

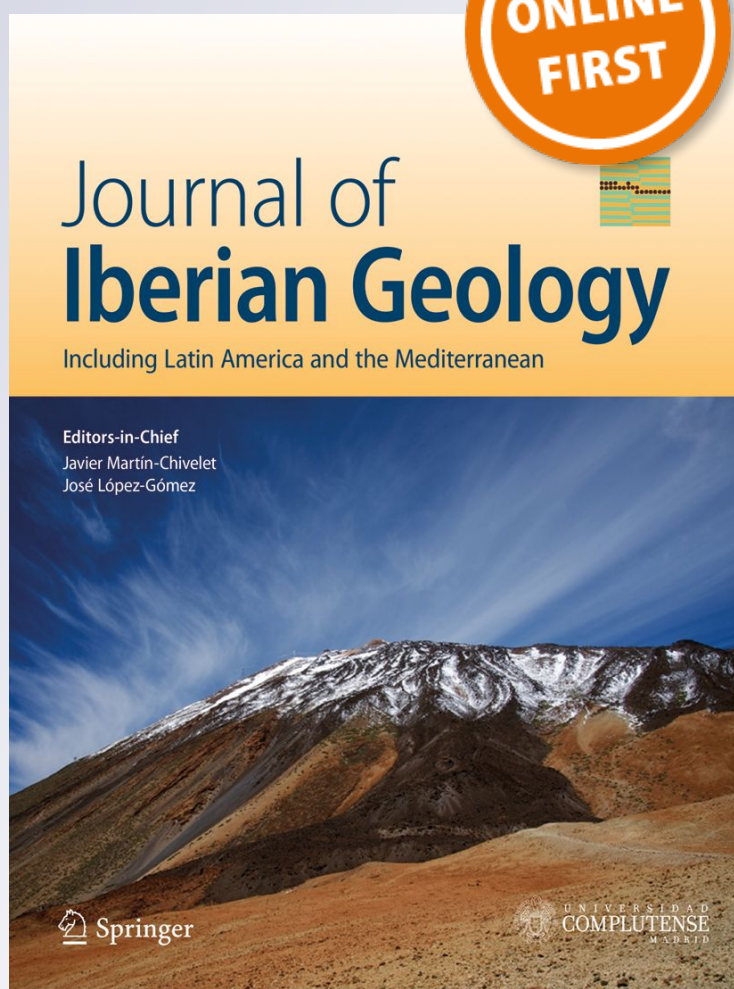
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Multiple Paleozoic magmatic-orogenic events in the Central Extremadura batholith (Iberian Variscan belt, Spain)

M. Francisco Pereira¹ · Antonio Castro² · Carlos Fernández² · Carmen Rodríguez^{2,3}

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Abstract

Background The Central Extremadura batholith located in the southeast part of the Central Iberian Zone (e.g. Iberian Autochthonous domain of the Iberian Variscan belt) was originally thought to have been generated entirely during Carboniferous igneous activity. However, some recent geochronological work has shown the existence of Ordovician plutonic rocks.

Purpose The aim of this study is to re-examine the age of granitic rocks in the Central Extremadura batholith and complement this information with new field and geochemical data. This data set is used: to constrain the relative timing of plutons emplacement, as well as deformation and metamorphism preserved in the host rocks; to track deep crustal rocks and granitic magma sources; and to discuss prevailing tectonic evolutionary models for the Paleozoic evolution of the Iberian Variscan belt.

Methods We use geochemical and SHRIMP U-Pb zircon geochronology data of three granitic plutons (Ruanes, Plasenzuela and Albalá) from the Central Extremadura batholith to track magmatic sources and provide a better understanding of temporal and spatial relationships between deformation and magmatism in the Iberian Variscan belt.

Results Ruanes tonalite dated at 464 ± 2 Ma is peraluminous, magnesian and calc-alkaline, as typical of a magmatic arc setting. We report, for the first time, the occurrence of a Middle Ordovician intrusion spatially and temporally related to host deformed rocks of the Central Iberian Zone (e.g. the Iberian Autochthonous domain), which reached high-grade metamorphic conditions. Plasenzuela two-mica leucogranite is strongly peraluminous and of anatectic origin and includes a Neoproterozoic and Ordovician population of inherited zircon grains. This granite possibly derived from the partial melting of a crustal source composed of Neoproterozoic metapelites and metagreywackes (Schist-Greywacke Complex) and/or Lower Ordovician gneisses (Ollo de Sapo Formation), both including greywackes of volcano-sedimentary origin and peraluminous composition. The crystallization age of 330 ± 7 Ma obtained for the syn-kinematic Plasenzuela two-mica leucogranite constrains the functioning of D2 dextral strike-slip shear zones within the Iberian Autochthonous domain. The age of 309 ± 2 Ma obtained for the Albalá cordierite-bearing monzogranite matches the age interval of the calc-alkaline magmatic suite post-dating the main Variscan D1–D3 structures in the Iberian Autochthonous domain.

Conclusion The new data presented in this study make it possible to recognize multiple Paleozoic magmatic-orogenic events (e.g. Caledonian, Variscan and Cimmerian) in the Central Extremadura batholith. During the Ordovician, the emplacement of intermediate magmas at shallow depths gave rise to extensive metamorphism due to heat transfer to the host rocks. The onset of this Ordovician plutonic–metamorphic complex in the Iberian Autochthonous domain is contemporaneous with the development of an active continental margin probably related to the subduction of the Iapetus–Tornquist Ocean (i.e. the Caledonian orogeny). During the Lower Carboniferous, these D2 strike-slip domains acted as lateral margins of large-scale gravitational collapses associated with the SE-direct transport of low-angle extensional shear zones (i.e. the Variscan cycle). The emplacement of Upper Carboniferous arc type granitic rocks is interpreted in the context of the amalgamation of Pangaea and the spatial proximity of Iberia relative to the Eurasian active margin in the course of Paleotethys subduction (i.e. the Cimmerian orogeny).

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Keywords Zircon geochronology · Ordovician plutonism-metamorphism · Carboniferous magmatism and deformation · Central Iberian zone · Magmatic-orogenic cycles

Resumen

Los datos geoquímicos y geocronológicos (edades SHRIMP de U-Pb en circones) de tres plutones graníticos del Batolito de Extremadura central han permitido obtener información sobre las fuentes magmáticas y comprender las relaciones espaciales entre la deformación y el magmatismo en el cinturón Varisco de Iberia. Este estudio nos ha llevado al reconocimiento de múltiples eventos magmáticos y orogénicos paleozóicos en este batolito. La tonalita de Ruanes, cuya edad es de 464 ± 2 Ma, es una roca calcoalcalina, peraluminica y magnesiánica, cuya fuente es la típica de un contexto de arco magmático. Demostramos, por primera vez, que una intrusión del Ordovícico medio está relacionada espacial y temporalmente con rocas encajantes deformadas de la Zona Centroibérica (es decir, del dominio Autóctono Ibérico), que alcanzaron condiciones metamórficas de alto grado. Durante el Ordovícico, el emplazamiento de magmas intermedios a bajas profundidades en la corteza dio lugar a un extenso metamorfismo debido a transferencia de calor hacia su encajante. El inicio de la formación de este complejo plutono-metamórfico ordovícico es consistente con el desarrollo de un margen continental activo, probablemente relacionado con la subducción del océano Iapetus–Tornquist (es decir, la orogenia Caledónica). El leucogranito de dos micas de Plasenzuela es de origen anatético, y fuertemente peraluminico, e incluye una población de circones heredados de edades neoproterozoicas y ordovícicas. Este granito posiblemente se produjo tras la fusión parcial de una fuente cortical compuesta por metapelitas y metagrauvas del Neoproterozoico (Complejo Esquisto-Grauváquico), y/o gneisses del Ordovícico inferior (Formación Ollo de Sapo). Ambos incluyen grauvas de origen volcano-sedimentario y de composición peraluminica. La edad de cristalización obtenida para el leucogranito sincinemático de dos micas de Plasenzuela (330 ± 7 Ma) precisa la edad de la actividad de las zonas de cizalla transcurrentes dexas de la fase D_2 en el dominio Autóctono Ibérico. Durante el Carbonífero inferior estos dominios transcurrentes de fase D_2 actuaron como los márgenes laterales de los grandes colapsos gravitacionales relacionados con zonas de cizalla extensionales de bajo ángulo y desplazamiento del bloque de techo hacia el SE (es decir, la orogenia Varisco). La edad de 309 ± 2 Ma obtenida para el monzogranito rico en cordierita de Albalá encaja con el intervalo temporal de la asociación magmática calcoalcalina que post-data las principales estructuras D_{1-3} variscas en el Dominio Autóctono Ibérico. El emplazamiento durante el Carbonífero superior de estas rocas graníticas de arco se interpreta en el contexto de la acreción de Pangea y de la proximidad espacial de Iberia al margen activo de Eurasia en el transcurso de la subducción del Paleotethys (es decir, la orogenia Cimérica).

Palabras-clave Geocronología U-Pb en circones · Plutonismo-metamorfismo ordovícico · Magmatismo y deformación carboníferas · Zona Centroibérica · Ciclos magmático-orogénicos

1 Introduction

In recent years, with the great advance in the capability and reliability of analytical methods, zircon geochronology has been intensively applied in the dating of granitic rocks, which constitute an important archive of crustal evolution (e.g. Williams 1992; Davis et al. 2003; Scherer et al. 2007). The isotopic information contained in zircon from granitic rocks is crucial for unraveling crustal growth and recycling through time (e.g. Cawood et al. 2013). The geochronological study of granitic rock crystallization is useful for identifying magmatic events over geological time, and providing maximum and minimum constraints for the ages of deformation events recorded in granites and host rocks (e.g. Corfu and Stott 1986; Cooper and Ding 1997; Fernández-Suárez et al. 2000; Pereira et al. 2010; Díez Fernández and Pereira 2016). Geochronology provides the missing link for transforming a “relative” dating constraint, inferred from granite cross-cutting relationships, into an “absolute” age constraint tied directly to granite-host rock deformation (e.g. Dumond

et al. 2008). Further, the age populations of inherited zircon found in granitic rocks are valuable for tracking deep crustal processes, and magma sources (Johnson 1989; Miller et al. 2007). Granitic rocks may have a wide range of sources, from mantle-derived basalts to pure crust, providing relevant information for geochemical fingerprinting of the relationships between magma source and tectonic setting (Pearce 1996 and references therein).

The nature of tectonic events, which are directly responsible for Paleozoic magmatism in the Iberian Variscan belt (Julivert et al. 1972; Matte 1991, 2002; Martínez Catalán et al. 2007 and references therein), has been the subject of much discussion in recent years. In NW Iberia, distinct magmatic-orogenic events have been recognized in relation to the diachronic closure of oceanic basins during the Paleozoic (Martínez Catalán et al. 2007). We highlight here the discovery of an Upper Cambrian–Middle Ordovician arc-continent collisional event recognized in NW Iberia (Arenas et al. 2007; Martínez Catalán et al. 2007, 2009). This early Paleozoic active margin is interpreted as being linked mainly

to the subduction of the Iapetus/Tornquist Ocean below the Gondwanan margin (Arenas et al. 2016 and references therein). Within a more global framework, the closure of the Iapetus/Tornquist Ocean ultimately led to the collision of Laurentia, Baltica and Avalonia (e.g. Caledonian orogeny; McKerrow et al. 2000) and the opening of two Paleozoic oceanic basins: the Rheic (Nance et al. 2015) and the Rheno-Hercynian (Stampfli et al. 2002). Despite the recognition in NW Iberia of the Upper Cambrian–Middle Ordovician magmatic-orogenic event, its spatial distribution and timing remain elusive in other areas of the Iberian Variscan belt (Abati et al. 1999, 2007, 2010; Arenas et al. 2007; Martínez Catalán et al. 2007). The Variscan orogeny (e.g. Matte 2001; Franke 2007) was responsible for main Carboniferous folding, cleavage formation and related metamorphism and syn-kinematic magmatism in the Iberian Variscan belt.

Therefore, greater importance has been given to the main basement structures, which include allochthonous units juxtaposed onto the Iberian Autochthonous domain (Martínez Catalán et al. 2007), reflecting the Laurussia–Gondwana collision in Carboniferous times (e.g. Martínez Catalán et al. 2007, 2009; Arenas et al. 2007, 2016; Díez Fernández and Arenas 2015). Interestingly, deformed Neoproterozoic–Paleozoic rocks of the Iberian Autochthonous domain are intruded by voluminous ca. 336–313 Ma syn-kinematic magmatism related with the Variscan orogeny (Dias et al. 1998; Valle Aguado et al. 2005; Teixeira et al. 2011, 2012; Díaz-Alvarado et al. 2013; Díez Fernández and Pereira 2016; López-Moro et al. 2017; Pereira et al. 2018) and ca. 311–299 Ma post-kinematic magmatism that has traditionally been regarded as late- and/or post-Variscan (e.g., Castro et al. 2002; Dias et al. 2002; Neiva et al. 2009; Villaseca et al. 2009; Fernández-Suárez et al. 2011; Gutiérrez-Alonso et al. 2011) (Table 1). However, recently Pereira et al. (2015) pointed out that the closure of oceanic basins separating Laurussia from Gondwana took place in the Upper Devonian at least ca. 60–70 Ma previously, suggesting that this late Paleozoic magmatism was most probably linked to the development of the Iberian-Armorican arc (e.g. Gutiérrez-Alonso et al. 2011) and Paleotethys subduction. In such a paleogeographic context, diachronic docking of the Cimmerian terranes (detached from the non-collisional northern margin of Gondwana) and the Eurasian active margin (e.g. Cimmerian orogeny; Stampfli and Borel 2002) led to the inception of a Paleotethyan arc in Iberia (Pereira et al. 2015).

In the present study, we have selected three granitic bodies from the Central Extremadura batholith, located in the southern domains of the Iberian Autochthonous domain, as representing the greatest exposed area of the Iberian Variscan belt (Fig. 1). Most of the prevailing age interpretations for the Central Extremadura batholith have been almost exclusively supported by field relationships between granitic rocks and deformation phases recognized in the

host rocks. The aim of this study is to re-examine the age of granitic rocks in the Central Extremadura batholith by using SHRIMP U–Pb zircon dating. New field, geochemical data (58 samples) and U–Pb geochronological data (three samples) were used to: (1) constrain the relative timing of granitic pluton emplacement, and deformation and metamorphism events preserved in the host rocks; (2) track deep crustal rocks and granitic magma sources; and (3) improve prevailing tectonic evolutionary models for the Paleozoic evolution of the Iberian Variscan belt.

2 Geological setting

The Central Iberian zone (Julivert et al. 1972; e.g. Iberian Autochthonous domain; Fig. 1) is located in the central part of the Iberian Variscan belt (Martínez Catalán et al. 2009), and represents a section of the Gondwana margin that experienced a complex geological history from the Ediacaran to the Carboniferous (Gutiérrez Marco et al. 1990; Valladares et al. 2000; Pereira et al. 2012; Martínez Catalán et al. 2014). The oldest metasedimentary series are composed of schists and metasediments of Ediacaran to Lower Cambrian age, the so-called Schist–Greywacke Complex (SGC—Sousa 1982; Vidal et al. 1994). Ediacaran–Cambrian metasedimentary rocks are largely exposed in the central and southern domains of the Central Iberian zone (Fig. 1), forming the SGC domain (Rodríguez Alonso et al. 2004). These SGC siliciclastic rocks were deposited in the context of the evolution of arc-related basins close to the northern Gondwana active margin (e.g. Cadomian magmatic arc; Bandrés et al. 2002; Rodríguez Alonso et al. 2004; Pereira et al. 2012; Villaseca et al. 2014).

An Ordovician siliciclastic sequence directly overlies the SGC domain (Gutiérrez Marco et al. 1990). An angular unconformity with the Ordovician shallow marine siliciclastic platform deposits lying directly over tilted Ediacaran–Cambrian strata has been considered compatible with an evolutionary stage of crustal extension during early Paleozoic times (McDougall et al. 1987; Pereira et al. 2012). Conspicuous pre-Variscan magmatic activity is recognized in the SGC domain (Valverde-Vaquero and Dunning 2000; Bea et al. 2003; Zeck et al. 2004), including meta-granites of the central Central Iberian zone that appear between Miranda do Douro and Toledo (i.e. Ollo de Sapo domain; ca. 498–462 Ma: Montero et al. 2007, 2009a; Talavera et al. 2013), and the calc-alkaline tonalite–granodiorite suite of the magmatic province that extends for about 150 km from Zarza de Montánchez to Fundão (i.e. Beira Baixa–Central Extremadura tonalite belt; ca. 483–470 Ma: Antunes et al. 2009; Neiva et al. 2009; Romão et al. 2010; Rubio-Ordóñez et al. 2012) (Table 1). Outside the SGC domain, pre-Variscan magmatism represented by a belt of Cambro–Ordovician

Table 1 Selection of Caledonian, Variscan and Cimmerian pluton ages from CIZ and northern OMZ

Caledonian plutonic rocks	Location	Age (Ma)	Method	References
Meta-granites	CIZ (Salamanca, Gredos, Guadarrama, Toledo)	498–462	U/Pb Zrn	Talavera et al. (2013)
Gabbros, diorites and granites	CIZ, northern OMZ (Portalegre, Carrascal)	493–471	U/Pb, Pb/Pb Zrn	Solá et al. (2008) and references therein
Diorites and granites	CIZ (Gredos)	485–480	U/Pb Zrn	Díaz Alvarado et al. (2016)
Granite	CIZ (Mação)	483	U/Pb Zrn	Romão et al. (2010)
Meta-granite	CIZ (Villadepera)	483	U/Pb Zrn	Bea et al. (2006)
Granodiorite	CIZ (Gouveia)	482	U/Pb Zrn	Neiva et al. (2009)
Tonalites and granodiorites	CIZ (Zarza la Mayor, Arroyo de la Luz, Zarza de Montánchez)	482–470	U/Pb Zrn, Mnz	Rubio-Ordóñez et al. (2012)
Tonalites, granodiorites and granites	CIZ (Oledo, Fundão)	481–478	U/Pb Zrn, Mnz	Antunes et al. (2009, 2012)
Meta-granite	CIZ (Hiendelaencina)	474	U/Pb Zrn	Montero et al. (2007)
Meta-granite	CIZ (Sanabria)	470	U/Pb Zrn	Montero et al. (2009a, b)
Tonalite	CIZ (Ruanes)	464	U/Pb Zrn	This study
Variscan plutonic rocks	Location	Age (Ma)	Method	References
Granites	CIZ (Carrazada de Anciães, Sabugal)	336–319	U/Pb Zrn, Mnz	Teixeira et al. (2011, 2012)
Granites	CIZ (Pinhel, Trancoso)	331–317	U/Pb Zrn	Díez Fernández and Pereira (2016)
Leucogranite	CIZ (Plasenzuela)	330	U/Pb Zrn	This study
Granites	CIZ (Ribera de Pelazas, Ledesma, Baruecopardo, Pelilla)	326–318	U/Pb Zrn	López-Moro et al. (2017)
Granites and granodiorites	CIZ (Sernacelhe)	322–317	U/Pb Zrn, Mnz	Costa et al. (2014)
Granites	CIZ (Mêda, Escalhão, Penedono)	319	U/Pb Zrn	Pereira et al. (2018)
Granites and granodiorites	CIZ (Ucanha-Vilar, Lamego, Sameiro and Refoios do Lima)	319–313	U/Pb Zrn, Mnz	Dias et al. (1998)
Granites and granodiorites	CIZ (Maceira)	314	U/Pb Zrn, Mnz	Valle Aguado et al. (2005)
Granodiorites	CIZ (Gredos)	313	U/Pb Zrn	Díaz-Alvarado et al. (2013)
Cimmerian plutonic rocks	Location	Age (Ma)	Method	References
Tonalites and gabbros	CIZ (Arges, Toledo, Guajaraz, La Bastida)	311–306	U/Pb Zrn	Bea et al. (2006)
Peraluminous granites and monogranites	CIZ (Casal Vasco, Junqueira, Cota)	311–307	U/Pb Zrn, Mnz	Valle Aguado et al. (2005)
Monzogranites and granites	CIZ (Braga, Celeirós, Briteiro, Gerês, Peneda)	311–290	U/Pb Zrn, Mnz	Dias et al. (1998)
Granites, monzogranites and granodiorites	CIZ (Gouveia)	310–289	U/Pb Zrn, Mnz	Neiva et al. (2009, 2012)
Granites	CIZ (Castelo Branco)	310	U/Pb Zrn	Antunes et al. (2008)
Monzogranites and tonalites	CIZ, northern OMZ (Nisa, Aldeia da Mata)	309–306	U/Pb Zrn	Solá et al. (2009)
Granitic rocks	CIZ (La Alberca, Villavieja de Yeltes, Ciperez, Trujillo, Merida, Albuquerque, Cabeza de Araya, Veiga, Orense, Caldas de Reis, Braga, Guarda, El Alamo, El Miron)	309–296	U/Pb Zrn	Gutiérrez-Alonso et al. (2011)
Granodiorites	CIZ (Los Pedroches)	308	U/Pb Zrn	Carracedo et al. (2008)
Granites and Crd-Monogranites	CIZ (Gredos)	307–304	U/Pb Zrn,	Díaz-Alvarado et al. (2013)
Granites	CIZ (Villacastin, Alpendrete, Hoyo de Pilares, Navas de Marques)	306–299	U/Pb Zrn	Orejana et al. (2012)
Leucogranites	CIZ (Cerro Mogábar)	304	U/Pb Zrn	Carracedo et al. (2008)
Granites and gabbro-diorites	Northern OMZ (Santa Eulália, Monforte)	303–297	U/Pb Zrn	Pereira et al. (2017)

Table 1 (continued)

Cimmerian plutonic rocks	Location	Age (Ma)	Method	References
Granites	CIZ (Almeida, Malpartida)	303	U/Pb Zrn	Díez Fernández and Pereira (2017)
Granites and Leucogranites	CIZ (La Cabrera)	302	Pb/Pb Zrn	Casquet et al. (2004)
Bt Monzogranites	CIZ (Vila Pouca de Aguiar)	299	U/Pb Zrn	Martínez Catalán et al. (2009)

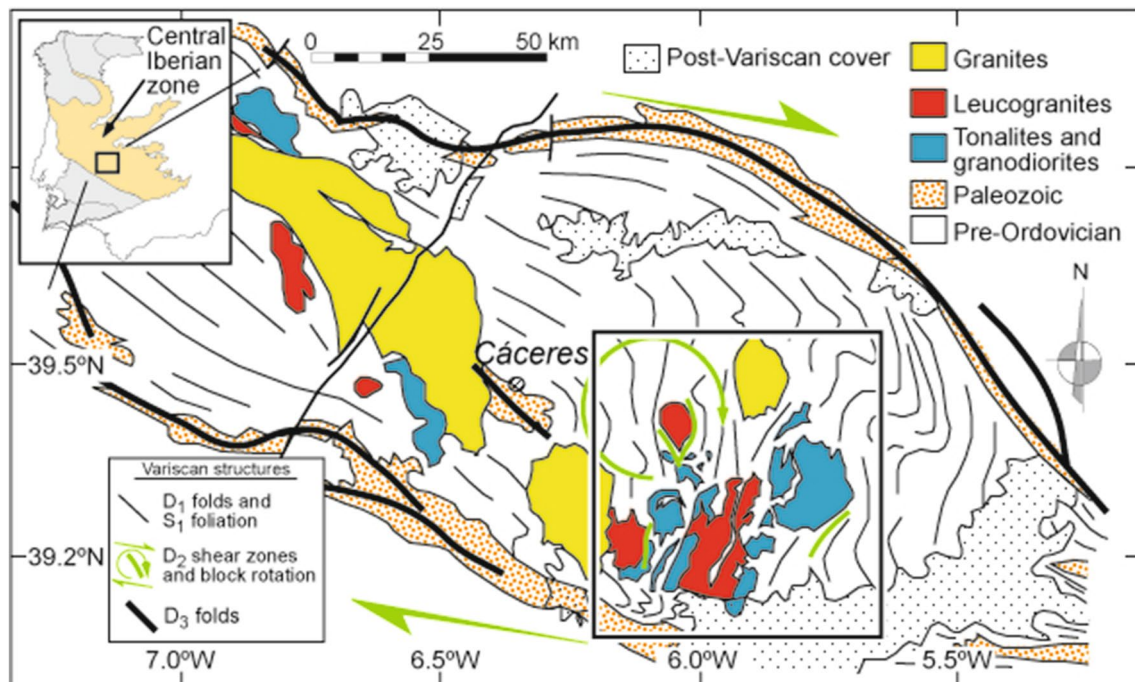


Fig. 1 Location of the studied area (black square) in the Central Extremadura batholith (southern Central Iberian zone). Inset (based on Farias et al. 1987) shows the Iberian Variscan belt (grey) highlighting the position of the Central Iberian zone (pale orange) and the Central Extremadura batholith (marked with a square). Traces of the

Variscan structures based on Castro and Fernández (1998), Martínez Catalán et al. (2014), and Clariana García et al. (2017). Sketch of the Central Extremadura batholith modified from Castro (1984, 1986) and Clariana García et al. (2017)

igneous-sedimentary rocks dated at ca. 493–471 Ma occurs in the southern Central Iberian zone and northern Ossa-Morena zone (Urroa formation; e.g., Solá et al. 2008 and references therein) (Table 1).

In the allochthonous units of the northwest Iberian Variscan belt, a Cambro–Ordovician magmatic arc and extensional back-arc/retro-arc igneous magmatism related to the Iapetus–Tornquist subduction has been recognized (Abati et al. 1999, 2007, 2010; Montero et al. 2009b; Castiñeiras et al. 2010; Díez Fernández et al. 2010; Díaz García et al. 2010; Sánchez Martínez et al. 2012; Dias da Silva et al. 2016).

In the southern Central Iberian zone, Paleozoic stratigraphy of the Cáceres and Sierra de San Pedro synclines (Tena-Dávila Ruiz et al. 1980; López Díaz et al. 1990) also include Silurian to Carboniferous siliciclastic sequences with minor

volcanic and carbonate rocks (Gutiérrez Marco et al. 1990; Martínez Poyatos et al. 2004).

During the late Paleozoic, contractional deformation related to the Laurussia–Gondwana collision (e.g. Variscan orogeny) caused crustal thickening (D_1 thrusting and folding). The D_1 contractional deformation phase, well-recognized in northern domains of the Iberian Variscan belt, culminated in the emplacement of a nappe stack (e.g. allochthonous units) juxtaposed onto autochthonous domains (Arenas et al. 1986; Ribeiro et al. 1990; Martínez Catalán et al. 2009, 2014; Dias da Silva et al. 2016; Díez Fernández and Arenas 2015). In early Carboniferous times, crustal thickening was assisted by intra-orogenic gravitational collapse, which gave rise to crustal thinning and a D_2 deformation phase with the development of large-scale low-angle extensional shear zones, migmatitic gneiss domes and

syn-kinematic plutonism (Escuder Viruete et al. 1994, 1998; Díez Balda et al. 1995; Díez Fernández et al. 2013; Martínez Catalán et al. 2014; Díez Fernández and Pereira 2016; Dias da Silva et al. 2017; Pereira et al. 2018) at ca. 336–313 Ma (Table 1). In late Carboniferous times, D₃–D₄ and D₅ contractional deformation phases were responsible for the folding of previous structures and the development of large-scale vertical-to-steeply-inclined strike-slip shear zones in the Iberian Variscan belt (Iglesias and Ribeiro 1981; Villar Alonso et al. 1992; González Clavijo and Díez Montes 2008; Martínez Catalán et al. 2014; Gutiérrez-Alonso et al. 2015; Díez Fernández and Pereira 2017; Dias da Silva et al. 2017). The emplacement of Carboniferous granitic bodies in the SCG domain was mostly related to post-D₁ deformation events (Dias et al. 1998; Fernández-Suárez et al. 2000, 2011; Castro et al. 2002; Valle Aguado et al. 2005; Solá et al. 2009; Neiva et al. 2009, 2012; Teixeira et al. 2011; Díaz-Alvarado et al. 2011; Gutiérrez-Alonso et al. 2011; Orejana et al. 2012; Costa et al. 2014; Díez Fernández and Pereira 2016, 2017; López-Moro et al. 2017; Pereira et al. 2017, 2018).

3 Analytical techniques

3.1 Whole-rock geochemistry

Major elements and Zr of samples listed on Table 2a (supplementary material) were analyzed by X-ray fluorescence (XRF) at the University of Oviedo (Spain) using glass beads. The average precision and accuracy for most of the elements were controlled by repeated analyses of G-2 (granite), GSP-1 (granodiorite), AGV-1 (andesite) and PCC-1 (peridotite) rock standards (Govindaraju 1984). They fall in the range of 5–10% relative. Trace element and rare earth elements (REE) were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) with an HP-4500 system at the University of Huelva, following digestion in a HF + HNO₃ (8:3) solution, drying and second dissolution in 3 ml HNO₃. The average precision and accuracy for most of the elements were controlled by repeated analyses of SARM-1 (granite) and SARM-4 (norite) international rock standards. They fall in the range of 5–10% relative.

Major and trace elements of samples listed on Table 2b (supplementary material) were determined by X-ray fluorescence (XRF) and inductively coupled plasma mass spectrometry (ICP-MS), respectively, at the Centro de Instrumentación Científica, University of Granada. Precision for major elements is better than 1.5%, for analyse concentration of 10%, using the following geostandards (Govindaraju 1994): BHVO-1 (basalt), G-2 (granite), RGM-1 (rhyolite), SDC-1 (mica schist), STM-1 (syenite), BIR-1 (basalt), DNC-1 (diabase), GH (granite), BR (basalt), MICA-Fe (biotite), MICA-Mg (phlogopite), DR-N (diiorite), UB-N (serpentine),

DT-N (kyanite), GS-N (granite), FK-N (K-Feldspar), AN-G (anorthosite), BE-N (basalt), MA-N (granite) and AL-I (albite). Analysis of trace elements was performed following the method described by Bea (1996), considering that the precision was approximately 2 and 5% error on concentrations of 50 and 5 ppm, respectively, using the standards PMS, WSE, UBN, BEN, BR and AGV, described in Govindaraju (1994).

3.2 U–Pb geochronology

Three samples of granitic rocks: Ruanes tonalite (A31505; UTM coordinates: X = 742,468.537, Y = 4,343,129.078), Plasenzuela two-mica leucogranite (A31506; UTM coordinates: X = 758,192.856, Y = 4,361,209.216) and Albalá cordierite-bearing monzogranite (A61412; UTM coordinates: X = 755,238.623, Y = 4,362,439.042) were crushed and sieved, separated via heavy liquids, and hand-picked under binocular microscope at Universidade de Évora and Universidad de Granada. Zircon concentrates were cast on a 3.5 cm diameter epoxy mount, together with zircon standards (TEMORA zircon, SL13 zircon and GAL zircon), then polished and documented using SEM-CL, at the IBERSIMS (University of Granada, Spain). Mounts were coated with gold (80-µm thick) and inserted into the SHRIMP for analysis.

Each selected spot was rastered with the primary beam during 120 s prior to analysis, and then analysed over 6 scans following the isotope peak sequence ¹⁹⁶Zr₂O, ²⁰⁴Pb, 204.1 background, ²⁰⁶Pb, ²⁰⁷Pb, ²⁰⁸Pb, ²³⁸U, ²⁴⁸ThO, ²⁵⁴UO. Every peak of each scan was measured sequentially 10 times with the following total counts per scan: 2 s for mass 196; 5 s for masses 238, 248, and 254; 15 s for masses 204, 206, and 208; and 20 s for mass 207. The primary beam, composed of ¹⁶O¹⁶O²⁺, was set to an intensity of 4–5 nA, using a 120-µm Kohler aperture, which generates 17 × 20 µm elliptical spots on the target. The secondary beam exit slit was set at 80 µm, achieving a resolution of about 5000 at 1% peak height. All calibration procedures were performed on the standards included on the same mount. Mass calibration was performed on the GAL zircon (ca. 480 Ma, very high U, Th and common lead content; Montero et al. 2008). Analytical sessions initially involved the measurement of SL13 zircon (Claoué-Long et al. 1995), which was used as a concentration standard (238 ppm U). TEMORA zircon (ca. 417 Ma, Black et al. 2003), used as isotope ratios standard, was then measured every four unknowns.

Data reduction was performed using SHRIMPTOOLS software specifically developed for IBERSIMS (available from www.ugr.es/~fbea). The intensity of each measured isotope was calculated in two steps using the software: first, the STATA letter-value display algorithm was used to find outliers in the ten replicates measured at each peak during

each scan, discarding them and averaging the rest once they had been normalized to SBM measurements; then, for each isotope, a robust regression of each scan average versus time, if measured, was performed. The final result for each isotope was calculated as the value at the mid-time of the analysis resulting from the robust regression line. Errors (95% confidence level) were calculated as the standard error of the linear prediction at the mid-point of analysis. $^{206}\text{Pb}/^{238}\text{U}$ was calculated from the measured $^{206}\text{Pb} + ^{238}\text{U}$ and $\text{UO} + ^{238}\text{U}$ following the method described by Williams (1998). For high-U zircons ($\text{U} > 2500$ ppm) $^{206}\text{Pb}/^{238}\text{U}$ was further corrected using the algorithm of Williams and Hergt (2000). Plotted and tabulated analytical uncertainties are 1σ precision estimates. Uncertainties in calculated mean ages are 95% confidence limits ($t\sigma$, where t is the Student's t multiplier) and, for mean $^{206}\text{Pb}/^{238}\text{U}$ ages, include the uncertainty in Pb/U calibration (0.3–0.5%). Common Pb corrections assumed a model common Pb composition appropriate to the age of each spot (Cumming and Richards, 1975). U–Th–Pb data are presented in Table 3 (supplementary material) and plotted using Isoplot 4 (Ludwig 2009).

4 The Central Extremadura batholith

The Central Extremadura batholith is located in the south-east part of the Central Iberian zone (Fig. 1). The petrological and structural characteristics of the Central Extremadura batholith have been described in Corretgé (1971), Castro (1984, 1986), Corretgé et al. (1985), Pérez del Villar (1988), Vigneresse and Bouchez (1997), Castro and Fernández (1998), and Fernández and Castro (1999). It is mainly intrusive into low-grade metasedimentary series composed of schists and metasandstones of Ediacaran–Cambrian age of the SGC domain (Rodríguez Alonso et al. 2004). The Central Extremadura batholith was originally thought to have been generated entirely during Variscan igneous activity. However, some recent geochronological work has shown the existence of Lower Ordovician plutonic rocks (ca. 482–470 Ma; Zarza la Mayor, Zarza de Montánchez and Arroyo de la Luz granitic rocks; Rubio-Ordóñez et al. 2012). With regard to the Variscan deformation recorded in the SGC domain, it is traditionally accepted that a first deformation phase (D_1) gave rise to NW–SE trending, kilometer-scale upright folds with associated regional, axial-plane foliation (S_1) (Castro 1984, 1986) (Fig. 1). However, some of the above-mentioned D_1 structures have been recently reinterpreted as being both younger and associated with the D_3 deformation phase (Martínez Catalán 2011; Martínez Catalán et al. 2014) (Fig. 1). Intrusion of Variscan plutons (e.g. Plasenzuela two-mica leucogranite) took place at shallow pressure (around 200 MPa, Castro 1984), inducing contact metamorphism near the granitic body

(Fig. 2) that overprinted the mineral assemblages associated with S_1 . The Plasenzuela two-mica leucogranite was emplaced during the second deformation phase (D_2 ; Castro and Fernández 1998; Fernández and Castro 1999). D_2 was responsible for the large-scale rotation and folding of S_1 that defines a huge Z-shaped structure (Fig. 1) and a cortege of shear zones heterogeneously affecting the plutons and their host rocks (Castro 1984, 1986; Castro and Fernández 1998; Fernández and Castro 1999). The kinematics of D_2 at the largest scale has been described as being associated with the movement along a deep-seated, E-W-trending and steeply dipping dextral shear zone (Fig. 1) favoring both the rotation of S_1 and the ascent and emplacement of Variscan plutons in tension gashes (Castro 1986; Fernández and Castro 1999). It is worth noting that recently dated plutons with Lower Ordovician ages (e.g., Zarza la Mayor; Rubio-Ordóñez et al. 2012) show no signs of internal deformation, even when penetrative S_1 Variscan foliation surrounds the intrusions. The third deformation phase (D_3) produced upright folds with kilometer-scale wavelengths, associated with minor folds and S_3 crenulation cleavage superimposed on earlier generations of structures. The Albalá pluton is intrusive on the SGC and also cross-cuts D_3 – D_1 Variscan structures, developing contact metamorphism in the Lower Paleozoic rocks of the northern limb of the D_3 Sierra de San Pedro syncline (López Díaz et al. 1990).

4.1 The Ruanes-Santa Cruz-Zorita plutonic–metamorphic complex

This plutonic–metamorphic complex occupies the south-east part of Central Extremadura batholith (Figs. 1, 2). The dimensions of this area exceed 40 km from east to west and at least 30 km from north to south (Fig. 2). A number of plutonic bodies (Zarza de Montánchez, Alijares, Villamesías, Ruanes, Santa Cruz and Zorita here collectively described as RSZ and composed of quartzdiorites, tonalites, granodiorites, and granites) comprise more than the 30% of the complex. RSZ plutons range in shape from laminar in the western zone of the complex, to rounded, in the east. Of this group of magmatic bodies, the only ones which have been dated so far are the Zarza de Montánchez (ca. 482 Ma; Rubio-Ordóñez et al. 2012) and Ruanes (ca. 464 Ma; this study) plutons. No absolute age determination is yet available for the Montánchez pluton, which is only tentatively associated here with the RSZ, although it shows pervasive solid-state deformation structures (Castro 1984, 1986). Small bodies, probably representing the exposure of the irregular top of more extensive plutons at depth, appear at the NW, south of Plasenzuela (e.g. in Ruanes). All these plutonic bodies are emplaced into the metasedimentary rocks of the SGC.

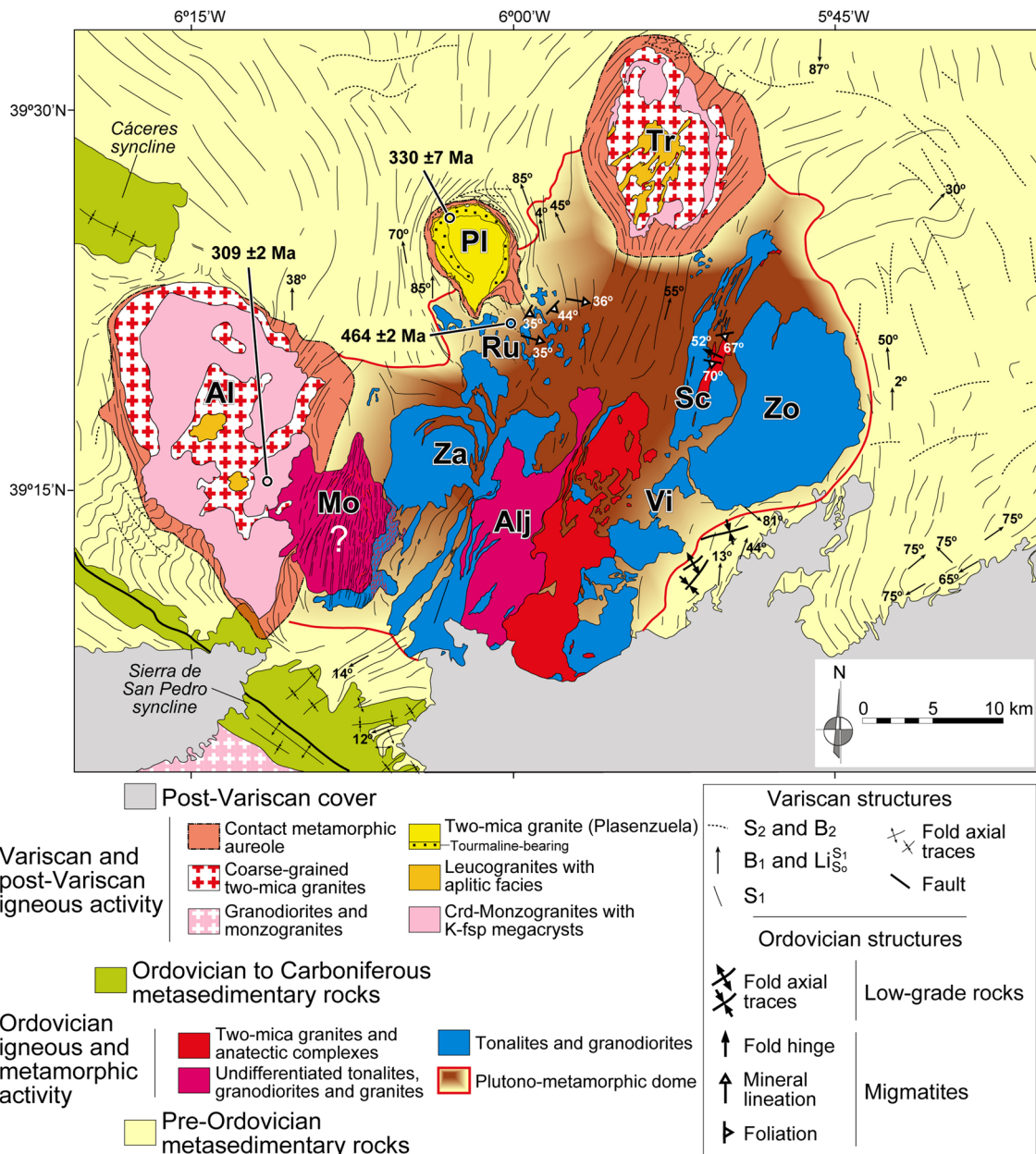


Fig. 2 Geological map of the studied area located in the Central Extremadura batholith (southern Central Iberian zone). Modified from Castro (1984) and Clariana García et al. (2017). Studied plutons: *Al* Albalá, *Alj* Alijares, *Mo* Montánchez, *Pl* Plasenzuela, *Ru*

Ruanes, *Sc* Santa Cruz, *Tr* Trujillo (296 ± 3 Ma—LA-ICPMS zircon, Gutiérrez-Alonso et al. 2011); *Vi* Villamesías, *Za* Zarza Montánchez (482 ± 10 Ma—EMPA monazite, Rubio-Ordóñez et al. 2012); *Zo* Zorita

Variscan S₁ foliation trending consistently from N-S to NNE-SSW encompasses the RSZ plutons, which have never been observed cross-cutting S₁. These field relationships suggest that S₁ is a younger fabric superimposed on a crust previously structured by the effects of Ordovician intrusions and their metamorphic imprint on the country rocks. The limit of the RSZ plutonic–metamorphic complex is marked by the boundary of its metamorphic effects on the host SGC. Metamorphism ranges from low- to high-grade, with the

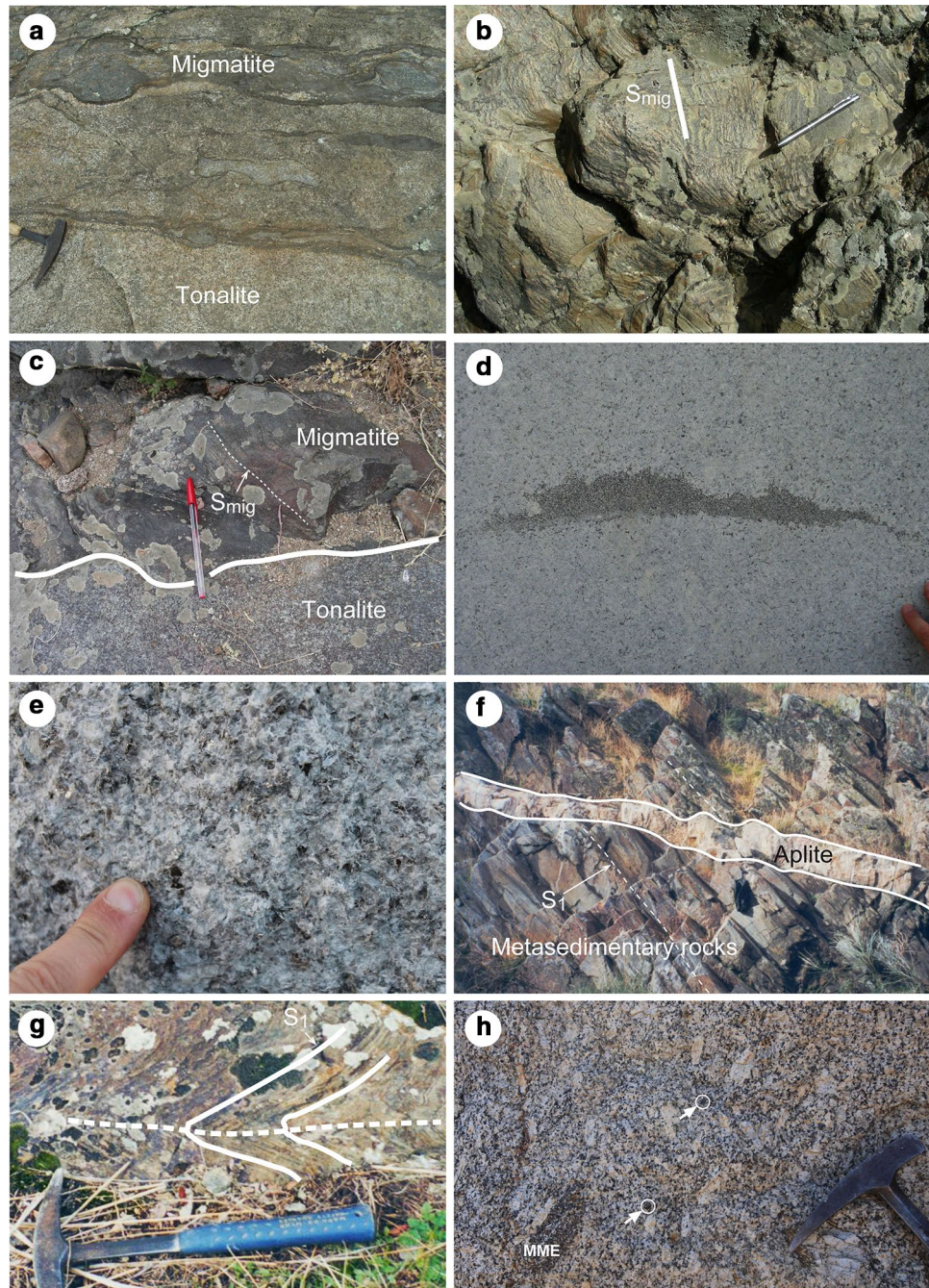
generation of extensive anatectic complexes with abundant migmatitic rocks (metatextite and diatextite) and leucogranites, particularly in the central part of the RSZ plutonic–metamorphic complex (Fig. 2), where a complex alternation of deformed granites and tonalites dominates a several kilometer-thick sequence. Shear bands are abundant, following a N-S general orientation, locally cross-cutting main contacts of granitic layers that follow a NNE-SSW orientation (Fig. 2). A distinct, E-W-to-ENE-WSW-trending foliation

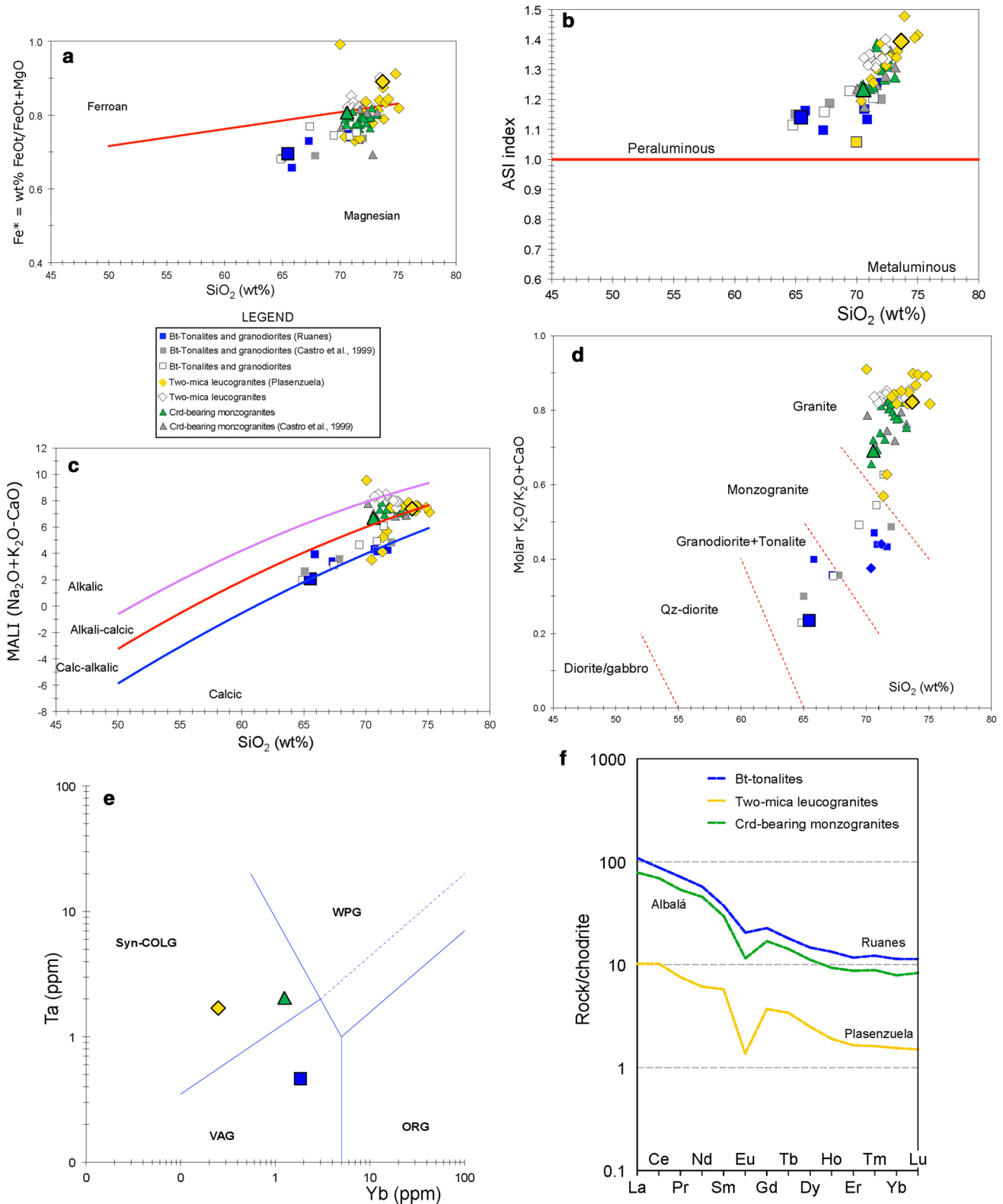
affecting the SGC appears in the region. This foliation is mainly preserved in high-grade areas, close to plutonic bodies, where it is recorded in migmatites (S_{mig} ; Fig. 3a, b), and is crosscut by contacts with the magmatic intrusions, their apophyses, or associated dikes (Fig. 3c). Given the age of the Ruanes tonalite, the pre-Variscan migmatitic foliation described above could be considered, for the first time, as being contemporary with the Ordovician intrusion of the magmatic bodies of the RSZ plutonic–metamorphic complex. This pre-Variscan high-grade (migmatitic) foliation has not been observed outside high-grade areas, which is

interpreted as being due to its weak intensity and the severe transposition effects of the Variscan S_1 . The arrangement of anatectic domains close to the approximate center of the area of study, as well as the position of the main plutonic bodies, point to a pre-Variscan dome-like geometry, with the most intense metamorphic effects located around and in the vicinity of the most voluminous and abundant plutonic bodies.

Furthermore, to the south of the RSZ plutonic–metamorphic complex, a fold train affecting the SGC host rocks and showing hectometric to kilometeric wavelengths is cut by S_1 foliation. Matas et al. (2005) interpreted this

Fig. 3 Field photographs of some relevant relationships observed in the studied area. **a** Banded structure with alternating layers of tonalite and migmatite (Santa Cruz de la Sierra). Resister boudins appear embraced by the main planar fabric within the migmatite, which is parallel to the contact with the tonalite layers. **b** Metatextites with stromatitic structure. The main migmatitic foliation (S_{mig}) is marked by the parallel arrangement of leucosomes and the preferred orientation of minerals in the mesosome. **c** Tonalite dike crosscutting the main foliation in its hosting migmatites. **b**, **c** southeast of Plasenzuela). **d** Coarse-grained Plasenzuela two-mica leucogranite (tourmaline-bearing). Although rather isotropic in the field, occasional schlieren can be seen close to the external contact of the pluton. **e** Close view of the Plasenzuela two-mica leucogranite. **f** Aplite dike associated with the Variscan Plasenzuela pluton crosscutting the S_1 Variscan foliation of the hosting SGC. **g** Variscan S_1 foliation folded by the Variscan D_2 phase in the SGC close to the northern contact of the Plasenzuela pluton. The white dashed line marks the location of the axial trace of a D_2 fold. **h** Field appearance of the Albalá monzogranite, porphyritic and rich in biotite, it also shows some cordierite crystals (white arrows) and mafic microgranular enclaves (MME). A magmatic planar fabric is defined by the preferred orientation of the K-feldspar megacrysts





train of folds as being pre-Variscan. The trend of the axial traces of the pre-Variscan folds is parallel to the measured migmatitic foliation within the RSZ plutonic–metamorphic complex (this study). It is therefore suggested here

that these pre-Variscan folds may represent the response of SGC sedimentary units to the deformation event that conditioned the emplacement at depth of the extensive cortege of coeval plutonic bodies.

Fig. 4 Geochemical diagrams of the studied 58 samples from the Central Extremadura batholith (Table 2a, b—supplementary material); tonalites and granodiorites from Ruanes, Zorita, Zarza, Santa Cruz; two-mica leucogranites from Plasenzuela, Montánchez and Santa Cruz; and Crd-bearing monzogranites from Albalá, Trujillo, Alcuescar, Garrovillas, and Cabeza de Araya). Data from Castro et al. (1999) are plotted together with those from this study in major-element diagrams. **a** SiO_2 vs Fe number diagram discriminates rocks between magnesian and ferroan types (Frost et al. 2001). **b** SiO_2 vs ASI index ($\text{Al}_2\text{O}_3/[\text{Na}_2\text{O} + \text{K}_2\text{O} + (\text{CaO} - 3.3 * \text{P}_2\text{O}_5)]$); Frost et al. 2001) diagram shows the peraluminosity of all studied rocks. **c** The MALI index (Frost et al. 2001) separates the intermediate rocks as calc-alkalic and most granite as alkali-calcic. **d** SiO_2 vs $\text{K}_2\text{O}/\text{K}_2\text{O} + \text{CaO}$ molar ratio, an empirical transformation of the QAP diagram, showing the geochemical variety of rocks from granodiorites/tonalites to granites. **e** The Yb vs Ta diagram plots the dated samples of the Plasenzuela two-mica leucogranite and the Albalá cordierite-bearing monzogranite into the Syn-COLG field whereas the dated sample from Ruanes tonalite plots into the VAG field (Pearce et al. 1984). **f** Chondrite normalized (Nakamura 1974) REE patterns point to a greater fractionation for leucogranites showing pronounced negative Eu anomalies. The three dated samples from Ruanes, Plasenzuela and Albalá plutons are marked with larger symbols

The RSZ plutons are made of medium-grained, I-type biotite-rich tonalites, granodiorites and S-type cordierite-bearing leucogranites. The silica contents vary from 64 to 73 wt% SiO_2 (Table 2a, b—supplementary material). The studied samples align in silica variation diagrams (not shown) defining a decrease in TiO_2 , FeO, MgO and CaO, and an increase in K_2O with magmatic differentiation (Castro 1984). These variations are observed at the scale of kilometer-sized plutons. These intermediate rocks are magnesian and peraluminous and follow a calc-alkalic trend according to the Peacock index (Table 2a, b—supplementary material; Fig. 4). A common feature is the alternation, at the scale of several meters, of tonalites (I-type) and cordierite-bearing leucogranites (S-type). This strongly favors a hypothesis of local interaction and assimilation, with the effect that tonalites acquire a peraluminosity that is higher than typical values for calc-alkaline, Cordilleran I-type granitic series (Fig. 4b). Some contaminated tonalites contain cordierite showing typical signs of local assimilation, similar to that of the granodiorites of the Central System batholith where tonalites are in contact with peraluminous migmatites (Díaz-Alvarado et al. 2011). Tonalites may contain mafic microgranular enclaves, showing the characteristic features of quenched autoliths.

The dated sample from the Ruanes pluton (this study) plots into the field of volcanic-arc granites in the Nb vs Y diagram (Pearce et al. 1984; Fig. 4e). The REE pattern of Ruanes tonalite is more enriched than that of two-mica leucogranites (Table 2b—supplementary material; Fig. 4f).

4.2 The Plasenzuela pluton

Emplacement of Variscan granitic rocks, such as the Plasenzuela pluton, has been ascribed to a D_2 deformation phase (Castro 1984, 1986; Fernández and Castro 1999). S_1 foliation is cross-cut by pluton contacts at outcrop and map scales (Fig. 2), indicating an intra-Variscan age for emplacement of granitic bodies close to the outer limit of the pre-Variscan RSZ plutonic–metamorphic complex described above. A contact metamorphic aureole is observed in the SGC host rocks around the Plasenzuela pluton. The metamorphic aureole is difficult to distinguish in the southern contact between the Variscan granitic intrusion and the pre-Variscan RSZ plutonic–metamorphic complex.

The Plasenzuela pluton (Corretgé et al. 1981; Castro 1984) is composed of coarse-grained two-mica leucogranite showing slight textural and mineralogical changes (Fig. 3d, e). Grain size is coarser in the central part of the pluton. A narrow band of tourmaline-bearing granites is disposed near the contacts with the host rocks. Samples were collected along a traverse from center to rim in order to reveal compositional changes. However, compositional homogeneity is the dominant feature (Table 2a, b—supplementary material). All rocks are classified as S-type alkali-feldspar granites (Chappell and White 1974), characterized by metamorphic minerals, restitic enclaves, high SiO_2 (> 70 wt%) and very low CaO (< 0.6 wt%). Chemically, they are ferroan and markedly peraluminous granites (Fig. 4a, b), with $\text{ASI} > 1.3$ and mostly alkali-calcic (Fig. 4c), showing a narrow silica range from 71.0 to 72.5 wt% SiO_2 (Table 2a, b—supplementary material; Fig. 4). The dated sample of the Plasenzuela two-mica leucogranite (this study) was analyzed for trace elements. The REE pattern shows a negative Eu anomaly indicating Pl fractionation and enrichment in HREE. In the Nb-Y discriminating diagram, the Plasenzuela pluton plots into the field of syn-collisional granites (Table 2b—supplementary material; Fig. 4e). Locally, biotite-rich accumulations (schlieren) are observed. Enclaves are very scarce and all of metamorphic or restitic origin. Aplites and pegmatites are disposed as ring dikes at the margins of the pluton and intruded into the host Neoproterozoic metasedimentary rock crosscutting the S_1 cleavage (Fig. 3f). Vertical-axis D_2 folds crenulate S_1 cleavage, mostly concentrated at the northern margin of the pluton (Fig. 3g). The relationship between the S_2 crenulation cleavage and the contacts of the Variscan granite formed the basis for formulating a model of emplacement compatible with the opening and rotation of large tensional gaps associated with a regional, E-W-oriented, steeply-dipping dextral shear zone (Castro 1986; Castro and Fernández 1998; Fernández and Castro 1999). Accordingly, the emplacement of the Plasenzuela pluton is coeval with a D_2 Variscan deformation phase.

Cordierite and andalusite are common minerals comprising the contact metamorphic aureole and transform the mineral assemblages associated with the first cleavage of host metasedimentary rocks (S_1 ; Castro and Fernández 1998). During ascent and emplacement, pluton margins experienced solid-state deformation which was coeval with the development of chevron folds, minor shear bands and crenulation foliation (S_2 ; Castro and Fernández 1998).

4.3 The Albalá pluton

The Albalá granitic pluton is concentrically zoned. Near the margins it contains relatively larger numbers of mafic types of monzogranite and locally granodiorite composition with mafic microgranular enclaves of tonalitic composition (Fig. 3h). Most leucocratic facies occupy large areas at the inner parts of the pluton, where U-bearing ore deposits are located. Some aplitic masses are located near the core of the pluton. The dated sample corresponds to the marginal facies. This sample is a porphyric, coarse-grained granite with a silica content of 71 wt% SiO_2 and peraluminous (Table 2b—supplementary material; Fig. 4b), and is characterized by large K-feldspar megacrysts, relatively calcic plagioclase (oligoclase–andesine), biotite, and euhedral cordierite (Table 2b—supplementary material; Fig. 4b).

These are chemically classified as cordierite-bearing monzogranites owing to their geochemical and petrological features. Due to the mixed characteristics among calc-alkaline granodiorites and anatectic leucogranites, they have been termed “mixed series” granites (Capdevila et al. 1973; Corretgé et al. 1977; Lagarde and Fourcade 1992), and are designated in the present study as monzogranites. According to the Yb vs Ta diagram, Albalá cordierite-bearing monzogranite belongs to the group of syn-collisional granites (Fig. 4e; Table 2b—supplementary material). Samples from the Albalá pluton are magnesian (Fig. 4a) and have an alkali-calcic signature (Fig. 4c). The REE pattern is also intermediate between tonalites and leucogranites (Fig. 4f; Table 2b—supplementary material) showing a less pronounced Eu anomaly than that of the two-mica leucogranites.

5 SHRIMP U–Pb zircon dating

The Ruanes, Plasenzuela and Albalá plutons of the Central Extremadura batholith were selected for geochronological survey. These three granitic bodies have the potential to provide an absolute age reference for the pre-Variscan, Variscan and post-Variscan structures of the region. Inherited zircon content was used to determine possible sources of granitic magmas.

5.1 Ruanes tonalite (sample A31505)

Ruanes tonalite is a medium-grained, biotite-rich, mesocratic rock composed of biotite, plagioclase and quartz. Cataclastic textures are common, with abundant quartz subgrains and lamellae surrounding subhedral plagioclase. Kinks and fish-shaped aggregates of biotite are common. Plagioclase shows complex oscillatory zoning with repeated dissolution surfaces. Accessory minerals are zircon and rutile. The latter forms acicular sagenitic inclusions in biotite. Muscovite, sericite and epidote are common secondary minerals.

Zircon grains ranging from 75 to 300 μm in size are mostly elongated euhedral crystals (Fig. 5). CL imaging shows that most grains have variable internal patterns (Fig. 5) such as banded zoning, concentric zoning, sector zoning and dark-CL unzoning. The 34 U–Th–Pb isotopic analyses carried out showed a wide range of U (192–1945 ppm) and Th (39–528 ppm) content (Table 3—supplementary material). The majority of Th/U values range from 0.11 to 0.82, giving an average of 0.41, and there is only one with Th/U = 0.07.

Thirty-four U–Th–Pb isotopic analyses of 24 zircon grains are listed in Table 3—supplementary material and plotted in Fig. 5. Common lead uncorrected isotope ratios gave $^{206}\text{Pb}/^{238}\text{U}$ ages of ca. 496–439 Ma. A total of 22 U–Th–U isotopic analyses with a discordance of < 5% yielded a weighted mean of 463 ± 10 Ma (MSWD = 0.18) and a concordia age of 464 ± 2 Ma (MSWD = 0.57; Middle Ordovician) (Fig. 5), which is interpreted as the best estimate for the crystallization age of the plutonic rock. The age calculation excluded spots with a discordance of > 5% (Analyses 2.1, 7.2, 9.1, 9.2, 11.2), and composite grains with ‘disturbed’ cores (Analyses 7.2, 12.2, 18.2—probably more affected by Pb-loss) surrounded by older rims (Analyses 7.1, 12.1, 18.1).

5.2 Plasenzuela two-mica leucogranite (sample A31506)

This is a coarse-grained leucocratic rock composed of quartz, albitic plagioclase, K-feldspar, muscovite and subordinated biotite. Accessory minerals are tourmaline, zircon and apatite. The texture is cataclastic with abundant quartz subgrains and fractures in feldspars. Most muscovite is primary.

Zircon grains ranging from 80 to 130 μm in size are morphologically extremely heterogeneous, including euhedral grains with simple oscillatory growth zoning and prismatic grains with banded zoning as well as composite grains composed of an unzoned, banded zoned or concentric zoned core surrounded by a weakly zoned or unzoned overgrowth. The 24 U–Th–Pb isotopic analyses of 21 zircon grains carried out are listed in Table 3 (supplementary

RUANES TONALITE

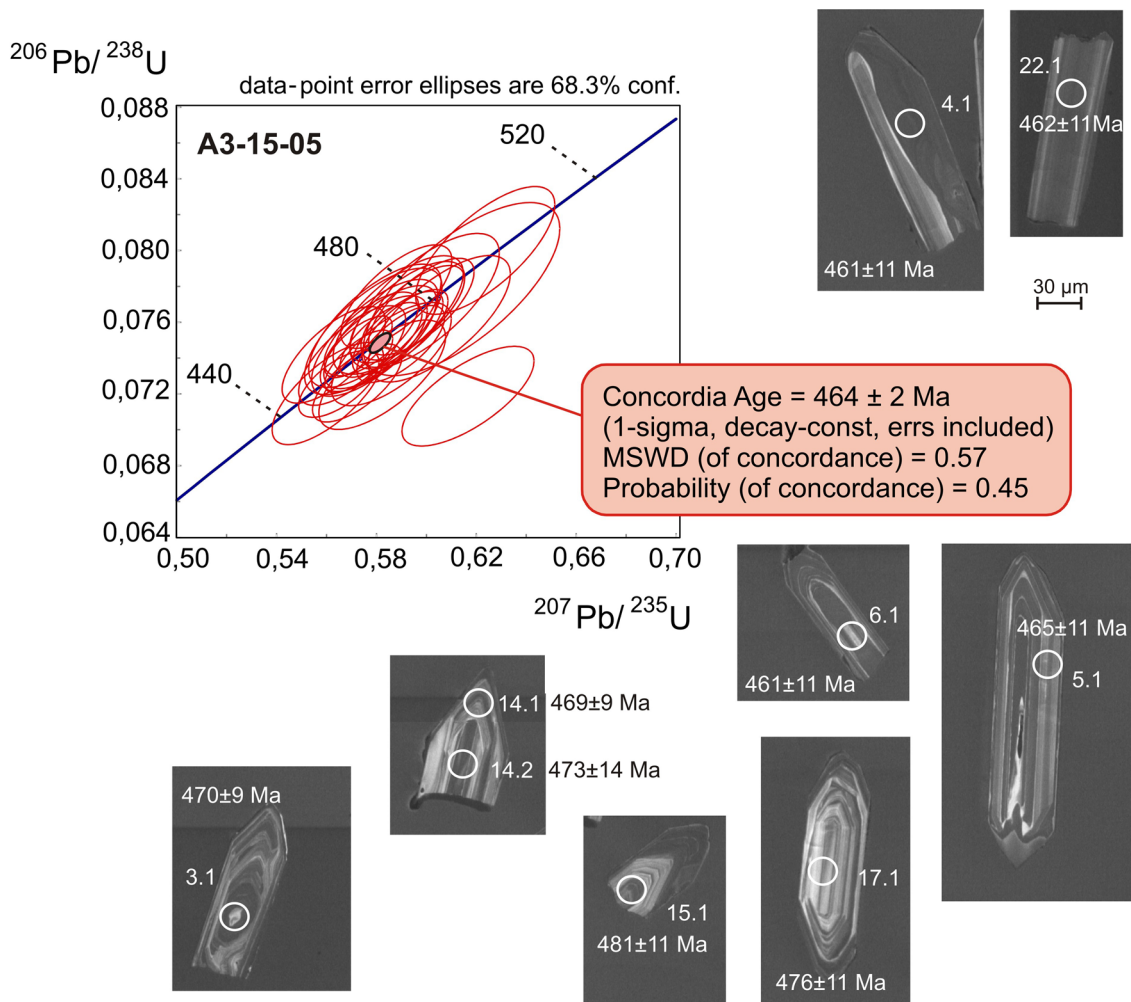


Fig. 5 Concordia plots with the U–Pb zircon ages of the Ruanes tonalite; MSWD–mean square of weighted deviates; cathodoluminescence (CL) images with reference to analyzed spots of most representative zircon grains

material) and plotted in Fig. 6. There is a large variation of U (61–1678 ppm) and Th (10–1074 ppm) content (Table 3—supplementary material). Common lead uncorrected isotope ratios gave $^{206}\text{Pb}/^{238}\text{U}$ ages of ca. 1817–321 Ma. A total of 18 U–Th–U isotopic analyses with a discordance of < 5% are divided into two main groups: the youngest 8 analyses have Carboniferous ages (ca. 342–323 Ma), and the oldest 10 represent an inherited component with ten grains ranging from Paleoproterozoic to Ordovician ages (ca. 1.8 Ga to 464 Ma; Fig. 6). The eight youngest analyses yielded a concordia age of 332 ± 2 Ma (MSWD = 4.2; Fig. 6) overlapping the weighted mean of 330 ± 7 Ma (MSWD = 0.41; Fig. 6), representing the best estimate of the crystallization age of the plutonic rock. The oldest grains of the inherited component are Paleoproterozoic (17; ca. 1.8 Ga), Neoproterozoic (3, 8, 10, 11 and 18; ca. 816–564 Ma) and Upper Cambrian (7; ca. 493 Ma). In addition, three analyses on two grains (1, 19)

yielded Lower-Middle Ordovician ages (ca. 477–464 Ma) that overlap in part with the zircon grain ages of Ruanes tonalite (sample A31505).

5.3 Albalá Crd-bearing monzogranite (sample A61412)

This is a coarse-grained, porphyritic rock, composed essentially of subhedral and zoned plagioclase, quartz, K-feldspar and biotite. Large (6–8 cm length) K-feldspar megacrysts are common. Cordierite may be locally present forming large (> 5 mm length) prisms with alteration to pinnite. Fine-grained microgranular enclaves, together with biotite-rich polycrystalline spots, are common.

U–Th–Pb isotopic analyses of 20 zircon grains are listed in Table 3 (supplementary material) and plotted in Fig. 7. Zircon grains range from 70 to 250 μm in size and are mostly

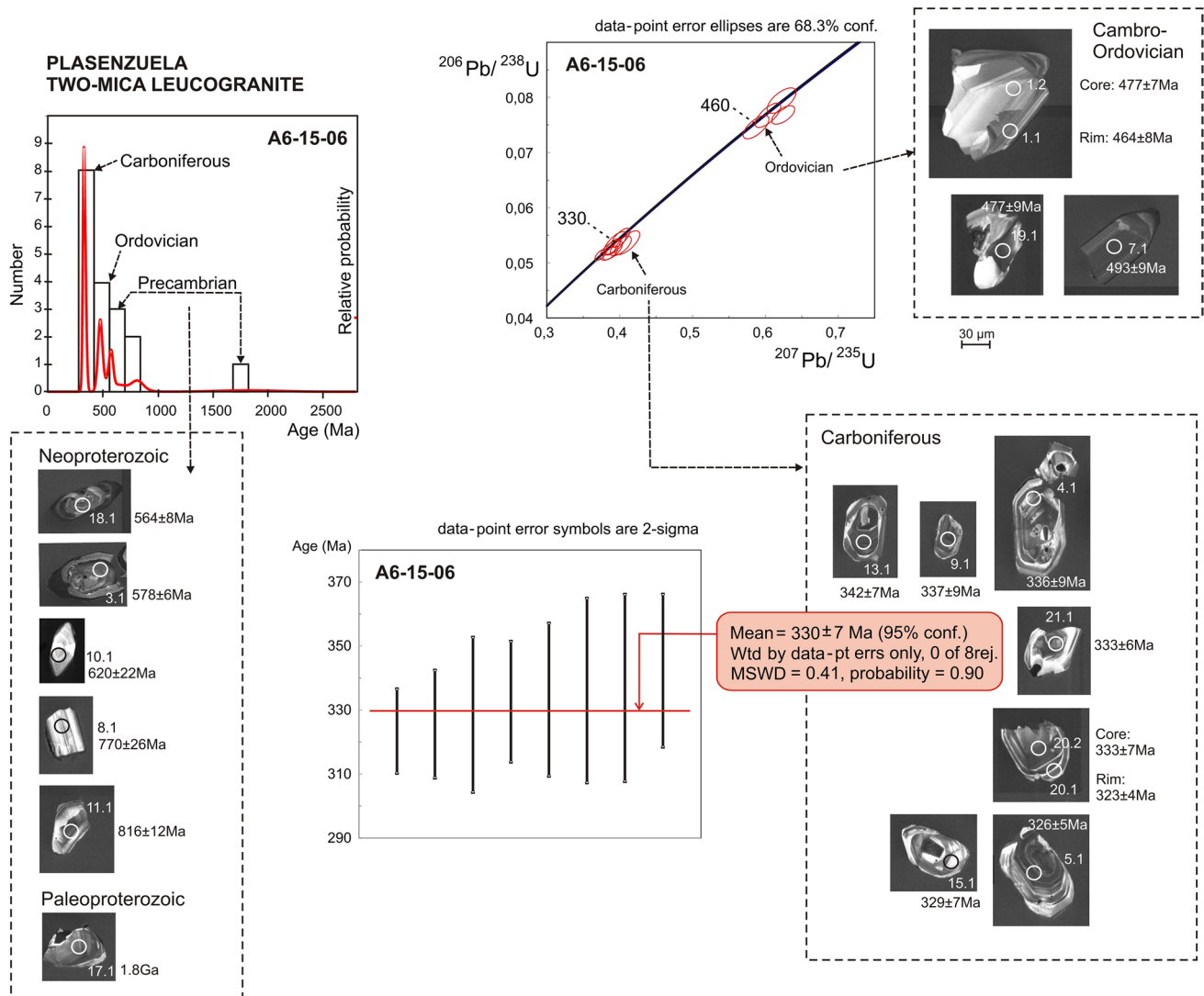


Fig. 6 Probability density plot of U–Pb zircon ages from the Plasenzuela two-mica leucogranite. Concordia plots with the Carboniferous and Ordovician U–Pb zircon ages; weighted average ages of the

youngest U–Pb zircon ages (Carboniferous); MSWD—mean square of weighted deviates; cathodoluminescence (CL) images with reference to analyzed spots of most representative zircon grains

needle-shaped acicular crystals (Fig. 7). CL imaging shows that the internal pattern of morphologically complex zircon consists of a variable-width concentric zoned rim surrounding a core. There are unzoned to weakly concentric zoned and banded zoned cores. The zircon population is characterized by a wide range of U (161–2710 ppm) and Th (15–677 ppm) content (Table 3—supplementary material). The average Th/U value for rims is 0.45. The highest Th/U value of 1.09 was obtained from a banded zoned acicular crystal (analysis 21.1) and four analyses yielded very low Th/U ratios (0.03–0.04; Analyses 1.1, 6.1, 12.1 and 20.1; Table 3—supplementary material). Common lead uncorrected isotope ratios gave $^{206}\text{Pb}/^{238}\text{U}$ ages of ca. 704–297 Ma. Apart from three spots with a discordance of > 5% (analyses 5.2, 6.1, 17.1) and a spot with a Neoproterozoic age of

ca. 572 Ma (grain 13), the remaining 16 analyses yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of $309 \pm 2\text{Ma}$ (MSWD=0.9; Fig. 7), representing the best estimate of the crystallization age of cordierite-bearing monzogranite.

6 Discussion

6.1 Ordovician plutonism-metamorphism in the Central Extremadura batholith

In the Central Extremadura batholith, early-middle Ordovician plutonism is represented by Ruanes tonalite dated at 464 ± 2 (this study; Fig. 5) and by Zarza la Mayor, Arroyo de la Luz and Zarza de Montánchez tonalites dated at ca.

ALBALÁ Crd-BEARING MONZOGRAHITE

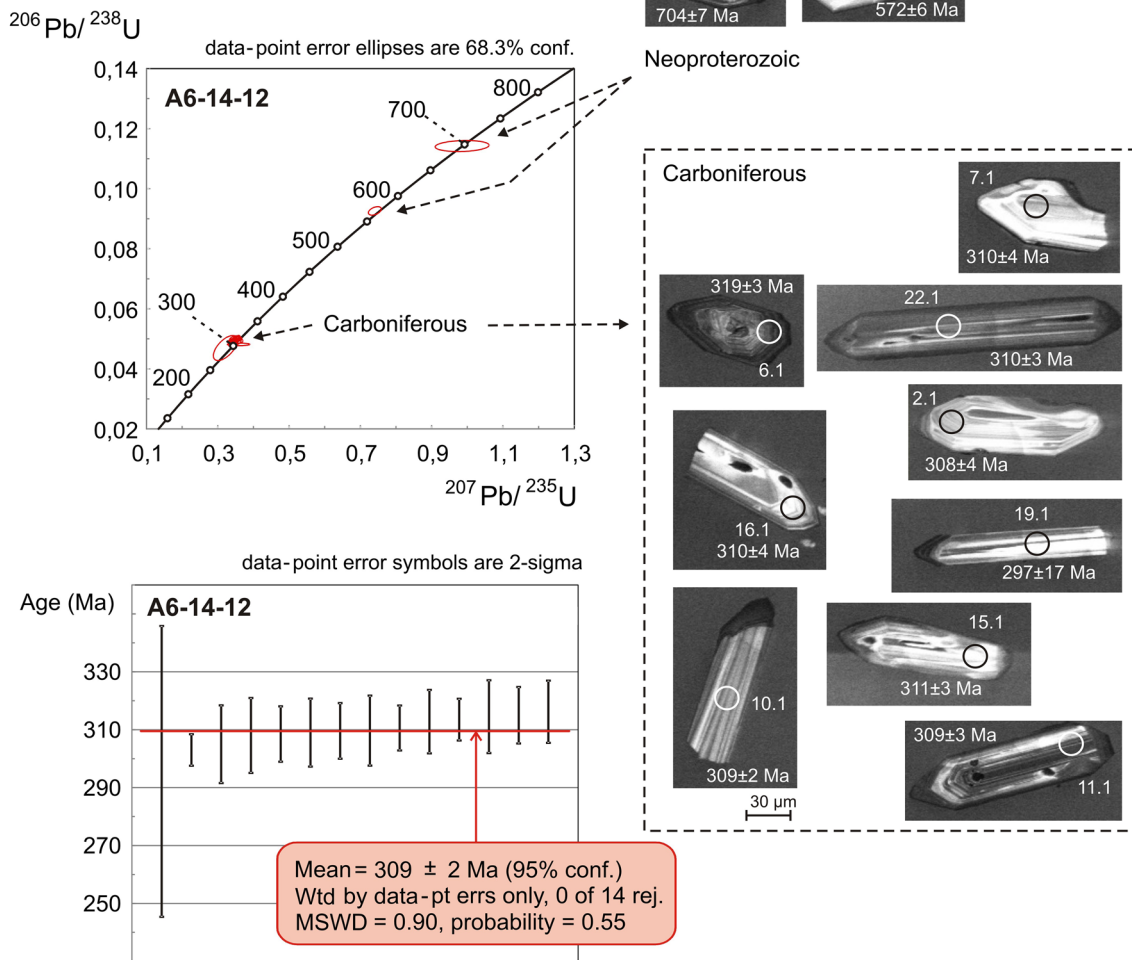


Fig. 7 Concordia plots with the U–Pb zircon ages of the Albalá cordierite-bearing monzogranite; weighted average age; MSWD—mean square of weighted deviates; cathodoluminescence (CL) images with reference to analyzed spots of most representative zircon grains

482–470 Ma (Rubio-Ordóñez et al. 2012) (Table 1). This plutonism extends westward into the Beira and Alto Alentejo regions where Cambro–Ordovician plutons have been dated (Portugal; ca. 493–471 Ma; Solá et al. 2008 and references therein; Antunes et al. 2009; Neiva et al. 2009; Romão et al. 2010; Table 1), defining a magmatic province which is more than 200 km in length.

In the particular case of Ruanes pluton, there is evidence of tonalitic dykes cut and/or developed contemporaneously and concordant with the migmatitic foliation of SGC host rocks. Our new U–Pb data also suggest that SGC host rocks of the Ruanes intrusion experienced a pre-Variscan deformation event. We are therefore able to posit the hypothesis of a Middle Ordovician plutonic–metamorphic event along which metamorphic conditions were met to form migmatites and anatectic S-type leucogranites contemporaneously with the intrusion of tonalites.

The study sample from Ruanes is representative of large plutons with massive tonalites and granodiorites in the region sharing identical geochemical signatures. All these plutons (Ruanes, Zarza de Montánchez, Alijares, Villame-sías, Santa Cruz and Zorita; Fig. 2) may be associated with a large input of calc-alkaline tonalitic magmatism, later modified by local contamination/assimilation, during the Lower-Middle Ordovician. The majority of analyzed zircon grains from Ruanes tonalite gave an average Th/U = 0.41, indicating magmatic origin probably associated with a felsic-intermediate metaluminous source, whereas for only one grain Th/U = 0.07, typical of zircon precipitated during high-grade metamorphism and/or partial melting of peraluminous rocks (Williams and Claesson 1987). Interestingly, the dated Ruanes sample is associated with sillimanite–cordierite migmatites that were developed around tonalitic intrusions. Near the dated sample, the neighboring Santa Cruz pluton

shows abundant migmatites and anatectic leucogranites that alternate in interfingered layers with intrusive tonalites at the meter- to kilometer-scale (Castro 1984). In sum, in this study, we are able to report for the first time the presence of a regional plutonic–metamorphic complex developed during the Middle Ordovician. The presence of penetrative, pre- to syn-metamorphic foliation in Ruanes migmatites is indicative of large-scale deformational episodes during the Middle Ordovician. These observations, together with the orogenic feature of the calc-alkaline magmatism prove the existence of Middle Ordovician orogeny (Sardic phase of a Caledonian event) in Iberia (Fig. 8).

6.2 Age, origin and tectonic settings of Carboniferous granitic rocks from the Central Extremadura batholith

The dated Carboniferous granitic rocks of the Central Extremadura batholith represent different magmas that were emplaced in two distinct tectonic settings linked to two orogenic cycles separated in time but coincident in space (Fig. 8).

6.2.1 Lower Carboniferous syn-kinematic magmatism

The Plasenzuela two-mica leucogranite is a Variscan intrusion dated at 330 ± 7 Ma (Lower Carboniferous; Fig. 6). This age dates the second phase of deformation in the Central Extremadura batholith. D_2 high-angle transcurrent shear zones are responsible for both the syn-kinematic

emplacement of the Plasenzuela granitic body (Castro and Fernández 1998) and the rotation of S_1 regional cleavage (Fig. 9).

The D_2 dextral strike-slip shear zones of the Central Extremadura batholith probably acted simultaneously with D_2 low-angle extensional shear zones, well-represented in the northern and central domains of the Central Iberian zone (Fig. 9b, c). The age of acting of these low-angle D_2 extensional shear zones coincides with the metamorphic peak and the intrusion of early syn-kinematic granitic rocks of the Central Iberian zone at ca. 336–313 Ma (Dias et al. 1998; Teixeira et al. 2012; Costa et al. 2014; Díez Fernández and Pereira 2016; López-Moro et al. 2017; Pereira et al. 2018; Table 1). The age of Plasenzuela two-mica leucogranite is, however, much older than the emplacement of the cordierite-bearing granitic rocks of the neighboring ca. 309 Ma-aged Albalá pluton (Fig. 7).

The markedly peraluminous granitic magmas of the Plasenzuela pluton were most probably transported from relatively deeper crustal domains (middle-upper crust) that experienced partial melting conditions during D_2 extension. The oldest inherited zircon grain in the Plasenzuela two-mica leucogranite is Paleoproterozoic (ca. 1.8 Ga). The Neoproterozoic age group is the largest one matching the ages of Pan-African and Cadomian zircon-forming events (e.g. Pereira et al. 2015 and references therein). These Precambrian inherited zircon ages (ca. 816–564 Ma) resemble the age population of detrital zircon of the Ediacaran–Cambrian SGC (Teixeira et al. 2011; Pereira et al. 2012; Talavera et al. 2012, 2015). The remaining inherited grains gave Cambrian

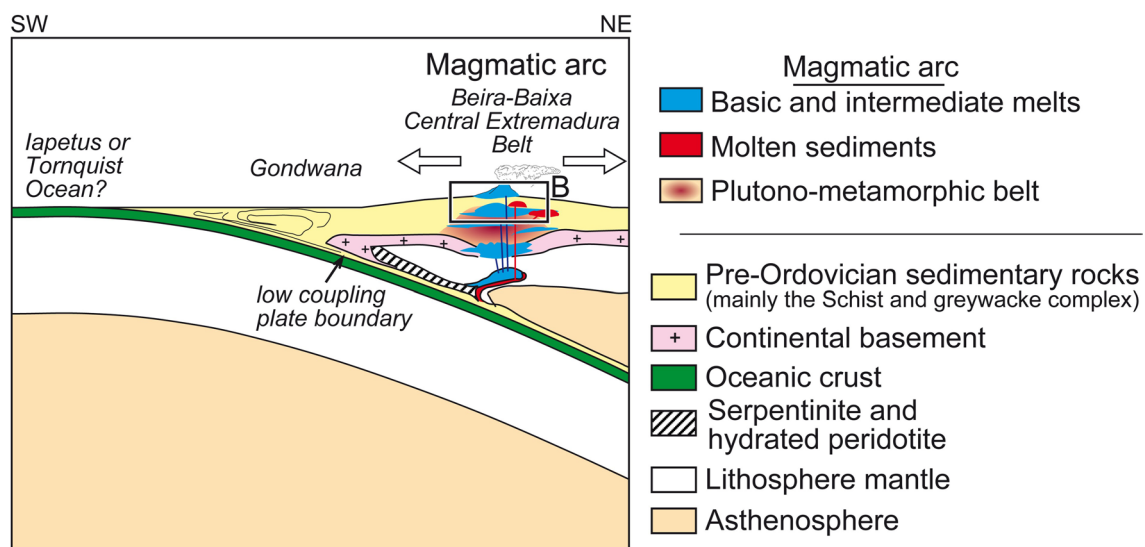
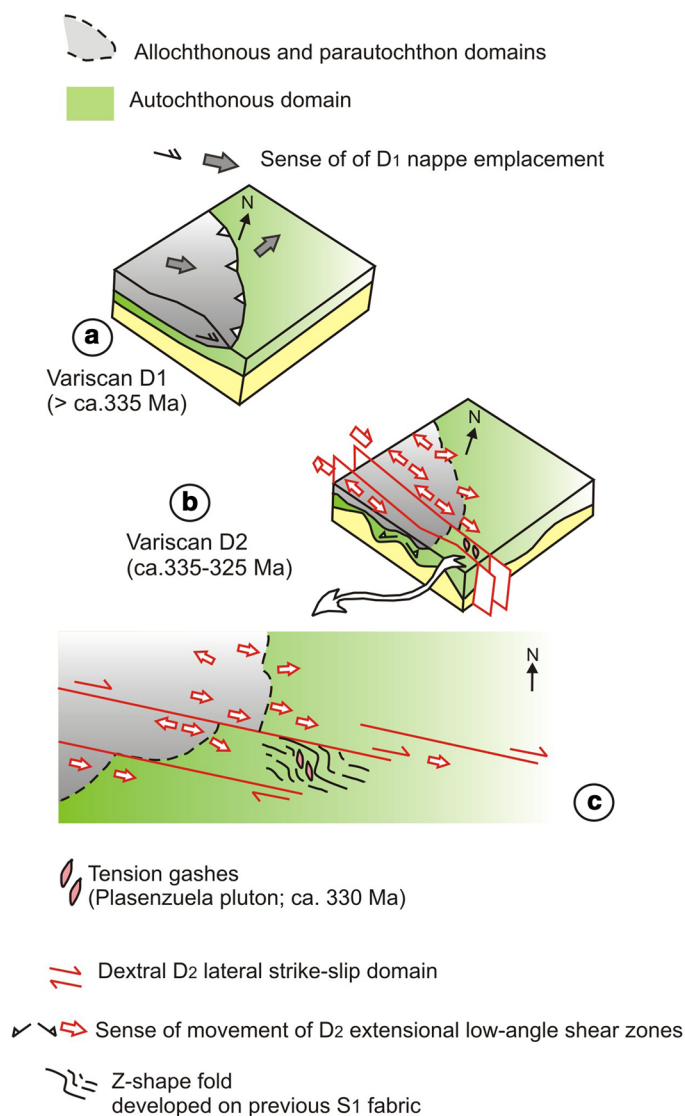


Fig. 8 Large-scale interpretative sketch of the studied zone in the framework of an Ordovician subduction of the Iapetus–Tornquist oceanic lithosphere beneath the Gondwana margin (modified from Díaz Alvarado et al. 2016). The Central Extremadura batholith was located

in an extensional setting associated with the arc or retro-arc section of the subduction orogeny (Iberian Caledonides). The rectangle shows the location of the area enlarged in Fig. 11b–d

Fig. 9 Interpretative sketches of the studied zone in the framework of the formation of the Central Iberian arc during the Variscan orogeny (modified from Martínez Catalán 2011; Martínez Catalán et al. 2014): **a** nappe emplacement and lithosphere thickening during D₁ contractional deformation; during phase D₁ there are different directions of movement (grey arrows): towards the N and NE (in the current coordinates) for the external zones (West Asturian-Leonese and Cantabrian zones) and SE-directed in internal zones (allochthonous domains including the Central Iberian zone); **b** intra-orogenic D₂ extensional deformation; during phase D₂ the extension occurs mainly in NW–SE direction, along with the transport of dextral transcurrent shear zones in the center-south part of the Central Iberian zone; **c** detail of D₂ dextral transcurrent shear zones expanded on a map; note the development of a dextral strike-slip domain, a Z-shape fold and a tension gash intruded by granitic magma (Plasenzuela pluton), during large-scale tectonic movement of a SE-directed gravitational detachment system. See text for more information. The north arrows indicate present coordinates



and Ordovician ages (ca. 493–464 Ma) that overlap in time with the magmatic events recorded in the Iberian Autochthonous domain (Table 1).

Although the data available are insufficient to enable a definite conclusion regarding the origin of the magmas to be drawn, some inferences may be stressed on the basis of comparisons with other extensively studied massifs in neighboring areas (e.g. Ollo de Sapo domain; Montero et al. 2007, 2009a). These syn-D₂ Variscan granitic magmas were neither associated with the assimilation of Ordovician tonalites, nor by their melting, since they are anatectic leucogranites with no contamination with a calc-alkaline source. On the basis of the findings of our preliminary study as described in this paper, we posit that the syn-D₂ Plasenzuela pluton probably derived from the partial melting of a peraluminous source, dating from the Cambro–Ordovician that may have contained older inherited zircon grains. Because

melting Ordovician tonalites is not suitable for the generation of S-type magmas, and inherited zircons have, in part, the same age as the tonalites, we suggest that the source of S-type magmas for Plasenzuela was, at least in part, peraluminous migmatites formed around the intruding tonalites. The remelting of migmatites to produce new S-type granites is not uncommon in the Variscan batholiths of the Central System (Díaz-Alvarado et al. 2011), where syn-D₂ migmatites remelted to form anatectic leucogranites and nebulites at the time of intrusion of large calc-alkaline batholiths ca. 21 Ma later (the ca. 309 Ma aged Albalá and Cabeza de Araya plutons—this study; Gutiérrez-Alonso et al. 2011).

In terms of age, source and composition, the Plasenzuela pluton correlates with some of the peraluminous S-type granites of the D₂ Tormes Dome (Escuder Viruete et al. 1994) and Pinhel shear zone (Pereira et al. 2017) located further north in the CIZ. Though metavolcanic in origin,

the singular chemistry of the Cambro–Ordovician Ollo de Sapo Formation, similar to that of metagreywackes, would lead to the production of such S-type peraluminous granites.

6.2.2 Upper Carboniferous post-kinematic magmatism

The Albalá cordierite-bearing monzogranite (309 ± 2 Ma; Fig. 7) does not fit the criteria of anatectic, S-type granites. Albalá and related granites are grouped into a mixed category and are regionally known as “mixed series granites” (e.g. Capdevila et al. 1973; Corretgé et al. 1977; Lagarde and Fourcade 1992). They are more closely linked to the calc-alkaline trends characteristic of the Upper Carboniferous batholiths in Iberia (ca. 311–297 Ma; Table 1). The U–Pb age of ca. 309 Ma obtained for post-kinematic Albalá cordierite-bearing monzogranite places an upper limit on the timing of D_3 folding. This Upper Carboniferous age is in agreement with the U–Pb date of 309 ± 2 Ma obtained for the post-kinematic Cabeza de Araya pluton (Gutiérrez-Alonso et al. 2011) that cut across D_3 Variscan structures (Cáceres and Sierra de San Pedro synclines; Tena-Dávila Ruiz et al. 1980; López Díaz et al. 1990).

6.3 Paleozoic tectonic evolutionary model

The findings of this study suggest that the geological record of the Central Extremadura batholith is the result of the succession in time and the overlap in space of multiple Paleozoic magmatic-orogenic cycles. The present study seems to show that the Central Extremadura batholith is the result of crustal growth caused by the successive accretion of three orogenic belts (e.g. Caledonian, Variscan and Cimmerian; Fig. 11).

6.3.1 Caledonian orogeny

The tectonic, geochemical and geochronological information, currently available regarding the central and northern domains of the Iberian Massif, points to the activity of a Cambro–Ordovician back-arc setting related to the subduction of the Iapetus–Tornquist oceanic lithosphere under the Gondwana margin, and the concomitant opening of the Rheic Ocean (e.g., Fernández et al. 2008; Abati et al. 2010; Díez Fernández et al. 2010; Dias da Silva 2014). Recently, Rubio-Ordóñez et al. (2012), Villaseca et al. (2014) and Díaz Alvarado et al. (2016) have suggested that the magmatic province that extends from Beira and Alto Alentejo (Portugal) to the Central Extremadura batholith, in the southern Central Iberian zone, is also evidence for Upper Cambrian–Middle Ordovician arc-related magmatism, including intermediate rocks (Fig. 8). Apart from the question of the exact location of the Central Extremadura batholith within such a pre-Variscan active continental margin, calc-alkaline

arc magmatism took place during the Lower-Middle Ordovician (ca. 470–464 Ma; Fig. 11b). Ascent and emplacement of intermediate magmas within Ediacaran–Cambrian SGC sedimentary rocks at low depths probably gave rise to extensive regional metamorphism due to heat advection and transfer towards the country rocks. This is, most probably, the origin of the RSZ plutonic–metamorphic complex described in this work, which eventually resulted in the partial melting of host SGC originating metatexites, diatexites and anatectic granites, with which, tonalites are extensively contaminated. Feedback relations between Ordovician plutons, high-grade metamorphism and deformation that generated the observed migmatitic foliation, in accordance with the model proposed by Brown and Solar (1998), may be suggested as an explanation for observed features and the rapid spatial transition (i.e. telescoped isograds) from migmatites to low-grade metamorphic rocks. An extensional setting is favored in the Central Extremadura batholith as an explanation for the rapid ascent and emplacement of calc-alkaline magmas (Fig. 11b). The extensional tectonic setting is supported by the analysis of depositional evolution of Lower-Middle Ordovician sedimentation (e.g., Matas et al. 2005 and references therein), which was accompanied by dacitic, subaerial volcanism (Roiz 1979). Mapped angular unconformity with Ordovician rocks lying directly over tilted SGC strata possibly developed as result of crustal extension (López Díaz et al. 1990; Pereira et al. 2012 and references therein; Dias da Silva et al. 2016). We therefore suggest that a low-coupling plate boundary or a pronounced roll-back of the subducting plate could have triggered widespread extension in the upper plate with normal fault-controlled basins and volcanism at the surface, extensional fault-related folds in the upper crust, and the generalized intrusion of subduction-related magmas at depth also in the upper crust (Fig. 8).

6.3.2 Variscan orogeny

After a long period of relative tectonic stability spanning most of the middle Paleozoic, the Central Iberian zone experienced Variscan orogeny. As a consequence of collision the Iberian continental crust became considerably thicker, with D_1 thrusting and folding in the allochthonous domain causing an increase in thickness of about 30 km (Martínez Catalán et al. 2014) (Fig. 9a). The Variscan D_1 phase led to the generation of NW–SE-trending folds in the metasedimentary rocks of the Iberian Autochthonous domain. In the southern Central Iberian zone, S_1 cleavage is the axial plane of these folds and cross-cut at depth pre-Variscan (Ordovician) folds and the RSZ plutonic–metamorphic complex, showing refraction and changes in its relative intensity in accordance with the rheological behavior of the heterogeneous crust, composed of distinct plutonic and metamorphic bodies (Fig. 11c). Subsequently, extension driven by

gravitational forces and thermal relaxation enabled a large enough increase in temperature to weaken the continental crust, thus producing ductile crustal flow and migmatitic

gneiss domes associated with the propagation of low-angle extensional shear zones (Martínez Catalán et al. 2014; Díez Fernández and Pereira 2016). Simultaneously, the propagation of high-angle transcurrent shear zones, which are located at the lateral margins of gravitational collapse structures (i.e. SE-direct sliding blocks over D₂ detachments), heterogeneously affected the previous structures (Fig. 9b). The functioning of a D₂ dextral, high-angle shear zone is responsible for the clockwise rotation of S₁ structures, and emplacement in the tension gashes of Lower Carboniferous syn-kinematic plutons (i.e. Plasenzuela two-mica leucogranite; Fernández and Castro 1999) in the Central Extremadura batholith (Figs. 9c, 11d).

6.3.3 Cimmerian orogeny

The emplacement in Iberia of granites with ca. 311–299 Ma age occurred after the collision of Laurussia and Gondwana, at an age ca. 60–70 Ma younger than the cessation of the Rheic/Rheno-Hercynian subduction (Pereira et al. 2015 and references therein). However, global paleogeographic reconstructions for Upper Carboniferous–Lower Permian times put Iberia in between the Rheic/Rheno-Hercynian suture and the Paleotethys subduction (Fig. 10). These Upper Carboniferous plutons mostly represent deep-seated silicic magmatism associated with intermediate-mafic suites (Castro et al. 2002 and references therein). Crystallization age of Albalá pluton is within the wider range of ages obtained for

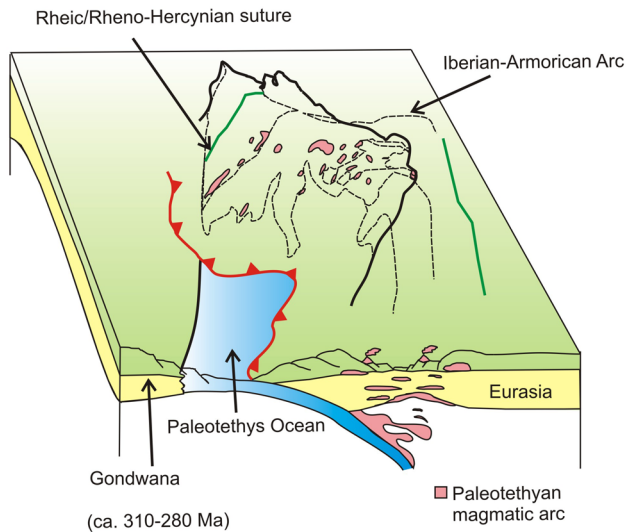


Fig. 10 Schematic diagram with the reconstruction of the Paleotethyan arc at Upper Carboniferous–Lower Permian times (e.g. Cimmerian orogeny), after the closing of the Rheic/Rheno-Hercynian oceans, showing the oceanic-continental subduction zone and the formation of plumes resulting from the dehydration of the subducted oceanic lithosphere, aqueous fluid transport, partial melting, melt extraction and melt emplacement (modified from Pereira et al. 2015)

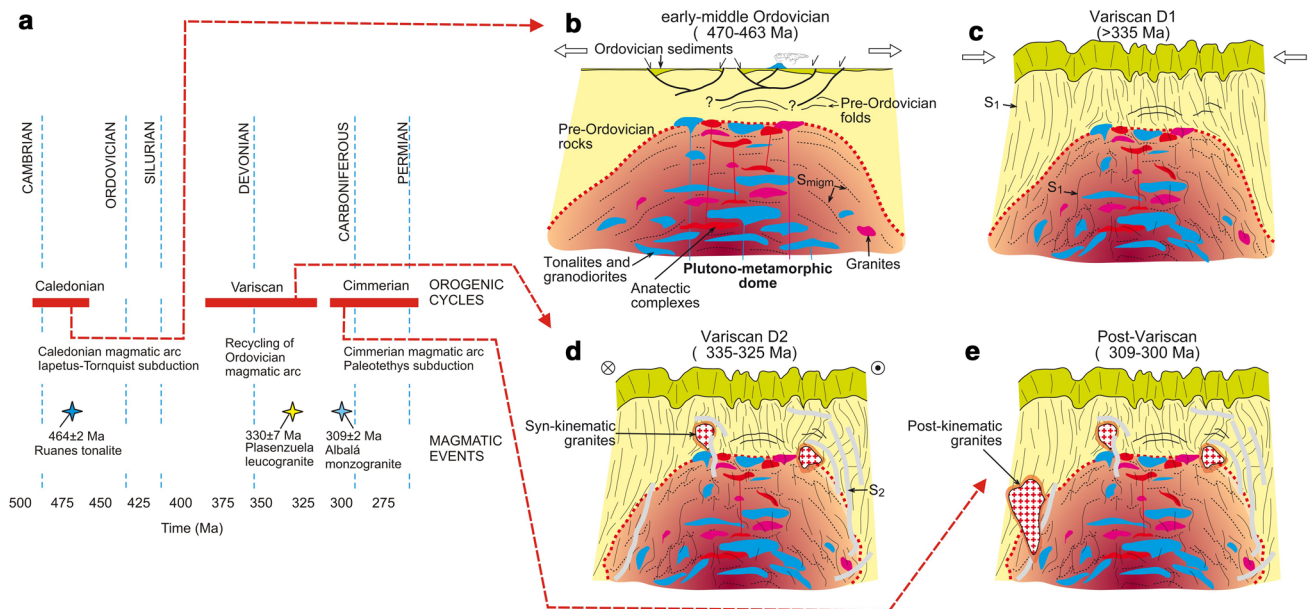


Fig. 11 a Illustrative diagram of the multiple Paleozoic magmatic-oregenic cycles recorded in the Central Extremadura batholith. It should be noted the absence of arc magmatic rocks related to the Rheic/Rheno-Hercynian subduction; b schematic reconstruction of the plutonic–metamorphic belt of the Central Extremadura batho-

lith during the early-middle Ordovician, the first (c) and the second (d) Variscan deformation phases and emplacement of syn-kinematic intrusions. e Emplacement of post-kinematic intrusions. See text for more information

the neighboring Nisa-Alpalhão, Los Pedroches and Santa Eulália-Monforte plutons (ca. 309–297 Ma; Carracedo et al. 2008; Solá et al. 2009; Pereira et al., 2017) consisting of S- (cordierite-bearing) and I-type granitic rocks and associated diorites and gabbros, showing striking similarities with Cordilleran batholiths (Pereira et al. 2015, 2017 and references therein). The emplacement and thermal effects of these silicic magmas into a fertile continental crust, dominated by several kilometer-thick peraluminous metasedimentary-volcanic successions with arc-like chemical signature, may explain significant modifications of melts through the local assimilation and the generation of peraluminous S-type granitic rocks. Albalá cordierite-bearing monzogranite (309 ± 2 Ma) represents this magmatic episode, which post-dates the main tectonic episodes of the Variscan cycle (Fig. 11e), and has been regarded as being unrelated to the Gondwana–Laurussia collision sensu stricto (e.g., Gutiérrez-Alonso et al. 2011; Pereira et al. 2015). It is therefore possible to posit an age connection between the emplacement of the Albalá pluton, the development of the Iberian-Armorican Arc (i.e. Cantabrian orocline; Gutiérrez-Alonso et al. 2015) and the onset of a Paleotethyan arc (i.e. Cimmerian cycle; Pereira et al. 2015).

7 Conclusions

New U–Pb zircon dating of granitic rocks from the Central Extremadura batholith demonstrates that the batholith was formed by multiple Paleozoic plutonic events, one Ordovician and two Carboniferous:

- (i) The Ruanes tonalite (464 ± 2 Ma) is spatially and temporally related to migmatitic host rocks. In spite of the influence of the local contamination, the peraluminous magnesian calc-alkaline signature of the tonalite-granodiorite suite, which belongs to the Ruanes pluton, is related to magmatic arc settings (i.e. Cordilleran batholiths). We suggest that the RSZ plutonic–metamorphic complex from the Central Extremadura batholith was probably formed in an Ordovician active continental margin related to the Iapetus–Tornquist subduction (e.g. Caledonian orogeny), representing the Iberian Caledonides.
- (ii) The markedly peraluminous Plasenzuela two-mica leucogranite (330 ± 7 Ma) resulted from continental crust recycling (partial melting of a peraluminous source such as the Ollo de Sapo Formation and/or the SGC). This granitic magma was emplaced in a tension gash during the functioning of a D₂ dextral strike-slip shear zone representing the lateral margins of regional gravitational collapses with SE-direct transport (e.g. Variscan orogeny).

- (iii) The Albalá cordierite-bearing monzogranite (309 ± 2 Ma) is part of the Upper Carboniferous–Lower Permian Iberian calc-alkaline magmatic suite that postdates main Variscan structures. These arc type granitic rocks represent a deep-seated silicic magmatism, linked to lithospheric sources, which underwent significant modifications by local assimilation with the upper crust peraluminous host. These granitic rocks are often associated with intermediate-mafic (diorite-gabbro) suites and are interpreted as being linked to the development of the Eurasian active margin in the course of the Paleotethys subduction (e.g. Cimmerian orogeny).

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