0.78	0.0566	2.3	487	14	489	13	476	51	103
A12 <i>rz.</i>	16803	0.6308	3.3	0.08122	2.8	0.85	0.0563	1.7	497	13	503	13	465	38	108

Isotopic ratios corrected for background signal, common Pb, laser induced elemental fractionation, instrumental mass discrimination and time-dependant elemental fractionation of Pb/Th and Pb/U. *Sample, zircon morphology*: *cz.* – concentric zone; *rz.* – resorbed zone; *c.* – core; *r.* – rim.

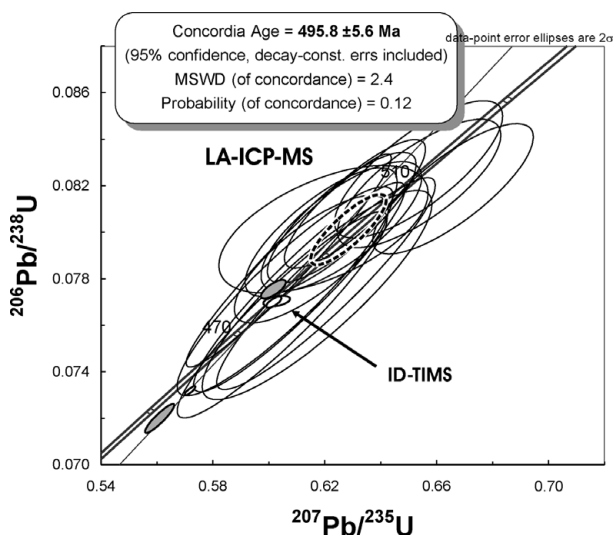


Figure 4. U–Pb LA-ICP-MS data, U–Pb concordia diagram of the LA-ICP-MS (large open ellipses) and the ID-TIMS data (small white filled ellipses – zircon; grey ellipses – monazite).

comprised 8 to 15 euhedral zircon prisms with a length/width ratio of 3:1 to 5:1, such as those in Figure 3. Two fractions, a monazite and a zircon, are discordant. The six fractions define a discordia line (MSWD 3.6) with an upper intercept of 476 ± 10 Ma and a lower intercept at 7 ± 380 Ma (Fig. 4). The upper intercept is best constrained by three concordant zircon fractions and a monazite fraction with a slight reverse discordia, but with an identical $^{207}\text{Pb}-^{235}\text{U}$ age (Fig. 5). The three concordant zircon fractions cluster at 478 Ma and provide a ‘concordia age’ of 478.13 ± 0.82 Ma (MSWD 0.25). We interpret this zircon crystallization age as the age of intrusion.

3.b. Monazite EMPA dating: Arroyo de la Luz and Zarza de Montánchez tonalites

Monazites from the Arroyo de la Luz granodiorite (sample 14445) and the Zarza de Montánchez granodiorite (sample 14449) were dated using the U–Th–Pb EMPA chemical dating method (Table 3). In the case of the Arroyo de la Luz sample, a total of 29 points on 12 monazite crystals were made. These monazites are Ce-rich, with a small xenotime component (X_{YPO_4} 0.1–0.7), plotting close to the brabantite compositional vector (Fig. 6). They show a high concentration of light rare earth elements (LREEs), common

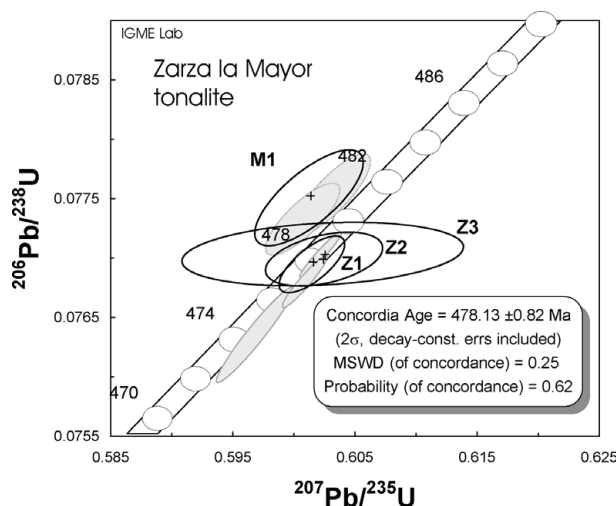


Figure 5. U–Pb concordia diagram with the concordant ID-TIMS data; crosses – centroids of the error ellipses. For comparison, grey ellipses are data from the Oledo granodiorite (Portugal; sample H1 of Antunes *et al.* 2009); M – monazite, Z – zircon.

in this kind of monazite (Förster, 1998). The individual ages range from 441 to 504 (± 78 –146) Ma, show a normal distribution, with a weighted average of 470 ± 15 Ma (MSWD 0.34) and a Th/Pb–U/Pb age of 470 ± 8 Ma (Fig. 7).

In the Zarza de Montánchez granodiorite, 21 points were analysed on 11 monazites and give ages from 439 to 549 (± 50 –250) Ma. These monazites are Ce-rich, as well, with a low Y content (X_{YPO_4} 0.1–0.9). They plot on the brabantite vector, with a larger spread of compositions than those from Arroyo de la Luz (Fig. 6). The age population displays a normal distribution with a calculated weighted average age of 482 ± 10 Ma (MSWD 0.38) and a Th/Pb–U/Pb age of 482 ± 10 Ma (Fig. 7).

4. Discussion

The age of 478 ± 1 Ma of the Zarza la Mayor granodiorite matches within error the ages of the Oledo pluton (Antunes *et al.* 2009) and the Manteigas granodiorite (Neiva *et al.* 2009) located along strike in Portugal, and the Mação-Penhascoso granite (*c.* 483 Ma, U–Pb zircon ID-TIMS; Romão *et al.* 2010) near the boundary with the Ossa-Morena Zone (Fig. 1). Sample H-1 of Antunes *et al.* (2009) is

Table 2. U–Pb ID-TIMS geochronological data, Zarza la Mayor tonalite

Fractions	Weight (mg)	U (ppm)	Pb (ppm)	Pb (pg)	Isotopic ratios						Ages (Ma)			corr. coef.		
					$^{206}\text{Pb}/^{204}\text{Pb}^*$	$^{208}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	% err	$^{207}\text{Pb}/^{235}\text{U}$	% err	$^{207}\text{Pb}/^{206}\text{Pb}$	% err	$^{206}\text{Pb}-^{207}\text{Pb}/^{238}\text{U}$		$^{207}\text{Pb}-^{206}\text{Pb}/^{235}\text{U}$	$^{207}\text{Pb}-^{206}\text{Pb}/^{206}\text{Pb}$
Z1 (15)	0.090	200.8	15.3	18	3155.6	0.078	0.076938	0.26	0.60136	0.37	0.05669	0.26	478	478	479	0.72
Z2 (8)	0.040	232.3	17.5	5	3299.9	0.062	0.077025	0.29	0.60227	1.57	0.05671	1.54	478	479	480	0.22
Z3 (10)	0.050	127.5	12.9	106	195.4	0.079	0.076981	0.24	0.60236	0.66	0.05675	0.60	478	479	482	0.41
Z4 (20)	0.103	220.4	15.7	19	3506.2	0.061	0.073100	0.23	0.57123	0.27	0.05668	0.15	455	459	479	0.84
M1 (6)	0.082	240.7	130.1	50	1356.4	6.940	0.077502	0.43	0.60113	0.61	0.05625	0.41	481	478	462	0.74
M2 (9)	0.090	842.1	321.8	81	3268.8	5.064	0.071890	0.71	0.56022	0.78	0.05651	0.31	448	452	473	0.92

Z – small (< 100 μm) euhedral zircon prisms 1:3 to 1:5 width/length ratio. All chemically abraded (CA; Mattison, 2005). Weight estimated before CA. M – clear monazite, 60 to 80 μm. Number of grains in each fraction is given within brackets. Pb (pg) – total common Pb blank. * Measured ratio corrected for blank and fractionation. Atomic ratios corrected for fractionation (0.11 ± 0.02 % AMU Pb; 0.10 ± 0.02 % AMU, U), spike ($^{208}\text{Pb}-^{235}\text{U}$), laboratory blanks (6 pg Pb; 0.1 pg U) and initial common Pb after Stacey & Kramers (1975). Errors are at the 2-sigma level. Data reduced with PbMacDat (Isachsen, Coleman & Schmitz, 2007; www.earth-time.org).

Table 3. EMPA analyses of monazite

Crystal/ analysis	P ₂ O ₅	SiO ₂	CaO	Y ₂ O ₃	La ₂ O ₃	Ce ₂ O ₃	Pr ₂ O ₃	Nd ₂ O ₃	Sm ₂ O ₃	Gd ₂ O ₃	Tb ₂ O ₃	Dy ₂ O ₃	Ho ₂ O ₃	Er ₂ O ₃	Yb ₂ O ₃	PbO	ThO ₂	UO ₂	Total	Age (Ma)	Error (2σ)
14445: Arroyo de la Luz Granodiorite																					
M01/02	29.43	0.32	1.14	2.42	12.62	26.34	2.97	12.96	2.08	1.59	0.13	0.61	0.03	0.15	0.00	0.148	6.650	0.175	99.76	481	110
M01/03	27.56	1.36	0.30	0.19	13.98	29.74	3.25	13.22	1.50	0.65	0.01	0.10	0.00	0.01	0.00	0.170	7.461	0.139	99.62	504	100
M01/04	29.83	0.11	1.30	2.75	10.58	25.23	3.10	13.90	2.89	2.10	0.19	0.78	0.04	0.15	0.00	0.152	6.981	0.316	100.38	446	101
M02/05	29.18	0.41	0.72	1.47	11.59	27.51	3.30	14.48	2.99	2.05	0.17	0.58	0.01	0.08	0.00	0.127	5.891	0.162	100.69	464	124
M02/06	29.79	0.07	1.30	2.84	11.07	24.40	3.11	13.75	2.72	2.05	0.19	0.79	0.05	0.16	0.00	0.162	7.024	0.425	99.90	453	95
M04/12	29.57	0.18	1.12	2.33	12.36	26.05	3.08	13.43	2.12	1.57	0.14	0.56	0.03	0.14	0.00	0.166	7.022	0.111	99.97	446	95
M04/13	29.47	0.21	1.25	3.36	10.79	24.54	3.04	13.31	2.61	2.05	0.19	0.81	0.06	0.20	0.00	0.158	7.764	0.175	99.98	484	85
M04/15	28.82	0.32	1.57	2.46	10.00	25.46	3.16	13.58	3.01	2.02	0.19	0.73	0.03	0.14	0.00	0.194	8.216	0.375	100.27	504	78
M05/18	29.18	0.49	1.06	2.91	10.91	24.83	3.08	13.46	2.55	2.02	0.19	0.75	0.04	0.17	0.00	0.145	8.171	0.049	100.01	447	83
M05/20	27.82	0.99	0.98	1.24	10.05	24.77	3.39	14.75	3.21	1.92	0.14	0.48	0.00	0.07	0.00	0.164	9.888	0.187	100.05	453	86
M06/23	29.18	0.37	1.06	3.01	11.29	25.04	3.06	13.55	2.50	1.93	0.18	0.75	0.05	0.17	0.00	0.178	7.743	0.092	100.16	481	119
M06/24	29.09	0.40	1.19	2.92	10.87	24.62	3.05	13.42	2.53	1.94	0.17	0.74	0.03	0.17	0.00	0.176	8.746	0.130	100.19	494	146
M07/30	29.32	0.27	1.05	2.51	12.13	25.79	3.11	13.74	2.18	1.66	0.14	0.62	0.01	0.14	0.00	0.169	7.156	0.034	100.01	444	104
M07/31	29.54	0.23	0.97	2.05	12.65	26.36	3.17	13.99	2.05	1.46	0.11	0.51	0.04	0.11	0.00	0.135	6.534	0.018	99.93	459	114
M08/33	29.18	0.36	1.03	1.36	13.55	27.80	3.08	13.43	1.78	1.13	0.08	0.33	0.03	0.08	0.00	0.132	7.324	0.001	100.65	467	108
M08/34	29.63	0.32	0.79	1.42	13.20	28.24	3.18	14.25	2.04	1.32	0.12	0.37	0.03	0.07	0.00	0.129	5.784	0.011	100.91	473	111
M09/37	29.69	0.19	1.09	2.48	12.28	25.81	3.10	13.72	2.24	1.64	0.15	0.62	0.03	0.13	0.00	0.135	6.413	0.156	99.85	478	82
M09/38	29.35	0.20	1.11	2.62	11.71	26.03	3.07	14.14	2.30	1.72	0.13	0.61	0.03	0.14	0.00	0.131	7.025	0.046	100.36	441	81
M09/39	29.36	0.27	1.16	2.50	11.63	25.92	3.07	13.95	2.30	1.71	0.13	0.62	0.04	0.14	0.00	0.144	6.969	0.092	99.99	498	83
M10/42	29.26	0.19	1.13	2.75	11.66	26.12	3.12	14.13	2.33	1.80	0.15	0.57	0.05	0.15	0.00	0.142	6.915	0.048	100.52	496	124
M11/43	29.54	0.18	1.11	2.69	11.68	26.10	3.10	14.06	2.35	1.79	0.14	0.67	0.04	0.15	0.00	0.166	6.834	0.082	100.66	461	108
M11/44	29.32	0.15	1.36	2.96	10.85	25.56	3.05	13.43	2.60	1.91	0.17	0.75	0.05	0.16	0.00	0.190	7.766	0.202	100.48	449	129
M11/46	29.10	0.14	1.53	3.12	10.58	24.30	2.96	13.24	2.54	1.95	0.20	0.85	0.06	0.19	0.00	0.182	8.687	0.325	99.94	471	127
M1147	29.09	0.15	1.47	3.19	10.59	24.44	2.94	13.33	2.54	1.96	0.19	0.85	0.05	0.18	0.00	0.204	8.596	0.317	100.08	459	125
M12/48	29.63	0.19	1.15	1.89	12.97	27.29	3.10	13.99	1.95	1.32	0.10	0.43	0.03	0.11	0.00	0.134	6.112	0.068	100.46	473	91
M12/49	29.44	0.24	1.05	1.29	13.47	27.83	3.10	13.55	1.71	1.12	0.08	0.32	0.00	0.08	0.00	0.140	7.099	0.010	100.52	445	88
M12/50	29.90	0.18	1.01	1.41	14.17	28.40	3.12	13.23	1.69	1.07	0.08	0.33	0.00	0.07	0.00	0.116	5.908	0.047	100.72	459	85
M12/53	29.56	0.20	1.12	1.44	13.52	26.86	3.15	13.49	1.76	1.14	0.08	0.34	0.04	0.09	0.00	0.152	6.886	0.033	99.85	457	80
M13/57	28.98	0.24	1.27	3.03	11.08	25.19	2.98	13.18	2.46	1.90	0.17	0.76	0.07	0.17	0.00	0.174	8.434	0.062	100.15	444	94

14449: Zarza de Montánchez Tonalite																					
M01/05	30.03	0.28	0.97	1.79	10.98	24.75	3.20	15.02	3.11	2.56	0.19	0.67	0.00	0.05	0.00	0.146	6.045	0.42	100.20	439	178
M02/07	30.01	0.04	0.91	3.81	11.91	25.24	3.11	13.84	2.49	1.95	0.18	0.89	0.07	0.25	0.02	0.131	4.541	0.49	99.88	455	250
M02/08	29.99	0.20	1.00	1.81	11.98	26.31	3.10	13.96	2.60	1.94	0.15	0.63	0.02	0.10	0.00	0.163	5.737	0.575	100.23	459	155
M02/10	29.98	0.10	1.01	1.46	11.88	26.39	3.25	14.47	2.60	1.64	0.11	0.40	0.00	0.06	0.00	0.164	5.859	0.578	99.94	459	71
M03/12	30.48	0.16	1.00	2.10	11.46	25.10	3.15	14.69	2.89	2.32	0.19	0.67	0.02	0.08	0.00	0.132	5.624	0.278	100.31	463	109
M03/15	30.11	0.20	1.10	1.24	12.09	26.05	3.25	14.23	2.49	1.63	0.10	0.38	0.00	0.05	0.00	0.156	5.52	0.536	99.10	468	95
M04/16	30.21	0.09	0.96	1.32	12.60	26.30	3.22	14.30	2.57	1.98	0.17	0.58	0.00	0.03	0.00	0.133	4.866	0.551	99.86	469	93
M04/19	30.87	0.07	1.13	1.66	12.21	25.09	3.19	14.26	2.45	1.85	0.14	0.57	0.02	0.05	0.00	0.157	5.605	0.661	99.97	474	123
M05/23	30.23	0.08	0.88	1.68	12.44	26.68	3.24	14.54	2.57	1.86	0.14	0.46	0.01	0.07	0.00	0.122	4.77	0.394	100.14	475	132
M06/27	29.90	0.08	1.27	0.94	12.55	26.34	3.15	13.86	2.43	1.53	0.08	0.28	0.00	0.04	0.00	0.193	6.524	0.807	99.97	480	114
M07/31	29.77	0.05	1.13	3.02	11.73	25.30	3.05	13.71	2.66	2.36	0.24	0.96	0.03	0.10	0.00	0.166	5.152	0.921	100.32	493	126
M07/32	30.02	0.03	1.11	1.79	12.33	26.47	3.18	13.91	2.53	1.89	0.14	0.49	0.00	0.07	0.00	0.16	5.506	0.68	100.31	494	91
M07/33	29.90	0.01	1.17	3.88	11.32	24.41	2.95	13.31	2.72	2.50	0.26	1.12	0.05	0.18	0.00	0.193	4.931	1.295	100.22	495	88
M08/37	30.22	0.00	1.15	2.86	12.62	26.23	3.01	12.99	2.27	1.77	0.17	0.77	0.05	0.16	0.00	0.16	4.931	0.809	100.15	495	108
M08/38	30.52	0.00	1.21	2.75	11.99	25.65	3.04	13.36	2.37	1.88	0.19	0.79	0.05	0.16	0.00	0.172	4.879	1.15	100.17	496	105
M08/39	30.18	0.03	1.36	2.47	11.89	25.40	2.93	13.03	2.35	1.92	0.15	0.76	0.04	0.15	0.00	0.208	5.731	1.384	99.95	496	57
M09/45	29.83	0.14	0.95	1.84	12.56	25.82	3.09	13.87	2.52	2.01	0.16	0.63	0.00	0.10	0.00	0.147	6.464	0.257	100.40	507	120
M10/50	30.29	0.02	1.10	3.12	12.48	25.68	3.08	13.36	2.36	1.84	0.18	0.83	0.06	0.19	0.00	0.144	4.996	0.624	100.34	509	85
M10/51	30.29	0.00	1.15	2.99	12.35	25.44	3.05	13.33	2.36	1.85	0.18	0.78	0.05	0.19	0.00	0.177	4.939	1.202	100.33	512	108
M10/54	30.40	0.04	1.04	3.03	12.32	26.07	3.12	13.58	2.57	1.87	0.20	0.82	0.05	0.20	0.02	0.135	4.468	0.607	100.54	537	93
M11/61	29.51	0.14	1.49	1.91	10.48	24.47	3.14	13.90	2.74	1.94	0.17	0.62	0.01	0.12	0.00	0.223	8.171	1.006	100.02	549	113

Calculated ages based on the method of Cocherie & Albarede (2001). Errors are at the 2-sigma level.

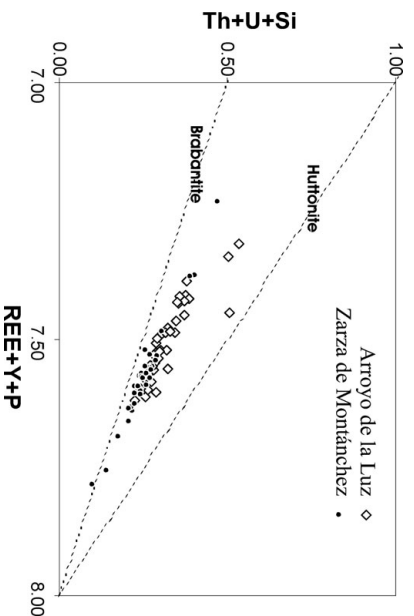


Figure 6. Monazite composition, Arroyo de la Luz and Zarza de Montánchez tonalites. Plot of the formula proportions (Th+U+Si) v. (REE+Y+P) calculated on the basis of 16 oxygen atoms. The arrows represent the brochantite (ThCaUPb(P₂O₇)₂) and huttonite (ThSiO₄) substitution vectors.

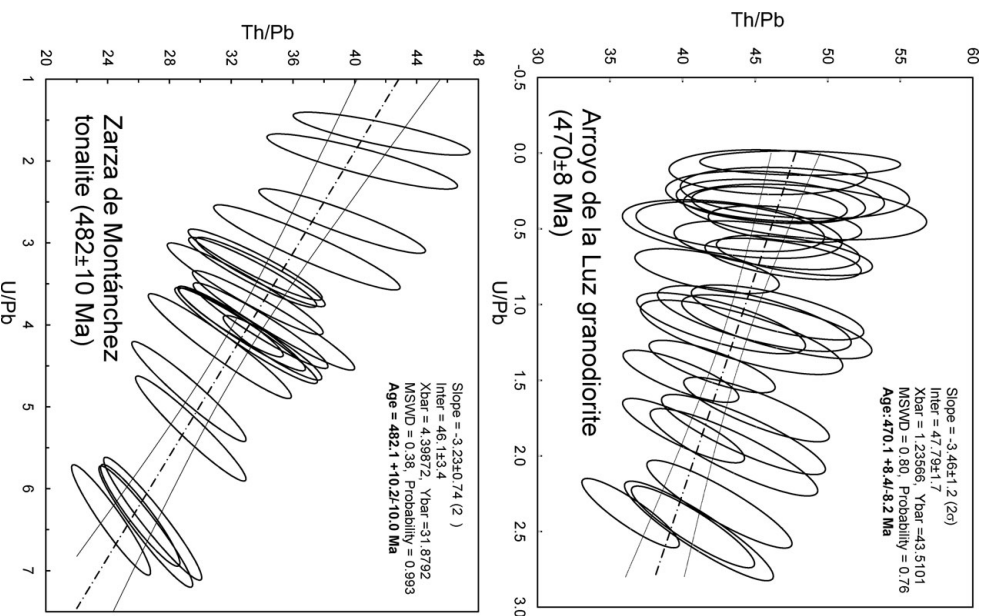


Figure 7. U–Th–Pb monazite EMPA chemical ages, Th/Pb–U/Pb diagrams: (a) Arroyo de la Luz; (b) Zarza de Montánchez.

plotted in the concordia diagram (Fig. 5) to show the high degree of overlap of the zircon and monazite TIMS data, including the slightly reverse discordant monazite. North of the Oledo pluton, Neiva *et al.* (2009) dated the Mantegas granodiorite with a U–Pb sensitive high-resolution ion microprobe (SHRIMP) zircon age of 481.8 ± 5.9 Ma. Like the Zarza la Mayor granodiorite, this biotite granodiorite also

contains zircons, without inheritance, with complex cores and concentric zoning of Early Ordovician age. The EMPA U–Th–Pb monazite chemical ages of 470–482 Ma for the Arroyo de la Luz and the Zarza de Montánchez granodiorites overlap within error with the U–Pb ages, confirming that these bodies belong to the same tonalite–granodiorite suite.

4.a. The Beira Baixa–Central Extremadura tonalite–granodiorite belt

This suite has a calc-alkaline affinity similar to the I-type granites of Chappell & White (1992), with juvenile Sr and Nd values (Castro *et al.* 1999; Antunes *et al.* 2009; Neiva *et al.* 2009). Portugal Ferreira (1982) recognized the unique character of this calc-alkaline suite, which he considered Variscan early/syn-kinematic (inter D1–D2). He grouped the tonalite–granodiorite bodies and the associated mafic dykes in what he defined as the Beira Baixa–Zarza la Mayor lineament. Since the tonalite–granodiorite belt extends for 250 km from the Beira Baixa region of Portugal to Central Extremadura (Spain), we propose to name it the Beira Baixa–Central Extremadura tonalite–granodiorite belt. This belt might also include other undated tonalites/granodiorites such as those of Fundão and Zebreira (Fig. 1; see Portugal Ferreira, 1982) or the Alijares and Santa Cruz plutons, which belong to the early-deformed granitoids of the Central Extremadura Batholith (Fig. 1; Castro, 1986).

4.b. Distribution of the Early Ordovician magmatism in the Central Iberian Zone

The age of intrusion of the Beira Baixa–Central Extremadura tonalite belt broadly coincides with the ages of the nearby calc-alkaline Carrascal granodiorite and the Portalegre granite, and the felsic volcanic rocks of the Urrea Formation in the transition zone between the Central Iberian and Ossa-Morena zones, the Obejo-Valsequillo Domain (Fig. 1; Lancelot & Allegret, 1982; Cordani *et al.* 2006; Solá *et al.* 2008). The presence of dioritic–gabbroic members in the Carrascal granodiorite with juvenile Sr and Nd numbers similar to those of the Oledo granodiorite is particularly remarkable (Solá *et al.* 2008; Antunes *et al.* 2009). This would suggest that this part of the Obejo-Valsequillo Domain was already in close proximity, if not already attached, to the Schistose-Greywacke Domain of the Central Iberian Zone.

The tonalitic–granodioritic event in the Schistose-Greywacke Domain is also contemporaneous with the Early Ordovician magmatic event along the northern Ollo de Sapo Domain of the Central Iberian Zone (U–Pb ages; Lancelot, Allegret & de Leon, 1985; Gebauer, Martínez García & Hepburn, 1993; Fernández-Suárez *et al.* 1999; Valverde-Vaquero & Dunning, 2000; Bea *et al.* 2006, 2007; Montero *et al.* 2007, 2009; Díez Montes, Martínez Catalán & Mulas, 2010). The broad extension of the tonalite–granodiorite belt (Fig. 1) reveals that magmatism of Early Ordovician age was widespread throughout the Central Iberian Zone. The Central Iberian Zone has strong Palaeozoic lithostratigraphic and palaeontological affinities with the West Asturian Leonese and the Cantabrian Zone in the north of the Iberian Massif (e.g. Julivert & Martínez, 1987), indicating that these three zones formed a single terrane since Early Cambrian time: the Iberian Autochthonous terrane (Quesada, 1991). The Early Ordovician magmatism in this terrane appears to form two major parallel belts running along the Central Iberian Zone: the Beira Baixa–Central Extremadura and the Ollo de Sapo magmatic belts (Fig. 8). The deep Cambro-Ordovician sedimentary trough of the West Asturian Leonese Zone (e.g. Aramburu *et al.* 1992) separates the Central Iberian Zone from the Cantabrian Zone, where coeval Early Ordovician

magmatism is also present as local discrete felsic ash beds (477.47 ± 0.93 Ma U–Pb zircon; Gutiérrez-Alonso *et al.* 2007) and within-plate alkaline basalts (Gallastegui *et al.* 1992). Such magmatism is also found east of the Central Iberian Zone in the Iberian Chains, where two separate Tremadocian–Arenig rhyolitic and dacitic volcanic events are followed by an Arenig within-plate alkaline basaltic flow (Álvaro *et al.* 2008).

4.c. Tectonic interpretation

Most characteristic of the Early Ordovician magmatism in the Central Iberian Zone is the Ollo de Sapo volcanism and the associated granite intrusions. These felsic volcanic rocks are ignimbrites with coarse feldspar crystals and volcanic quartz (see Schäfer, 1969; Díez-Montes, Martínez Catalán & Mulas, 2010). Fernández *et al.* (2008) have noted the striking geochemical and petrographic analogies between the Ollo de Sapo Formation and the ferrosilicic Cambro-Ordovician felsic volcanics of the eastern Puna eruptive belt in the Famatinian orogen of northern Argentina, and proposed the formation of the Ollo de Sapo volcanism in a continental back-arc environment. The outward position of the Beira Baixa–Central Extremadura calc-alkaline belt of I-type granitoids with respect to the Ollo de Sapo magmatic belt further strengthens the analogies with the Famatinian orogen, as it resembles the position of the calc-alkaline western Puna magmatic belt (Pankhurst *et al.* 1998; Pankhurst, Rapela & Fanning, 2000). This belt, formed by I-type granite, a calc-alkaline trondhjemite–tonalite–granodiorite (TTG) suite and S-type peraluminous granite, represents the continental magmatic arc bounding the eastern Puna back-arc. Owing to their geochemistry and the local association with Cu-porphyry mineralization, Portugal Ferreira (1982) interpreted the calc-alkaline tonalites and granodiorites of the Beira Baixa–Central Extremadura belt as a magmatic arc. This might suggest that the Beira Baixa–Central Extremadura belt represents an outward continental magmatic arc bounding the Ollo de Sapo continental back-arc. The presence of within-plate alkaline basalts in the Cantabrian Zone and the Iberian Chains indicate the injection of plume-like mantle-derived melts in a more internal position of the Iberian Autochthonous terrane, during or shortly after this felsic magmatic event (Fig. 8). Therefore, the proposed tectonic scenario needs to be taken with caution, since continental rifting has also been considered as a possible explanation of the Ollo de Sapo magmatic event (e.g. Fernández-Suárez *et al.* 2000; Bea *et al.* 2007).

So far the only detailed petrogenetic study in this tonalite–granodiorite belt is that of Antunes *et al.* (2009), which has demonstrated the coexistence of coeval calc-alkaline, I-type hybrid melts and S-type peraluminous melts. We would like to point out that the mafic igneous bodies in the Early Ordovician Beira Baixa–Central Extremadura tonalite–granodiorite belt still preserve their primary mineralogy and igneous features, making them a prime target for future geochemical studies. Such studies will be key to understanding the nature of the mantle component, and thus crucial for testing the different tectonic models proposed to explain Early Ordovician magmatism in the Central Iberian Zone (e.g. Valverde-Vaquero & Dunning, 2000; Bea *et al.* 2007; Fernández *et al.* 2008).

5. Conclusions

The U–Pb CA-ID-TIMS dating of the Zarza la Mayor tonalite provides an intrusion age of 478 ± 1 Ma, coeval within error with the 480–478 Ma Oledo granodiorite across the border

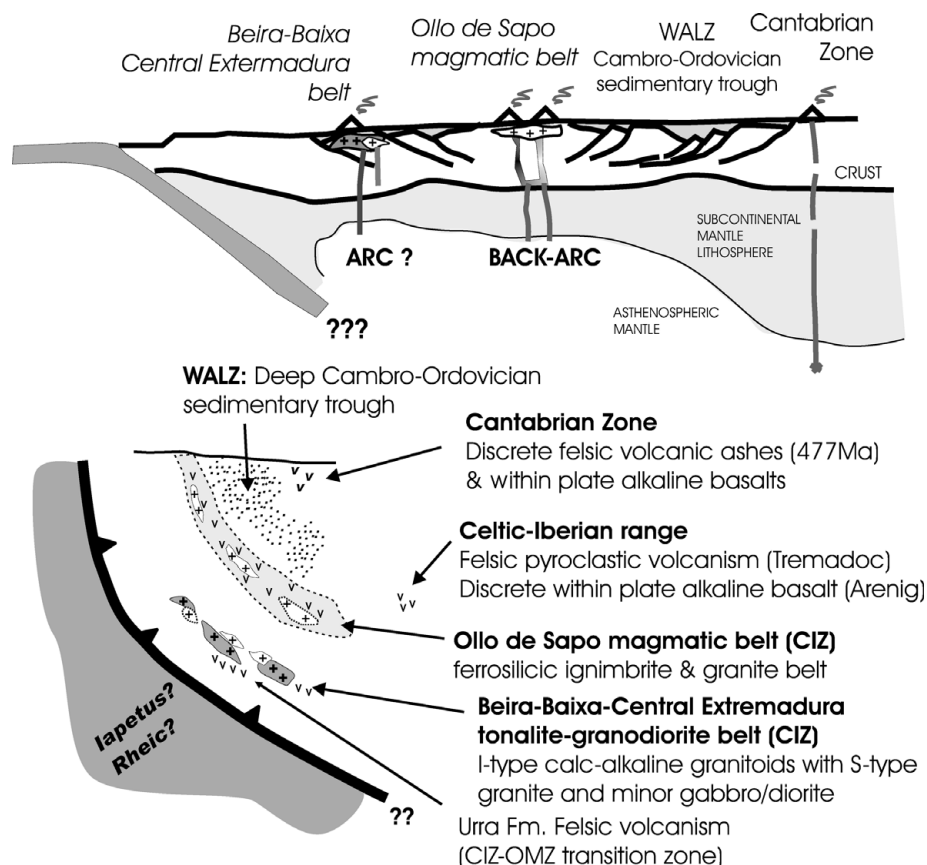


Figure 8. Tectonic model and distribution of the Early Ordovician magmatism in the Central Iberian Zone and neighbouring areas of the Iberian Autochthonous Terrane.

in Portugal (Antunes *et al.* 2009). The LA-ICP-MS dating of individual crystals indicate that these zircons, including some with complex internal features, do not contain Precambrian inherited cores. This feature is also observed in the zircons from the SHRIMP-dated 482 ± 6 Ma Manteigas granodiorite in Portugal (Neiva *et al.* 2009).

The monazite U–Th–Pb EMPA chemical ages from the Arroyo de la Luz granodiorite (470 ± 15 Ma) and the Zarza de Montánchez tonalite (482 ± 10 Ma) coincide with the U–Pb age of Zarza la Mayor, and demonstrate that a significant number of the deformed tonalites of the Central Extremadura Batholith are Early Ordovician in age.

The Zarza la Mayor and Zarza de Montánchez tonalites, and the Arroyo de la Luz granodiorite with the Oledo and Manteigas granodiorites in Portugal, define the Early Ordovician Beira Baixa–Central Extremadura tonalite–granodiorite belt. This belt extends for 250 km along the Schistose-Greywacke Domain of the Central Iberian Zone, and it is contemporaneous with the Ollo de Sapo magmatic event in the Central Iberian Zone.

The Beira Baixa–Central Extremadura tonalite–granodiorite belt is tentatively interpreted as a continental volcanic arc. This interpretation has to be taken with caution, and needs to be tested with future petrogenetic studies of the mafic end-members of the suite.

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Appendix. Analytical methods

Rock pulverization and mineral separation using a Wilfley table, heavy liquids and a Frantz isodynamic separator were done at the University of Oviedo (Spain). The selected zircon and monazite fractions for U–Pb LA-ICP-MS and ID-TIMS work were hand-picked under a microscope at IGME.

U–Pb LA-ICP-MS method

The zircon mount for LA-ICP-MS was made using double-sided tape, a plexiglass ring and Buehler Epoxycure resin. The grain mount was polished and back-scattered electron images were taken with the Cameca SX100 electron microprobe of the University of Oviedo of each zircon crystal to assess the internal morphology before carrying out the laser work.

Zircon was analysed for U, Th and Pb isotopes by LA-ICP-MS techniques at the Institute of Geosciences, Johann Wolfgang Goethe-University Frankfurt, using a Thermo-Finnigan Element II sector field ICP-MS coupled to a New Wave UP213 ultraviolet laser system. Laser spot-sizes varied from 20 to 40 μm for zircon and were placed based on the scanning electron microscope and cathodoluminescence (CL) images of the individual grains. The typical depth of the ablation crater was $\sim 20 \mu\text{m}$. Data were acquired in peak-jumping mode over 900 mass scans during 20 second background measurement followed by 32 second sample ablation. A teardrop-shaped, low volume laser cell was used to enable the precise detection of heterogeneous material (e.g.

inclusion or different growth zones) during time-resolved data acquisition (see Janousek *et al.* 2006). The signal was tuned for maximum sensitivity for Pb and U while keeping oxide production well below 1%. A common-Pb correction based on the interference- and background-corrected ^{204}Pb signal and a model Pb composition (Stacey & Kramers, 1975) was carried out if necessary. The necessity of the correction is judged on whether the corrected $^{207}\text{Pb}/^{206}\text{Pb}$ lies outside of the internal errors of the measured ratios. Raw data were corrected for background signal, common Pb, laser-induced elemental fractionation, instrumental mass discrimination and time-dependant elemental fractionation of Pb/Th and Pb/U using an Excel[®] spreadsheet program. Laser-induced elemental fractionation and instrumental mass discrimination were corrected by normalization to the reference zircon GJ-1 (Jackson *et al.* 2004), which was analysed during the analytical session under exactly the same conditions as the samples. Prior to this normalization, the change of elemental fractionation (e.g. the Pb/Th and Pb/U ratios as a function of ablation time and thus crater depth) was corrected for each set of isotope ratios (*c.* 40) collected during the time of each single spot analysis. The correction was done by applying a linear regression through all measured ratios, excluding some outliers ($> \pm 2$ s.e.), and using the intercept with the *y*-axis as the initial ratio. Datasets obtained under optimal analytical conditions required that less than 10% of the raw data were treated as outliers. Exceptions arise when the laser penetrates domains with distinct Pb/U ratios (Janousek *et al.* 2006), the epoxy resin, mineral inclusions in zircons and/or zircon zones affected by Pb-loss either due to metamictization or along cracks. All these effects, however, can be detected by careful monitoring of the time-resolved signal. Commonly they are obvious from abrupt changes in the signal strength of the measured isotopes and/or the isotope ratios. Nevertheless, small age differences (< 3 s.e. of the individual analysis) between distinct zircon growth domains or different grains cannot be resolved. The total offset of the measured drift-corrected $^{206}\text{Pb}/^{238}\text{U}$ ratio from the ‘true’ ID-TIMS value of the analysed GJ-1 grain was about 3–4%. Reported uncertainties (2σ) were propagated by quadratic addition of the external reproducibility (2 s.d.) obtained from the standard zircon GJ-1 ($n = 20$; 1.3% and 1.2% for the $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{206}\text{Pb}/^{238}\text{U}$, respectively) during the analytical session and the within-run precision of each analysis (2 s.e.). Concordia diagrams (2σ error ellipses) and concordia ages with 2 sigma uncertainty were produced using Isoplot/Ex 2.49 (Ludwig, 2001). For further details on analytical protocol and data processing for the U–Th–Pb method see Gerdes & Zeh (2006).

U–Pb ID-TIMS method

The zircon fractions processed for ID-TIMS at IGME were pre-treated with the chemical abrasion method (Mattinson, 2005). Zircon annealing was carried out at 900 °C for 48 hours and the chemical attack was done in Parrish-type minibombs inside Parr bombs at 180 °C for 12 hours. Final zircon dissolution was achieved after placing the bomb at 240 °C for 72 hours (Parrish, 1987). The procedure for extraction and purification of Pb and U is a scaled-down version of that of Krogh (1973). A ^{208}Pb – ^{235}U spike was used to obtain the U/Pb ratios by isotope dilution (ID); this is the spike used in Valverde-Vaquero *et al.* (2000). For a control, the 91500 (Wiedenbeck *et al.* 1995) and R33 reference zircons (Black *et al.* 2004) were dated and provided ‘concordia’ ages of 1065 ± 2.3 Ma and 419.7 ± 1.9 Ma. The spike was also checked against the 500 Ma artificial solution of the Earthtime Network (www.earth-time.org), and

recalibrated using the Earthtime gravimetric solutions. The purified Pb and U of the ID fraction were collected together. The Pb and U from the IC and ID fractions were loaded in outgassed single rhenium filaments with a mixture of SiGel and H₃PO₄ (Gerstenberger & Haase, 1997). Total procedural blanks for zircon are below 5 pg Pb and 0.2 pg U. Isotopic ratios were measured with a Triton TIMS multi-collector mass spectrometer equipped with a MassCon axial secondary electron multiplier (SEM) ion counter. The instrument is set up to do measurements both in static and peak-jumping mode using the SEM. For static measurements, the ²⁰⁴Pb was measured with the calibrated SEM (92–93 % yield calibration). The Pb measurements were done in the 1300–1460 °C range, and U was measured at 1420–1500 °C. For further details on mass spectrometry see Valverde-Vaquero (2009). The linearity of the SEM and deadtime correction were checked using the U500 and NBS982 standards, with a similar method to that in Arden & Gale (1974) and Richter *et al.* (2001). These standards were also used to estimate an instrumental fractionation of 0.10 ± 0.02 % AMU for U and 0.11 ± 0.02 % AMU for Pb. Data reduction was done using the PbMacDat spreadsheet (Isachsen, Coleman & Schmitz, 2007) and checked with PBDAT (Ludwig, 1991). All isotopic ratios are corrected for mass fractionation, blank and initial common Pb, the latter after the model of Stacey & Kramers (1975). Ages and uncertainties were calculated with

the decay constants of Jaffey *et al.* (1971), and are reported at the 2σ level; ‘concordia ages’ were calculated with Isoplot (see Ludwig, 1999).

Monazite U–Th–Pb EMPA chemical dating method

The EMPA chemical dating of monazite (Montel *et al.* 1996; Suzuki & Adachi, 1991) was done with the Cameca SX100 electron microprobe at the University of Oviedo (Spain) using polished grain mounts. The samples were coated with graphite. The analyses followed the protocols of Scherrer *et al.* (2000) for U, Th, Pb and rare earth elements (REEs), in addition to Si, P, Y, Al and Ca. The chemical age calculations were done with the program provided with the Cameca SX100 geochronology option, which is based on Williams, Jercinovic & Terry (1999) and Montel *et al.* (1996), and with the procedure of Cocherie & Albarede (2001). The error on each age determination is reported at the 2-sigma level. To assure quality control we have used our own monazite standard with a U–Pb ID-TIMS age of 1083 ± 1 Ma (Valverde-Vaquero *et al.* 2005) and we have dated the Jefferson Mountain (370 ± 15 Ma EMP age) and the Iveland (951 ± 33 Ma EMP age) monazite standards, for further details see Fernández González *et al.* (2009). Cumulative plots and weighted average ages were done with Isoplot 3.0 (Ludwig, 1999).