Geol. Mag. **149** (5), 2012, pp. 927–939. © Cambridge University Press 2012
doi:10.1017/S0016756811001129

RAPID COMMUNICATION

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

A. RUBIO-ORDÓÑEZ*, P. VALVERDE-VAQUERO‡†, L. G. CORRETGÉ*,
A. CUESTA-FERNÁNDEZ*§, G. GALLASTEGUI¶,
M. FERNÁNDEZ-GONZÁLEZ§ & A. GERDES‖

*Área de Petrología y Geoquímica, Departamento de Geología, Universidad de Oviedo,
c/ Arias de Velasco s/n, Oviedo (Asturias), 33005, Spain
‡Área de Laboratorios, Instituto Geológico y Minero de España (IGME),
c/ La Calera 1, 28760, Tres Cantos (Madrid), Spain
§Unidad de Microsonda Electrónica, Centro Cientifico Técnico 'Severo Ochoa', Universidad de Oviedo,
Campus 'El Cristo', 33006, Oviedo (Asturias), Spain
¶Instituto Geológico y Minero de España (IGME), c/ Matemático Pedrayes 25, 33005, Oviedo (Asturias), Spain
‖Institut für Geowissenchaften, Goethe Universität, Altenhöferallee 1, 60438, Frankfurt, Germany

(*Received* 20 June 2011; *accepted* 9 December 2011; *first published online* 16 January 2012)

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

---

†Author for correspondence: p.valverde@igme.es

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 (Díez 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 ± biotite granite and aplitic leucogranite (Corretgé, 1971). The muscovite ± 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 $An_{50–60}$ and rims with $An_{6–10}$, 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 adcumulate texture, K-feldspar-rich syenite formed by the hydrothermal alteration of monzonite–monzodiorite, minor amphibole-bearing dioritic porphyry and hornblendite (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 ± 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 Montanchez 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.

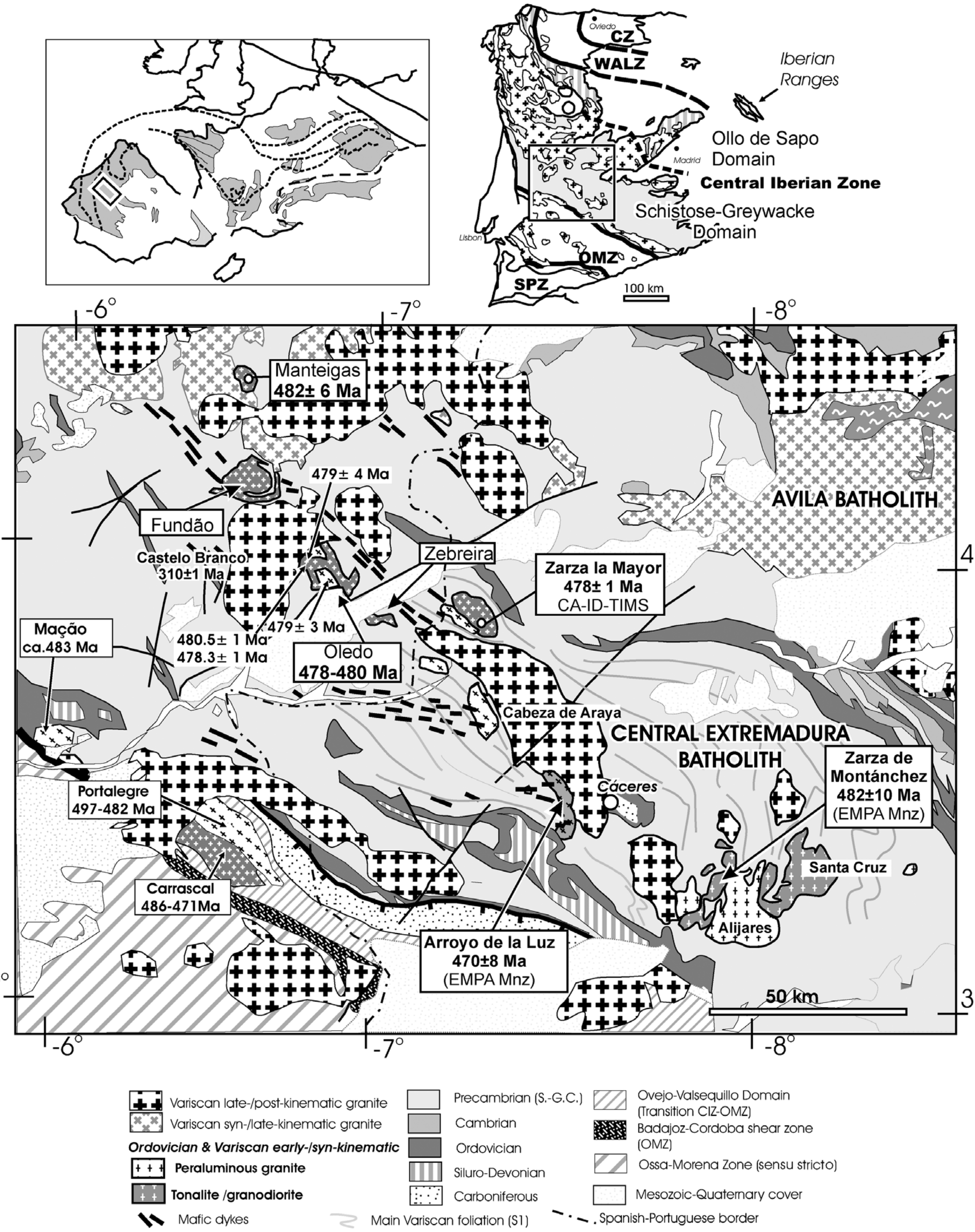

Figure 1. Simplified geological map of the Central Extremadura portion of the Schistose-Greywacke Domain of the Central Iberian Zone showing the location of the different plutons of the Beira Baixa–Central Extremadura tonalite belt (after IGME-LNEG 1:1 000 000 scale map, unpub. data). U–Pb ages, see 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

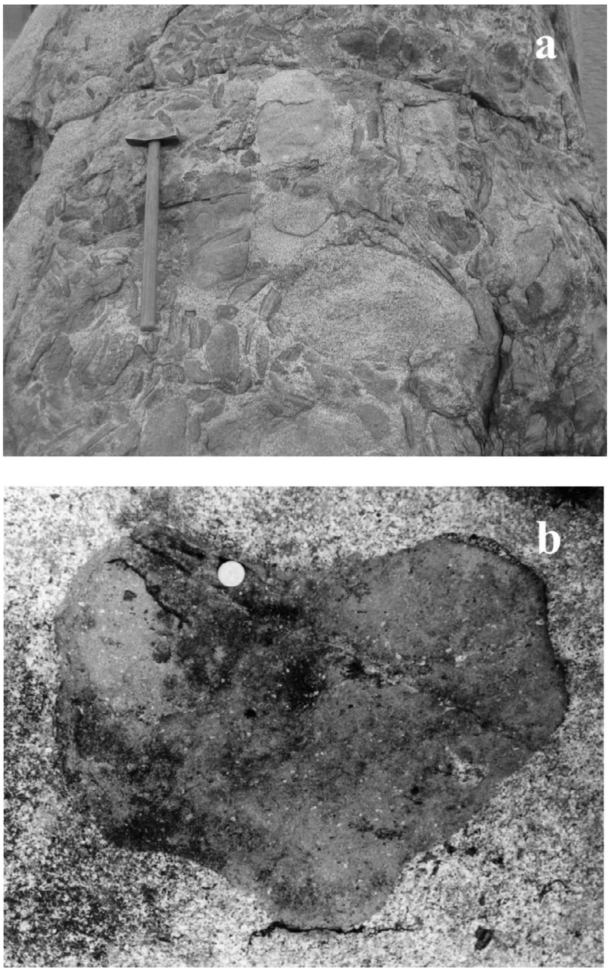

Figure 2. Zarza la Mayor tonalite: (a) enclaves of metasediments from the country rock Schistose-Greywacke complex and blobs of tonalite; (b) undeformed mafic microgranular enclave.

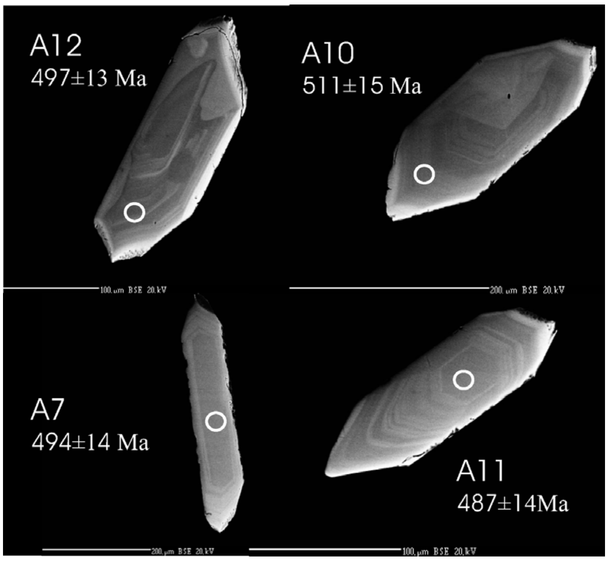

Figure 3. Back-scattered electron images of the zircons dated by LA-ICP-MS. Top, zircons with complex cores and resorption features; bottom, zircons with a simple concentric zoning.

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 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

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

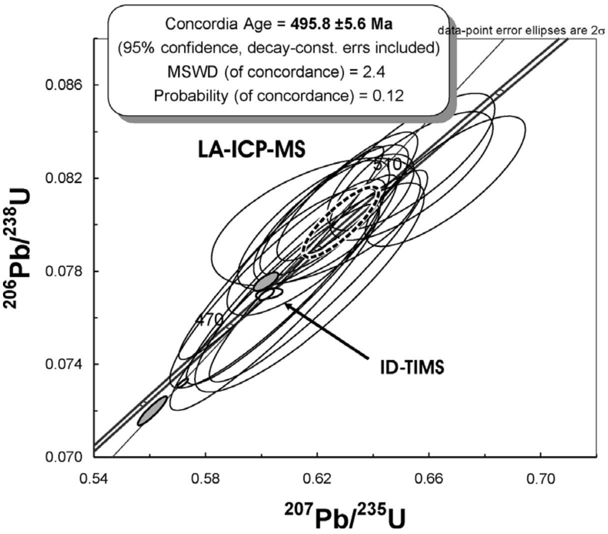

Figure 4. U–Pb LA-ICP-MS data, U–Pb concordia diagram of the LA-ICP-MS (large open ellipses) and the ID-TIMS data (small white filled ellipses – zircon; grey ellipses – monazite).

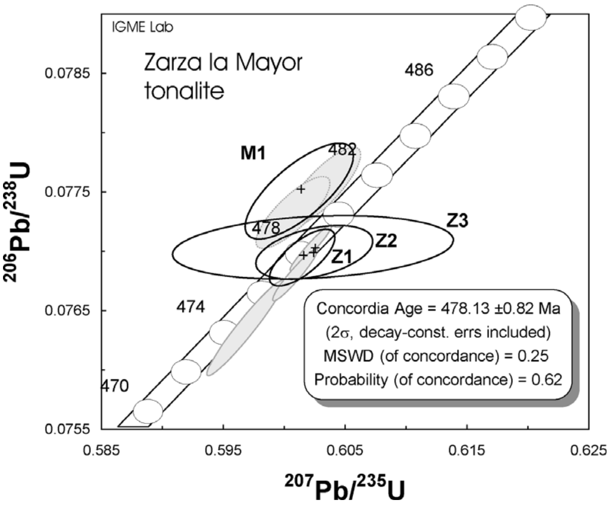

Figure 5. U–Pb concordia diagram with the concordant ID-TIMS data; crosses – centroids of the error ellipses. For comparison, grey ellipses are data from the Oledo granodiorite (Portugal; sample H1 of Antunes *et al.* 2009); M – monazite, Z – zircon.

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}Pb–^{235}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_{YPO4} 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 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_{YPO4} 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

					Isotopic ratios								Ages (Ma)			
Fractions	Weight (mg)	U (ppm)	Pb (ppm)	*Pb (pg)*	^{206}Pb/^{204}Pb*	^{208}Pb/^{206}Pb	^{206}Pb/^{238}U	% err	^{207}Pb/^{235}U	% err	^{207}Pb/^{206}Pb	% err	^{206}Pb–^{238}U	^{207}Pb–^{235}U	^{207}Pb–^{206}Pb	*corr. coef.*
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}Pb–^{235}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_2O_5	SiO_2	CaO	Y_2O_3	La_2O_3	Ce_2O_3	Pr_2O_3	Nd_2O_3	Sm_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Yb_2O_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.

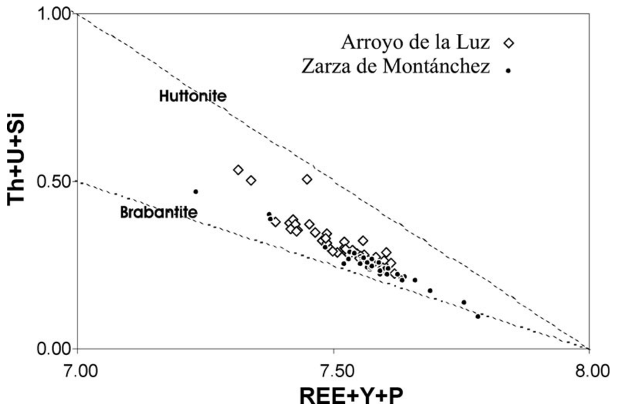

Figure 6. Monazite composition, Arroyo de la Luz and Zarza de Montánchez tonalites. Plot of the formula proportions (Th+U+Si) v. (REE+Y+P) calculated on the basis of 16 oxygen atoms. The arrows represent the brabantite ($ThCaUPb(PO_4)_2$) and huttonite ($ThSiO_4$) substitution vectors.

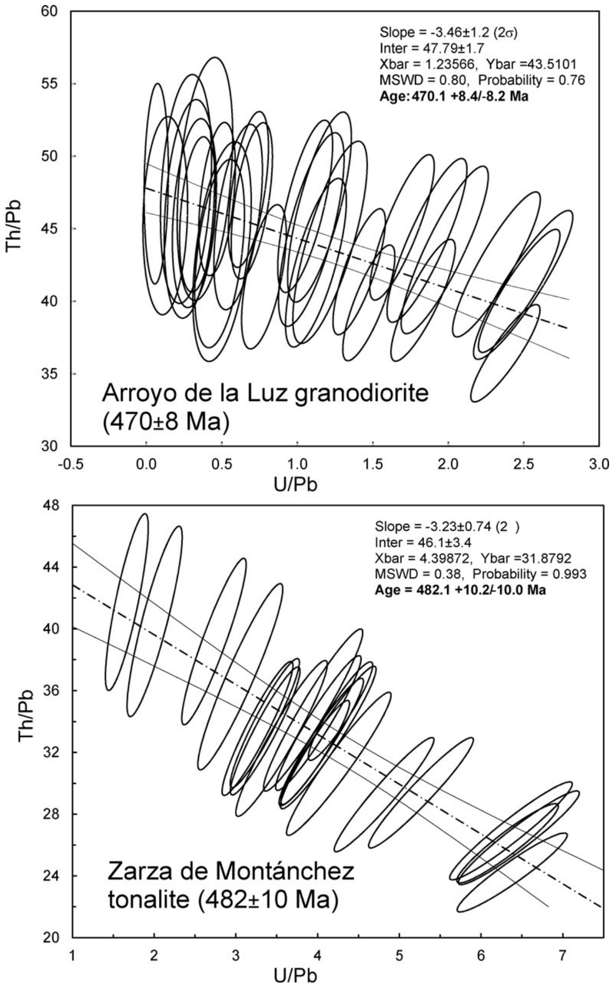

Figure 7. U–Th–Pb monazite EMPA chemical ages, Th/Pb–U/Pb diagrams: (a) Arroyo de la Luz; (b) Zarza de Montánchez.

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 Manteigas 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 Urra 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 & Martinez, 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, Martinez Catalán & Mulas, 2010). Fernandez *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

https://doi.org/10.1017/S0016756811001129

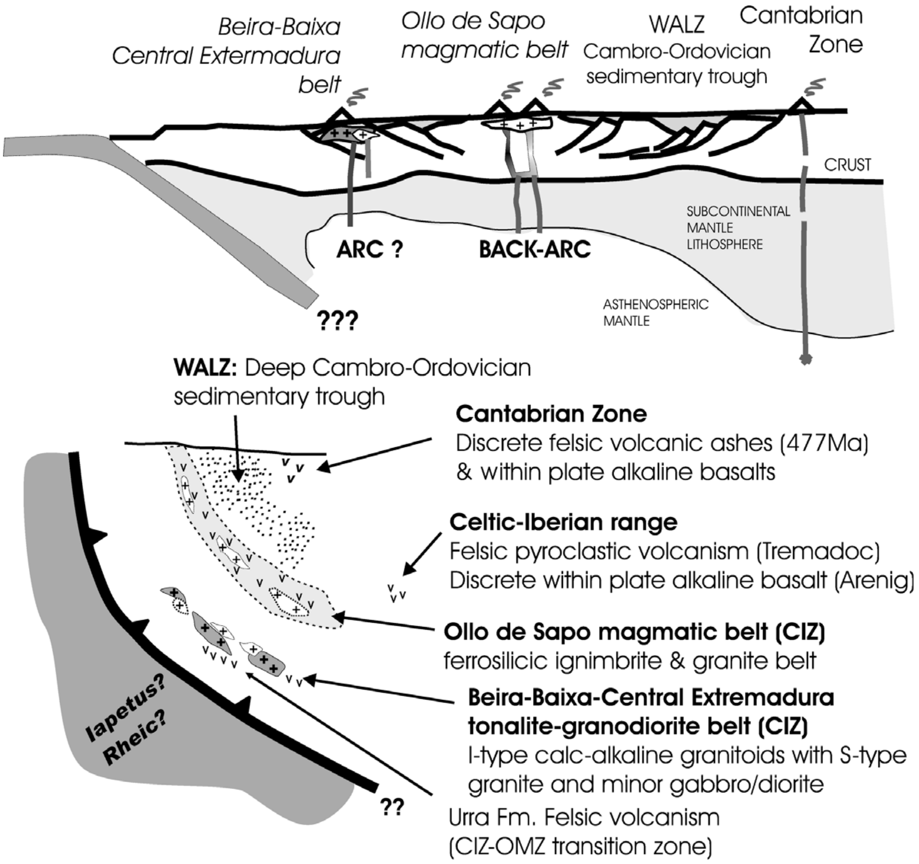

Figure 8. Tectonic model and distribution of the Early Ordovician magmatism in the Central Iberian Zone and neighbouring areas of the Iberian Autochthonous Terrane.

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.

Acknowledgements. We thank Fernando Corfu and Jane Scarrow for helpful and constructive reviews. This research was done within the frame of projects CGL2004-05681/BTE and CGL2008-05952-CO2-O2 to P.V.V., and CGL2004-06808-C04-03 to L.G.C. from the Spanish Ministry of Science and Innovation (MICINN).

References

Álvaro, J. J., Ezzouhairi, H., Ribeiro, M. L., Ramos, J. F. & Solá, R. 2008. Early Ordovician volcanism in the Iberian Chains (NE Spain) and its influence on the preservation of shell concentrations. *Bulletin de la Societe Geologique de France* **179**, 569–81.

Antunes, I. M. H. R., Neiva, A. M. R., Silva, M. M. V. G. & Corfu, F. 2008. Geochemistry of S-type granitic rocks from the reversely zoned Castelo Branco pluton (central Portugal). *Lithos* **103**, 445–65.

Antunes, I. M. H. R., Neiva, A. M. R., Silva, M. M. V. G. & Corfu, F. 2009. The genesis of I- and S-type granitoid rocks of the Early Ordovician Oledo pluton, Central Iberian Zone (central Portugal). *Lithos* **111**, 168–85.

Aramburu, C., Truyols, J., Arbizu, M., Méndez-Bedia, I., Zamarreño, I., García-Ramos, J. C., Suárez de Centi, C. & Valenzuela, M. 1992. El Paleozoico Inferior de la Zona Cantábrica. In *Paleozoico Inferior de Ibero-América* (eds J. G. Gutiérrez-Marco, J. Saavedra & I. Rábano), pp. 397–421. Badajoz: Universidad de Extremadura Publicaciones.

Arden, J. W. & Gale, N. H. 1974. Separation of trace amounts of uranium and thorium and their determination by mass spectrometric isotope dilution. *Analytical Chemistry* **46**, 687–91.

Bascones, L., Martín Herrero, D. & Corretgé, L. G. 1987. *Hoja y Memoria explicativa del Mapa Geológico Nacional a escala 1:50,000 serie 2, n° 620, Zarza la Mayor*. Madrid: IGME.

Bea, F., Montero, P. & Zinger, T. 2003. The nature, origin, and thermal influence of the granite source layer of Central Iberia. *Journal of Geology* **111**, 579–95.

Bea, F., Montero, P., Talavera, C. & Zinger, T. 2006. A revised Ordovician age for the Miranda do Douro orthogneiss, Portugal. Zircon U-Pb ion-microprobe and LA-ICPMS dating. *Geologica Acta* **4**, 395–401.

Bea, F., Montero, P., Gonzalez-Lodeiro, F. & Talavera, C. 2007. Zircon inheritance reveals exceptionally fast crustal magma generation processes in Central Iberia during the Cambro-Ordovician. *Journal of Petrology* **48**, 2327–39.

Black, L. P., Kamo, S. L., Allen, C. M., Davis, D. W., Aleinikoff, J. N., Valley, J. W., Mundil, R., Campbell, I. H., Korsch, R. J., Williams, I. S. & Foudoulis, C. 2004. Improved ^{206}Pb/^{238}U microprobe geochronology by the monitoring of a trace-element-related matrix effect; SHRIMP, ID-TIMS, ELA-ICP-MS and oxygen isotope documentation for a series of zircon standards. *Chemical Geology* **205**, 115–40.

Carracedo, M., Gil Ibarguchi, J. I., García de Madinabeitia, S. & Berrocal, T. 2005. Geocronología de los granitoides hercínicos de la serie mixta. *Revista de la Sociedad Geológica de España* **18**, 77–88.

Castro, A. 1986. Structural pattern and ascent model in the Central Extremadura batholith, Hercynian belt, Spain. *Journal of Structural Geology* **8**, 633–45.

Castro, A., Patiño Douce, A. E., Corretgé, L. G., De La Rosa, J. D., El-Biad, M. & El-Hmidi, H. 1999. Origin of peraluminous granites and granodiorites, Iberian massif, Spain: an experimental test of granite petrogenesis. *Contributions to Mineralogy and Petrology* **135**, 255–76.

Cocherie, A. & Albarede, F. 2001. An improved U-Th-Pb age calculation for electron microprobe dating of monazite. *Geochimica et Cosmochimica Acta* **65**, 4509–22.

Cordani, U. G., Nutman, A. P., Andrade, A. S., Santos, J. F., Azevedo, M. R., Mendes, M. H. & Pinto, M. S. 2006. New U-Pb SHRIMP zircon ages for pre-Variscan orthogneisses from Portugal and their bearing on the evolution of the Ossa-Morena Tectonic Zone. *Anais da Academia Brasileira de Ciencias* **78**, 133–49.

Corretgé-Castañón, L. G. 1969. Las diferenciaciones aplíticas cupuliformes en la tonalita de Zarza la Mayor-Ceclavín (Cáceres) y su interpretación petrogenética. *Acta Geológica Hispánica* **5**(IV), 119–23.

Corretgé, L. G. 1971. Estudio petrológico del batolito de Cabeza de Araya. PhD thesis, Departamento de Petrología y Geoquímica. Salamanca, Universidad de Salamanca, Spain. Published thesis.

Corretgé, L. G., Bea, F. & Suárez, O. 1985. Las características geoquímicas del batolito de Cabeza de Araya (Cáceres, España): Implicaciones petrogenéticas. *Trabajos de Geología* **15**, 219–38.

Chappell, B. W. & White, A. J. R. 1992. I- and S-type granites in the Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **83**, 1–26.

Díez Balda, M. A., Vegas, R. & González Lodeiro, F. 1990. Structure (Central Iberian Zone). In *Pre-Mesozoic Geology of Iberia* (eds R. D. Dallmeyer & E. Martínez García), pp. 172–88. Berlin-Heidelberg: Springer-Verlag.

Díez Montes, A., Martínez Catalán, J. R. & Mulas, F. B. 2010. Role of the Ollo de Sapo massive felsic volcanism of NW Iberia in the Early Ordovician dynamics of northern Gondwana. *Gondwana Research* **17**, 363–76.

Fernández-Suárez, J., Gutiérrez-Alonso, G., Jenner, G. A. & Tubrett, M. N. 1999. Crustal sources in Lower Palaeozoic rocks from NW Iberia: insights from laser ablation U-Pb ages of detrital zircons. *Journal of the Geological Society, London* **156**, 1065–8.

Fernández-Suárez, J., Gutiérrez-Alonso, G., Jenner, G. & Turbett, M. N. 2000. New ideas on the Proterozoic-Early Palaeozoic evolution of NW Iberia: insights from U–Pb detrital zircon ages. *Precambrian Research* **102**, 185–206.

Fernández, C. & Castro, A. 1999. Pluton accommodation at high strain rates in the upper continental crust. The example of the Central Extremadura batholith, Spain. *Journal of Structural Geology* **21**, 1143–49.

Fernández, C., Becchio, R., Castro, A., Viramonte, J. M., Moreno-Ventas, I. & Corretgé, L. G. 2008. Massive generation of atypical ferrosilicic magmas along the Gondwana active margin: implications for cold plumes and back-arc magma generation. *Gondwana Research* **14**, 451–73.

Fernández González, M., Cuesta Fernández, A., Rubio-Ordóñez, A. & Valverde-Vaquero, P. 2009. Datación química U-Th-Pb de monacita por microsonda electrónica (CHIME-EPMA Dating): Puesta a punto y resultados. In *VII Congreso Ibérico; X Congreso Nacional de Geoquímica*, pp. 170–77. Soria: Diputación Provincial de Soria.

Förster, H. J. 1998. The chemical composition of REE–Y–Th–U-rich accessory minerals from peraluminous granites of the Erzgebirge–Fichtelgebirge region, Germany. I. The monazite-(Ce)–brabantite solid solution series. *American Mineralogist* **83**, 259–72.

Gallastegui, G., Aramburu, C., Barba, P., Fernández, L. P. & Cuesta, A.1992. El volcanismo del Paleozoico inferior de la Zona Cantábrica. In *Paleozoico Inferior de Ibero-América* (eds J. Rábano, J. C. Gutiérrez-Marco & J. Saavedra), pp. 43–5. Badajoz: Universidad de Extremadura Publicaciones.

García de Figuerola, L. C., Corretgé, L. G. & Suárez, O. 1971. Estudio petrológico de la formación plutónica de Zarza la Mayor (Provincia de Cáceres). *Boletín Geológico y Minero de España* **32**, 217–33.

García de Figuerola, L. C., Corretgé, L. G. & Bea, F. 1974. El dique de Alentejo-Plasencia y haces de diques básicos de Extremadura (Estudio comparativo). *Boletín Geológico y Minero de España* **85**, 308–37.

Gebauer, D., Martínez García, E. & Hepburn, J. C. 1993. Geodynamic significance, age and origin of the Ollo de Sapo Augengneiss (NW Iberian Massif, Spain). In *Annual Meeting of the Geological Society of America, abstracts*, p. 342. Boston: Geological Society of America.

Gerdes, A. & Zeh, A. 2006. Combined U-Pb and Hf isotope LA(MC)ICP-MS analyses of detrital zircons: comparison with SHRIMP and new constraints for the provenance and age of an Armorican metasediment in Central Germany. *Earth and Planetary Science Letters* **249**, 47–62.

Gerstenberger, H. & Haase, G. 1997. A highly effective emitter substance for mass spectrometric Pb isotope ratio determinations. *Chemical Geology* **136**, 309–12.

Gil Serrano, G., Pérez Rojas, A. & Pineda Velasco, A. 1982. *Hoja y Memoria explicativa del Mapa Geológico Nacional a escala 1.50,000 serie 2, n° 730, Montánchez*. Madrid: IGME.

Gutiérrez-Alonso, G., Fernández-Suárez, J., Gutiérrez-Marco, J. C., Corfu, F., Murphy, J. B. & Suárez, M. 2007. U-Pb depositional age for the upper Barrios Formation (Armorican Quartzite facies) in the Cantabrian zone of Iberia: implications for stratigraphic correlation and paleogeography. In

The Evolution of the Rheic Ocean: From Avalonian-Cadomian active margin to Alleghenian-Variscan collision (eds U. Linneman, D. Nance, P. Kraft & G. Zulauf), pp. 287–96. Geological Society of America, Special Papers no. 423.

Isachsen, C. E., Coleman, D. S. & Schmitz, M. 2007. PbMacDat program. Available at http://www.earth-time.org.

Jackson, S. E., Pearson, N. J., Griffin, W. L. & Belousova, E. A. 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology. *Chemical Geology* **211**, 47–69.

Jaffey, A. H., Flynn, K. F., Glendenin, L. E., Bentley, W. C. & Essling, A. M. 1971. Precision measurement of half-lives and specific activities of U235 and U238. *Physical Review C* **4**, 1889.

Janousek, V., Gerdes, A., Vrana, S., Finger, F., Erban, V., Friedl, G. & Braithwaite, C. J. R. 2006. Low-pressure granulites of the Lisov Massif, Southern Bohemia: Visean metamorphism of Late Devonian plutonic arc rocks. *Journal of Petrology* **47**, 705–44.

Julivert, M. & Mártinez, F. J. 1987. The structure and evolution of the Hercynian Fold Belt in the Iberian Peninsula. In *The Anatomy of Mountain Belts* (eds J. P. Schaer & J. Rodgers), pp. 65–103. Princeton: Princeton University Press.

Lancelot, J. & Allegret, A. 1982. Radiochronologie U/Pb de l'orthogneiss alcalin de Pedroso (Alto Alentejo, Portugal) et évolution anté-hercynienne de l'Europe occidentale. *Neues Jahrbuch für Mineralogie – Monatshefte* **9**, 385–94.

Lancelot, J. R., Allegret, A. & de Leon, M. I. P. 1985. Outline of Upper Precambrian and Lower Paleozoic evolution of the Iberian Peninsula according to U-Pb dating of zircons. *Earth and Planetary Science Letters* **74**, 325–37.

Ludwig, K. R. 1991. PBDAT, v.1.23.

Ludwig, K. R. 1999. ISOPLOT/Ex. version 2.00.

Ludwig, K. R. 2001. *Users' manual for Isoplot/ex rev. 2.49: a geochronological toolkit for Microsoft Excel*. Berkeley Geochronology Center Special Publication 1a, 56 pp.

Mattauer, M. 2004. Orthogneisses in the deepest levels of the Variscan belt are not a Precambrian basement but Ordovician granites: tectonic consequences. *Comptes Rendus Geosciences* **336**, 487–89.

Mattinson, J. M. 2005. Zircon U-Pb chemical abrasion ("CA-TIMS") method: Combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages. *Chemical Geology* **220**, 47–66.

Montel, J.-M., Foret, S., Veschambre, M., Nicollet, C. & Provost, A. 1996. Electron microprobe dating of monazite. *Chemical Geology* **131**, 37–53.

Montero, P., Bea, F., González-Lodeiro, F., Talavera, C. & Whitehouse, M. J. 2007. Zircon ages of the metavolcanic rocks and metagranites of the Ollo de Sapo Domain in central Spain: implications for the Neoproterozoic to Early Palaeozoic evolution of Iberia. *Geological Magazine* **144**, 963–76.

Montero, P., Talavera, C., Bea, F., Lodeiro, F. G. & Whitehouse, M. J. 2009. Zircon geochronology of the Ollo de Sapo Formation and the age of the Cambro-Ordovician rifting in Iberia. *Journal of Geology* **117**, 174–91.

Neiva, A. M. R., Williams, I. S., Ramos, J. M. F., Gomes, M. E. P., Silva, M. M. V. G. & Antunes, I. M. H. R. 2009. Geochemical and isotopic constraints on the petrogenesis of Early Ordovician granodiorite and Variscan two-mica granites from the Gouveia area, central Portugal.*Lithos* **111**, 186–202.

Pankhurst, R. J., Rapela, C. W., Saavedra, J., Baldo, E., Dahlquist, J., Pascua, I. & Fanning, C. M. 1998. The Famatinian magmatic arc in the central Sierras Pampeanas: an Early to Mid-Ordovician continental arc on the Gondwanan margin. In *The proto-Andean Margin of Gondwana* (eds R. J. Pankhurst & C. W. Rapela), pp. 343–67. Geological Society of London, Special Publication no. 142.

Pankhurst, R. J., Rapela, C. W. & Fanning, C. M. 2000. Age and origin of coeval TTG, I- and S-type granites in the Famatinian belt of NW Argentina. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **91**, 151–68.

Parrish, R. R. 1987. An improved micro-capsule for zircon dissolution in U-Pb geochronology. *Chemical Geology (Isotope Geoscience Section)* **66**, 99–102.

Portugal Ferreira, M. 1982. A magmatic arc in the Iberian segment of the Hercynian chain: the northwest-southeast lineament between Oporto (Portugal) and Zarza la Mayor (Spain). *Memorias e Noticias. Publicaçoes do Museu e Laboratorio Mineralógico e Geológico da Universidade de Coimbra* **94**, 32–47.

Pupin, J. P. & Turco, G. 1972. Une typologie originale du zircon accessoire. *Bulletin de la Société Française du Cristallografie* **95**, 348–59.

Quesada, C. 1991. Geological constraints on the Paleozoic tectonic evolution of tectonostratigraphic terranes in the Iberian Massif. *Tectonophysics* **185**, 225–45.

Richter, S., Goldberg, S. A., Mason, P. B., Traina, A. J. & Schwieters, J. B. 2001. Linearity tests for secondary electron multipliers used in isotope ratio mass spectrometry. *International Journal of Mass Spectrometry* **206**, 105–27.

Romão, J., Dunning, G., Marcos, A., Dias, R. & Ribeiro, A. 2010. The Mação-Penhascoso laccolith granite: age and implications (SW-Central Iberian Zone). *e-Terra* **16**, 1–4.

Rubio-Ordóñez, A., Corretgé, L. G. & Cuesta, A. 2007. Morfología de los circones como indicadores petrogenéticos de la asociación tonalita-leucogranito: el caso del plutón de Zarza la Mayor (Cáceres-España). *Geogaceta* **41**, 187–90.

Rubio, J. I. 1982. Nota sobre las dioritas del NW. de Zarza la Mayor (Cáceres). *Cuadernos del Laboratorio Xeolóxico de Laxe* **3**, 75–81.

Schäfer, G. 1969. Geologie und petrographie im östlichen Katilischen Hauptscheidegebirge (Sierra de Guadarrama, Spanien). *Münsterche Forschungen zur Geologie und Palaeontologie* **10**, 1–207.

Scherrer, N. C., Engi, M., Gnos, E., Jakob, V. & Liechti, A. 2000. Monazite analysis; from sample preparation to microprobe age dating and REE quantification. *Schweizerische Mineralogische und Petrographische Mitteilungen* **80**, 93–105.

Solá, A. R., Pereira, M. F., Williams, I. S., Ribeiro, M. L., Neiva, A. M. R., Montero, P., Bea, F. & Zinger, T. 2008. New insights from U-Pb zircon dating of Early Ordovician magmatism on the northern Gondwana margin: The Urra Formation (SW Iberian Massif, Portugal). *Tectonophysics* **461**, 114–29.

Stacey, J. S. & Kramers, J. D. 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth and Planetary Science Letters* **26**, 207–21.

SUZUKI, K. & ADACHI, M. 1991. The chemical Th-U-total Pb isochron ages of zircon and monazite from the gray granite of the Hida Terrane, Japan. *The Journal of Earth Sciences, Nagoya University* **38**, 11–38.

VALVERDE-VAQUERO, P. 2009. Método de datación U-Pb ID-TIMS en el laboratorio geocronológico del IGME (Tres Cantos). *Comunicaciones VII Congreso Ibérico de Geoquímica*, pp. 758–65. Soria: Diputación Provincial de Soria.

VALVERDE-VAQUERO, P., CARRIÓN, C., REYES ANDRÉS, J., MARTÍN RUBÍ, J. A. & PARADAS HERRERO, A. 2005. Un estándar de monacita para dataciones U-Th-Pb: IGME 6883-A. *Comunicaciones V Congreso Ibérico de Geoquímica*, pp.1–6. Soria: Diputación Provincial de Soria.

VALVERDE-VAQUERO, P., DÖRR, W., BELKA, Z., FRANKE, W., WISZNIEWSKA, J. & SCHASTOK, J. 2000. U-Pb single-grain dating of detrital zircon in the Cambrian of central Poland: implications for Gondwana versus Baltica provenance studies. *Earth and Planetary Science Letters* **184**, 225–40.

VALVERDE-VAQUERO, P. & DUNNING, G. R. 2000. New U-Pb ages for Early Ordovician magmatism in Central Spain. *Journal of the Geological Society, London* **157**, 15–26.

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

WIEDENBECK, M., ALLÉ, P., CORFU, F., GRIFFIN, W. L., MEIER, M., OBERLI, F., QUADT, A. V., RODDICK, J. C. & SPIEGEL, W. 1995. Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses. *Geostandards newsletter* **19**, 1–23.

WILLIAMS, M. L., JERCINOVIC, M. J. & TERRY, M. P. 1999. Age mapping and dating of monazite on the electron microprobe: Deconvoluting multistage tectonic histories. *Geology* **27**, 1023–26.

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 Epoxicure 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 ~ 20 μm. 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}Pb/^{206}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 (> ±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}Pb/^{238}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}Pb/^{206}Pb and ^{206}Pb/^{238}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 renium filaments with a mixture of SiGel and H_3PO_4 (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 ^{204}Pb 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).