

# Peralkaline and alkaline magmatism of the Ossa-Morena zone (SW Iberia): Age, source, and implications for the Paleozoic evolution of Gondwanan lithosphere

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## ABSTRACT

The Ossa-Morena zone in SW Iberia represents a section of the northern margin of West Gondwana that formed part of a Cordilleran-type orogenic system during the Neoproterozoic (Cadomian orogeny). The crustal section in this zone preserves the record of rifting that led to the opening of the Rheic Ocean in the early Paleozoic and the collision of Gondwana and Laurussia in the late Paleozoic (Variscan orogeny). We present U-Pb zircon data from three alkaline to peralkaline syenites that intruded Neoproterozoic and Cambrian strata and give crystallization ages ranging between ca. 490 Ma and 470 Ma. Lu/Hf isotopic data from these zircons give positive initial  $\epsilon_{\text{Hf}}$  values ( $0 \leq \epsilon_{\text{Hf}(t)} \leq +11.5$ ) that approach the model values for the depleted mantle at the time of crystallization. This suggests that a significant proportion of the magma was derived from the mantle, with limited mixing/assimilation with crustal-derived melts. Alkaline/peralkaline magmatic suites of similar age and chemical composition intruded other sections of the northern margin of West Gondwana and along the boundaries of the continental blocks that today make up Iberia. These blocks are further characterized by the presence of high-pressure metamorphic belts that formed during accretion and subsequent collision of peri-Gondwanan domains against Laurussia during the Devonian and Carboniferous (Variscan orogeny). Our U-Pb and Lu-Hf data set indicates that during the Cambrian–Ordovician transition, lithosphere extension reached a stage of narrow intracontinental rifting, where deeply sourced magmas, probably coming from the lower crust and/or the upper mantle, intruded continental upper crust across various sections of previously stretched crust. We propose that necking of the Gondwana lithosphere into several continental microblocks with fertile mantle beneath them compartmentalized extension (multiblock model), which favored the onset of early Paleozoic peralkaline and alkaline magmas. The boundaries of microblocks represent zones of inherited crustal weakness that were later reactivated during the late Paleozoic as major accretionary faults related to the amalgamation of Pangea during the Variscan orogeny. Our dynamic model provides an explanation for the unusual spatial relationship between peralkaline and alkaline igneous provinces (usually shallow in the crust) and the occurrence of high-pressure rocks. Our observations suggest that Cordilleran-type orogens subjected to extension after long-lived subduction can develop wide continental platforms that feature multiple continental blocks. In addition, the formation of sequenced high-pressure belts in collisional orogens can be explained as the ultimate consequence of multiple necking events within continental lithosphere during previous collapse of a Cordilleran-type orogen.

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## INTRODUCTION

Peralkaline and alkaline magmatism is most commonly associated with lithospheric extension (Fitton and Upton, 1987, and references therein), although it does occur less commonly in some intraplate settings (Clague, 1987; Fitton, 1987; MacDonald et al., 1987) and along some convergent plate margins where partial melting occurs in the deeper parts of subduction zones (Barker, 1987). Peralkaline and alkaline magmatism also occurs in a variety of other tectonic settings, including: continental rifts (e.g., the East African Rift—Peccerillo et al., 2007), hotspots (e.g., Canary Islands—Sumner and Wolff, 2003), island arcs (e.g., Miyakejima volcano in Japan—Macdonald, 2012; Mayor Island in New Zealand—Houghton et al., 1992; New Guinea—Zirakparvar et al., 2013), and collisional orogens that undergo postcollisional delamination, which may produce within-plate alkaline magmatism (Bonin, 2004).

Furthermore, it is relatively common for active plate margins to switch from subduction-related calc-alkaline magmatism to extensional alkaline

magmatism. Tectonic mode switching occurs either after the cessation of subduction or during slab rollback, and it results in extension in the upper plate (James and Henry, 1991; Collins, 2002; Touil et al., 2008; Rey and Müller, 2010).

Despite the numerous petrogenetic models that have been used to explain the anomalous composition of peralkaline rocks and their relationship with basaltic magmas, there is a general agreement that deeply sourced fluids play a significant role in the formation of peralkaline silicic rocks (Collins et al., 1982; Whalen et al., 1987; Eby, 1992; Bonin, 2007). Most models fall between two end-member hypotheses. The first suggests derivation from continuous fractional crystallization from basaltic magmas, possibly with crustal contamination (Barberi et al., 1975; Civetta et al., 1998; Peccerillo et al., 2003), whereas the second proposes a mantle origin for the basaltic liquid and a crustal source for the silicic rocks (i.e., old crust or underplated mafic crust; Davies and MacDonald, 1987; Black et al., 1997; Trua et al., 1999). Peralkaline granitoids, particularly syenites, are very rare at lower-crustal depths, and most of their occurrences are located at the subvolcanic level (Macdonald, 2012). They are commonly associated with normal faults and typically form ring complexes beneath calderas (Anderson, 1936;

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Lipman, 1997; Johnson et al., 2002). Extensional structures presumably act as pathways to the upper crust for deeply sourced fluids and magmas.

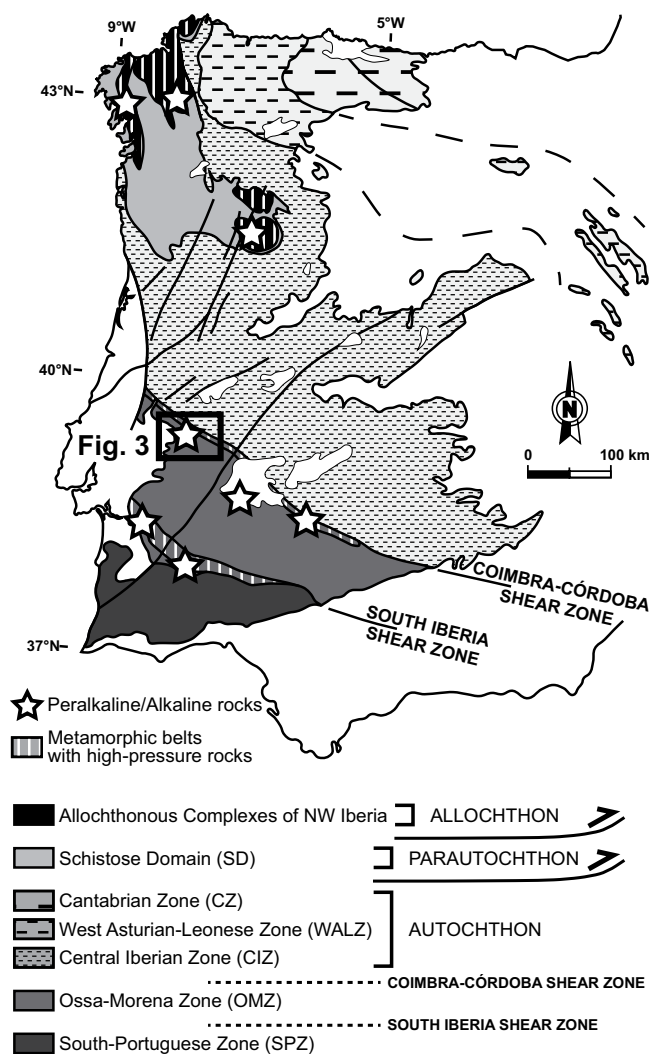
The U-Pb age and the Hf isotopic composition of zircon from peralkaline and alkaline granitoids have the potential to provide insights into the timing of extension affecting the crust in which they intruded, as well as the nature of the underlying mantle and/or lower crust from which they originated (Kemp et al., 2005, 2007; Hawkesworth and Kemp, 2006). We performed an integrated U-Pb and Hf study of zircon extracted from three samples of peralkaline and alkaline syenites exposed in the Ossa-Morena zone to obtain information about the tectonic settings of peralkaline and alkaline magmatism to help decipher the tectonic history of the zone. The Ossa-Morena zone represents one of the major tectonic divisions of Iberia, which formed in the late Paleozoic Variscan orogeny due to the collision of multiple terranes with the margin of Gondwana during the formation of Pangea (Martínez Catalán et al., 2007). Early Paleozoic peralkaline and alkaline magmatism in Iberia formed after a period of continental arc activity (Eguíluz et al., 2000; Linnemann et al., 2008; Díez Fernández et al., 2012a; Rubio-Ordóñez et al., 2015). The alkaline provinces in Iberia are mainly restricted to terrane boundaries and are closely associated with metamorphic belts with high-pressure rocks (Fig. 1). The spatial association of shallow peralkaline and alkaline igneous rocks with high-pressure metamorphic rocks is unusual and requires a dynamic model. In this paper, we: (1) better constrain the timing of the peralkaline and alkaline magmatism in SW Iberia; (2) characterize the sources of the magmatism and (3) related structures formed during extreme extension and thinning of continental lithosphere and structures reactivated during the late Paleozoic Variscan orogeny; and (4) provide a model that explains the close relationship between alkaline magmatism and high-pressure metamorphism in Iberia. The results also have implications for tectonic switching during late- to post-Cordilleran-type orogenesis.

## GEOLOGICAL SETTING AND RATIONALE

### Variscan Metamorphic Belts with High-Pressure Rocks in Iberia

Iberia consists of several continental blocks (zones) separated by major shear zones (Julivert et al., 1980; Martínez Catalán et al., 2007). These major shear zones contain rocks with both continental and oceanic affinity that are inferred to represent sutures due to the presence of high-pressure metamorphic rocks (eclogites and blueschists). Relatively abundant mafic rocks (mid-ocean-ridge basalts [MORBs]) in the shear zone have been interpreted by some authors as ophiolitic fragments (Arenas et al., 1986; Quesada et al., 1991; Crespo-Blanc, 1992; Azor et al., 1994; Araújo et al., 2005; Simancas et al., 2005; Martínez Catalán et al., 2009; Ribeiro et al., 2010). The breakup and dispersal of these terranes from the northern Gondwana margin took place during the early Paleozoic, when numerous microplates rifted from the continental margin (Crowley et al., 2000; Stampfli et al., 2002; Nance et al., 2010). Closure of the oceanic domains separating these microplates and final accretion followed the collision of Laurussia and Gondwana in the late Paleozoic. The record of this event in Europe is referred to as the Variscan orogeny (Franke, 2000; Matte, 2001; Ballèvre et al., 2009; Martínez Catalán et al., 2007, 2009; Simancas et al., 2009).

In the N-NW part of Iberia, the Cantabrian, West Asturian–Leonese, and Central Iberian zones represent an autochthonous continental assemblage of northern Gondwana affinity (Fernández-Suárez et al., 2000; Martínez Catalán et al., 2004; Pastor-Galán et al., 2013). Above these units, the Schistose domain is a parautochthonous section of the Gondwana margin (Ribeiro et al., 1990; Martínez Catalán et al., 2007; Díez Fernández et al., 2012b), which in turn is overlain by a thrust stack of allochthonous terranes. The NW Iberian allochthonous terranes host a



**Figure 1.** Map of the Iberian Massif; similarly colored areas (background) indicate the principal continental blocks, whereas the different textures highlight the terrane subdivisions. The distribution of peralkaline/alkaline suites and major high-pressure belts is included.

rootless oceanic suture (ophiolitic complexes) separating the Cantabrian zone–West Asturian–Leonese zone–Central Iberian zone–Schistose domain ensemble (autochthonous and parautochthonous) from tectonic slices of a Cambrian continental arc of northern Gondwana derivation (Fig. 1; Fernández-Suárez et al., 2003; Fuenlabrada et al., 2010). Some sections of this arc experienced high-pressure metamorphism at ca. 400–390 Ma (Ordóñez Casado et al., 2001; Fernández-Suárez et al., 2007) and may have been part of the leading edge of the Gondwana continent by the Early–Middle Devonian (Arenas et al., 2014). The base of the suture zone rests below ophiolitic units (Sánchez Martínez et al., 2009) and consists of strongly deformed continental and transitional crust. This section of the continent was also involved in a continental subduction system at ca. 380–370 Ma (Martínez Catalán et al., 1996; Abati et al., 2010).

The entire orogenic system was exhumed and emplaced over the Gondwanan platform along with ophiolitic units and sections of the overriding Cambrian arc, causing strong gravitational instabilities within the orogenic crust and its eventual extensional collapse (Martínez Catalán et al., 2002; Gómez Barreiro et al., 2010; Díez Fernández et al., 2012c).

The units are therefore now exposed as a set of dismembered tectonic units, bounded by extensional detachments and reactivated thrusts, which contain high-pressure rocks (blueschists and eclogites) and are affected by late strike-slip shear zones (Díez Fernández et al., 2011).

At least two additional continental blocks can be distinguished in SW Iberia: the Ossa-Morena zone, which was part of the northern margin of West Gondwana from the late Neoproterozoic onwards (Fernández-Suárez et al., 2002; Chichorro et al., 2008; Linnemann et al., 2008; López-Guijarro et al., 2008; Pereira et al., 2007, 2012a, 2012c), and the South Portuguese zone (Fig. 1), which has been correlated with the Meguma terrane (Laurussia; Braid et al., 2011). The Ossa-Morena zone–South Portuguese zone boundary was initially defined along the Southern Iberian shear zone (Crespo-Blanc and Orozco, 1988), which deforms an ophiolitic unit (Quesada et al., 1994) and forms part of the Aracena metamorphic belt (Díaz Azpiroz et al., 2004, 2006). This metamorphic belt extends for ~250 km (Évora–Aracena–Lora del Río metamorphic belt; Pereira et al., 2009a) and includes high-pressure rocks (blueschists and eclogites; Araújo et al., 2005; Pereira et al., 2007; Rosas et al., 2008; Rubio Pascual et al., 2013). However, the displacement of this alleged Variscan suture involving allochthonous ophiolitic units remains disputed (Ribeiro et al., 2007; Pereira et al., 2009b).

The degree of separation of the Ossa-Morena zone from the Cantabrian zone–West Asturian–Leonese zone–Central Iberian zone–Schistose domain ensemble also remains controversial. This boundary is set by the Coimbra–Córdoba shear zone (Burg et al., 1981), which is a 600-km-long Variscan metamorphic belt with high-pressure rocks (granulites and eclogites; Fig. 1; Eguíluz et al., 1990; Azor et al., 1994; Pereira et al., 2008a, 2010). This shear zone is either a Variscan suture accounting for closure of an early Paleozoic marine basin of unknown extent (Azor et al., 1994; Ordóñez Casado, 1998; Gómez-Pugnaire et al., 2003; Simancas et al., 2005), or it is a Neoproterozoic suture reworked during the Variscan cycle (Ábalos et al., 1991; Quesada, 1991; Eguíluz et al., 2000).

### Neoproterozoic–Cambrian Magmatism in Iberia

The Precambrian basement of Iberia (ca. 750–540 Ma) formed as an Andean-style continental convergent margin orogen associated with subduction of oceanic lithosphere beneath during the Cadomian orogeny (Fernández-Suárez et al., 2000; Nance et al., 2002; Linnemann et al., 2007). This peripheral orogen is traceable through central and northern Europe and occupied the northern margin of the Gondwanan supercontinent (Murphy and Nance, 1991; Linnemann et al., 2008). In the case of Iberia, and particularly for the Ossa-Morena zone, the Cadomian belt is typified by (1) bimodal arc-type magmatism intruding immature sedimentary series (e.g., Bandrés et al., 2004), (2) deposition of recycled material in basins filled with thick volcanogenic sequences (Pereira et al., 2011, 2012d), and (3) deformation and metamorphism (e.g., Eguíluz and Ábalos, 1992; López-Munguira and Nieto García, 2004).

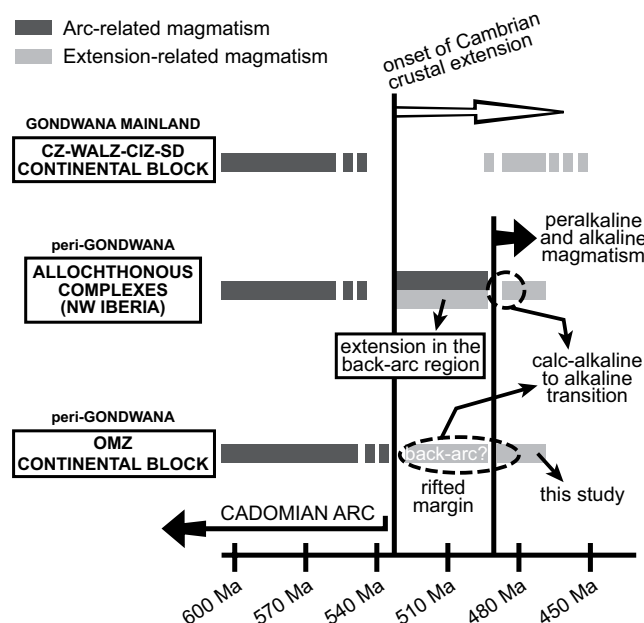
### Cambrian–Ordovician Magmatism in Iberia

A magmatic suite of mafic and felsic (mostly alkaline) rocks outcrops along the boundaries of the continental blocks that today make up Iberia, particularly within zones of Gondwanan affinity. In Iberia, peralkaline and alkaline magmatism is associated with the development of highly subsided early Paleozoic sedimentary basins (von Raumer and Stampfli, 2008), ring dike structures and normal faults (Galindo, 1989; Díez Fernández and Martínez Catalán, 2009), and chemical compositions indicating significant mantle input (Mata and Munhá, 1986, 1990; Galindo, 1989; Galindo et al., 1990; Pin et al., 1992; Sagredo and Peinado, 1992; Sánchez-García et al., 2003; Montero et al., 2009). All of these characteristics indicate an

extensional setting (intracontinental rifting) for magma generation from which the peralkaline and alkaline rocks were derived (Ribeiro, 1987; Ribeiro and Floor, 1987; Pin et al., 1992; Ribeiro et al., 1992, 1997; Sánchez-García et al., 2003; Galindo and Casquet, 2004; Montero and Floor, 2004). Interestingly, early Paleozoic peralkaline and alkaline magmatic rocks were either part of, or adjacent to, continental sections that were presumably involved later in Variscan continental subduction (late Paleozoic). For example, peralkaline and alkaline magmatic rocks of Cambrian–Ordovician age occur: (1) within the lower allochthonous continental nappes of NW Iberia that separate the upper continental-arc units from the Cantabrian zone–West Asturian–Leonese zone–Central Iberian zone–Schistose domain ensemble (Floor, 1966; Arps, 1970; Ancochea et al., 1988; Díez Fernández et al., 2010), (2) in the Coimbra–Córdoba shear zone (Chacón, 1979; Burg et al., 1981; Ábalos, 1990; Gómez-Pugnaire et al., 2003; Pereira et al., 2008a, 2010), (3) within the Ossa-Morena zone (Gonçalves, 1971; Lancelot and Allegret, 1982; Oliveira et al., 1991; Sánchez-García et al., 2003), and (4) by the Southern Iberian shear zone (Díaz Azpiroz et al., 2004, 2006; Araújo et al., 2005; Pereira et al., 2007; Chichorro et al., 2008).

Previous geochronological work indicates an early Paleozoic age for the mafic to felsic, peralkaline and alkaline magmatism found along the different terranes that form the western European Variscan belt (Pin, 1990; Thiéblemont and Cabanis, 1994; Crowley et al., 2000).

In NW Iberia (Fig. 2), the peralkaline and alkaline magmatism is Ordovician (ca. 485–470 Ma; Valverde-Vaquero et al., 2005; Rodríguez et al., 2007; Montero et al., 2009; Díez Fernández et al., 2012a) and postdates two magmatic pulses that followed in sequence: a Cambrian calc-alkaline, arc-related event spanning ca. 530–495 Ma (Ordóñez Casado, 1998; Abati et al., 1999, 2007, 2010; Santos et al., 2002; Fernández-Suárez et al., 2007; Arenas et al., 2009; Castiñeiras et al., 2010; Díez Fernández et al., 2012a) and a Late Cambrian–Early Ordovician alkaline-calcic event that was also associated with crustal extension at ca. 494–478 Ma (Díez Montes et al., 2010; Talavera et al., 2013; Dias da Silva et al., 2014).



**Figure 2.** Chronological chart juxtaposing the different Gondwanan and peri-Gondwanan domains of Iberia, showing the ages of arc-related and extension-related igneous suites. See citations in the text for precise ages and data sources. Abbreviations as in Figure 1.

In the Central Iberian–Ossa-Morena transition zone, immediately north of the Coimbra–Córdoba shear zone (Figs. 2 and 3), series of calc-alkaline, high-K, igneous rocks were dated at ca. 494–488 Ma and interpreted to represent, in part, melting of older crustal rocks (Solá et al., 2008). In the Ossa-Morena zone (Fig. 2), a sequence of extension-related magmatic events developed in Cambrian times (ca. 530–500 Ma), with a melt production peak at ca. 515–505 Ma (Galindo et al., 1990; Oliveira et al., 2002; Sánchez-García et al., 2003, 2008, 2010; Chichorro et al., 2008) and minor peralkaline and alkaline rocks dated at ca. 500–499 Ma (Galindo et al., 1990; Ochsner, 1993; Montero et al., 2000; Pereira et al., 2012c). Additionally, the Ossa-Morena zone (Fig. 2) has a number of plutonic rocks that have yielded younger radiometric ages (whole-rock and mineral Rb–Sr and K–Ar, and U–Pb zircon conventional methods), which have been interpreted as cooling ages rather than crystallization ages (ca. 500–470 Ma; Gonçalves and Fernandes, 1973; Lancelot and Allegret, 1982; Galindo and Portugal Ferreira, 1989; Galindo et al., 1990; Ochsner, 1993; Salman, 2002, 2004, and references therein). Moreover, the Ossa-Morena zone has calc-alkaline mafic metavolcanic rocks that are interbedded with metasedimentary rocks with Ordovician fossils (Mata et al., 1993), which may be coeval with peralkaline and alkaline igneous rocks (ca. 495–480 Ma; Ordóñez Casado, 1998), and in some cases, could be coeval with or predate the development of low-angle normal faults in nearby domains (ca. 480 Ma; Expósito et al., 2003).

The ca. 20–30 m.y. age difference between the onset of extension-related magmatism in NW Iberia (ca. 490–470 Ma; Ordovician) and SW Iberia (ca. 530–505 Ma; Cambrian) may be the result of rift propagation, with each domain representing different sections along a single continental margin (northern margin of West Gondwana; Nance et al., 2008, 2010). This is consistent with the Cambrian age (ca. 515–505 Ma) estimated for a ridge subduction event proposed in SW Iberia (Sánchez-García et al., 2008), as opposed to an Ordovician age (ca. 480–475 Ma) of a similar process proposed for the NW Iberian domain (Sánchez Martínez et al., 2012). However, preliminary radiometric ages available for peralkaline and alkaline magmatism reveal an apparent synchrony between the northern and southern sections of Iberia during the ca. 485–470 Ma interval. Our work is focused in clarifying whether or not various sections of the northern margin of West Gondwana were coupled to a similar intracontinental rifting process during the Early Ordovician by providing new U–Pb ages of peralkaline and alkaline rocks from the Ossa-Morena zone (SW Iberia) and comparing the results with recently published data from NW Iberia.

### Lithostratigraphy of the Ossa-Morena Zone: Host Rocks of the Peralkaline and Alkaline Magmatism

Stratigraphic divisions of the Ossa-Morena zone follow four stages of geodynamic evolution in Neoproterozoic and Paleozoic times: (1) Ediacaran magmatic arc activity during the Cadomian/Pan-African cycle; (2) Cambrian intracontinental rifting that evolved into an Ordovician passive margin (Pereira and Quesada, 2006); (3) the Ordovician to Early Devonian passive margin (Robardet and Gutiérrez Marco, 2004); and (4) sedimentation associated with the Variscan orogeny. The onset of the Variscan orogeny produced an important stratigraphic gap in the Middle–Late Devonian strata (Quesada, 1990; Oliveira et al., 1991); however, sparse outcrops of mid-Devonian rocks do occur as olistoliths in Mississippian basins (Pereira et al., 2012b, and references therein) or in fault contact with Carboniferous volcanic rocks (Machado et al., 2009). The main Variscan rocks are Carboniferous synorogenic strata associated with voluminous magmatism (Quesada, 1990; Oliveira et al., 1991; Pereira et al., 2012b).

The oldest rocks exposed in the Ossa-Morena zone constitute a thick succession of siliciclastics, with a few limestone layers (Serie Negra

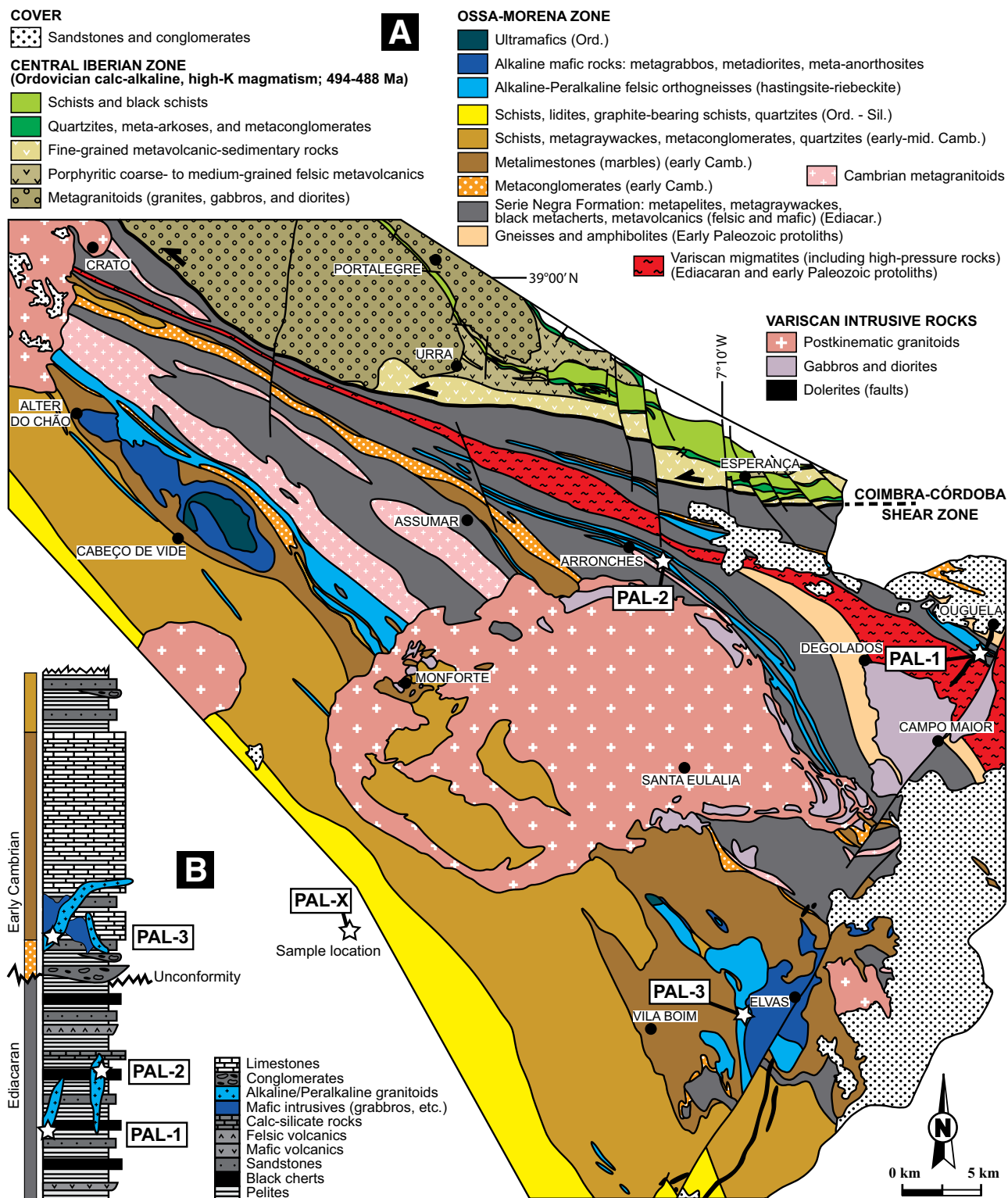
succession; Alia, 1963; Carvalhosa, 1965; Apalategui et al., 1990; Gonçalves and Carvalhosa, 1994; Eguíluz et al., 2000; Pereira and Quesada, 2006; Pereira et al., 2006) that have a maximum depositional age of ca. 590–545 Ma (Eguíluz et al., 2000; Linnemann et al., 2008; Pereira et al., 2008b, 2011, 2012d). These sediments are interpreted as the infill of a back-arc basin formed along the northern margin of West Gondwana (Eguíluz et al., 2000; Pereira et al., 2006, 2011, 2012a; Linnemann et al., 2008). The Ediacaran succession is unconformably overlain by Early Cambrian sedimentary rocks (Liñán and Quesada, 1990), which are the base of a rift sequence containing volcanic rocks concentrated at two main stratigraphic levels (Sánchez-García et al., 2003, 2010). The lower level contains siliciclastics interbedded with felsic volcanic and volcanoclastic rocks of calc-alkaline (peraluminous) affinity (Sánchez-García et al., 2003, 2008). Felsic rocks of this event were dated at ca. 530–526 Ma (Romeo et al., 2006; Chichorro et al., 2008; Sánchez-García et al., 2008, 2014; Pereira et al., 2011). Rhyolites occur locally in an upper stratigraphic position and have been dated at ca. 522 Ma and 517–515 Ma (Chichorro et al., 2008; Sánchez-García et al., 2008). Culminating the rift sequence, there is a volcanic-sedimentary complex (Sánchez-García et al., 2008, 2010) with massive bimodal magmatism of Middle Cambrian age (ca. 505–502 Ma; Sánchez-García et al., 2003; Pereira et al., 2004, 2007; Chichorro et al., 2008). The Cambrian series of the Ossa-Morena zone was subjected to uplift, tilting, erosion, and/or nondeposition during and after sedimentation. This resulted in significant lateral variability in thickness and facies, and in a sedimentary gap that generally affects the Late Cambrian and probably the Early Ordovician strata, but that may also include the Early Cambrian units in some parts of the basin (Liñán and Quesada, 1990; Pereira and Quesada, 2006).

Overlying the Cambrian rift sequence, a passive margin succession constitutes the Early Ordovician record (Liñán and Quesada, 1990; Robardet et al., 1998) with interbedded felsic and mafic calc-alkaline volcanic rocks (Oliveira et al., 1991; Mata et al., 1993). This package is succeeded by a mostly siliciclastic series (also of Ordovician age), and then covered by a condensed, euxinic series of Silurian age (Robardet et al., 1998; Robardet and Gutiérrez Marco, 2004). The siliciclastic formations of the lowermost Devonian mark the transition to a synorogenic environment heralding the Variscan orogeny (Robardet and Gutiérrez Marco, 1990, 2002).

These successions of the Ossa-Morena zone, particularly the Ediacaran rocks, are intruded by a number of peralkaline and alkaline granitoids. In the Coimbra–Córdoba shear zone, the igneous rocks occur as elongated massifs of weakly foliated granitoids or as narrow bands of orthogneiss alternating with schists and paragneisses due to the intense deformation and metamorphism that took place during Variscan orogeny (Fig. 3; Gonçalves and Assunção, 1970; Gonçalves, 1971; Gonçalves and Fernandes, 1973; Gonçalves et al., 1975). Further south, in the Alter do Chão–Elvas sector (Oliveira et al., 1991), the peralkaline and alkaline syenites show a weak foliation and intrude the low-grade metasedimentary rocks of the Early Cambrian (Gonçalves and Assunção, 1970). At a regional scale, these peralkaline and alkaline granitoids are found in close relation with alkaline mafic rocks, such as amphibolites, gabbros, and ultramafic rocks (Assunção, 1956a, 1956b; Assunção and Gonçalves, 1970; Gonçalves and Assunção, 1970; Gonçalves, 1971; Canilho, 1973; Carrilho Lopes et al., 1996, 1993; Carrilho Lopes, 2004).

### Selected Samples: General Description

Three rock samples were collected for U–Pb and Lu–Hf laser ablation–multicollector–inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS) analysis on zircon. Sample locations are indicated in Figure 3. We collected two samples of strongly sheared peralkaline and alkaline orthogneiss (syenite) close to the northern boundary of the Ossa-Morena



**Figure 3. (A) Geologic map of the Ossa-Morena zone in the Alentejo region (Gonçalves, 1971; Solá et al., 2008). Sample locations are shown. (B) Synthetic stratigraphic column including the Ediacaran to Early Cambrian succession of the Ossa-Morena zone in the study area.**

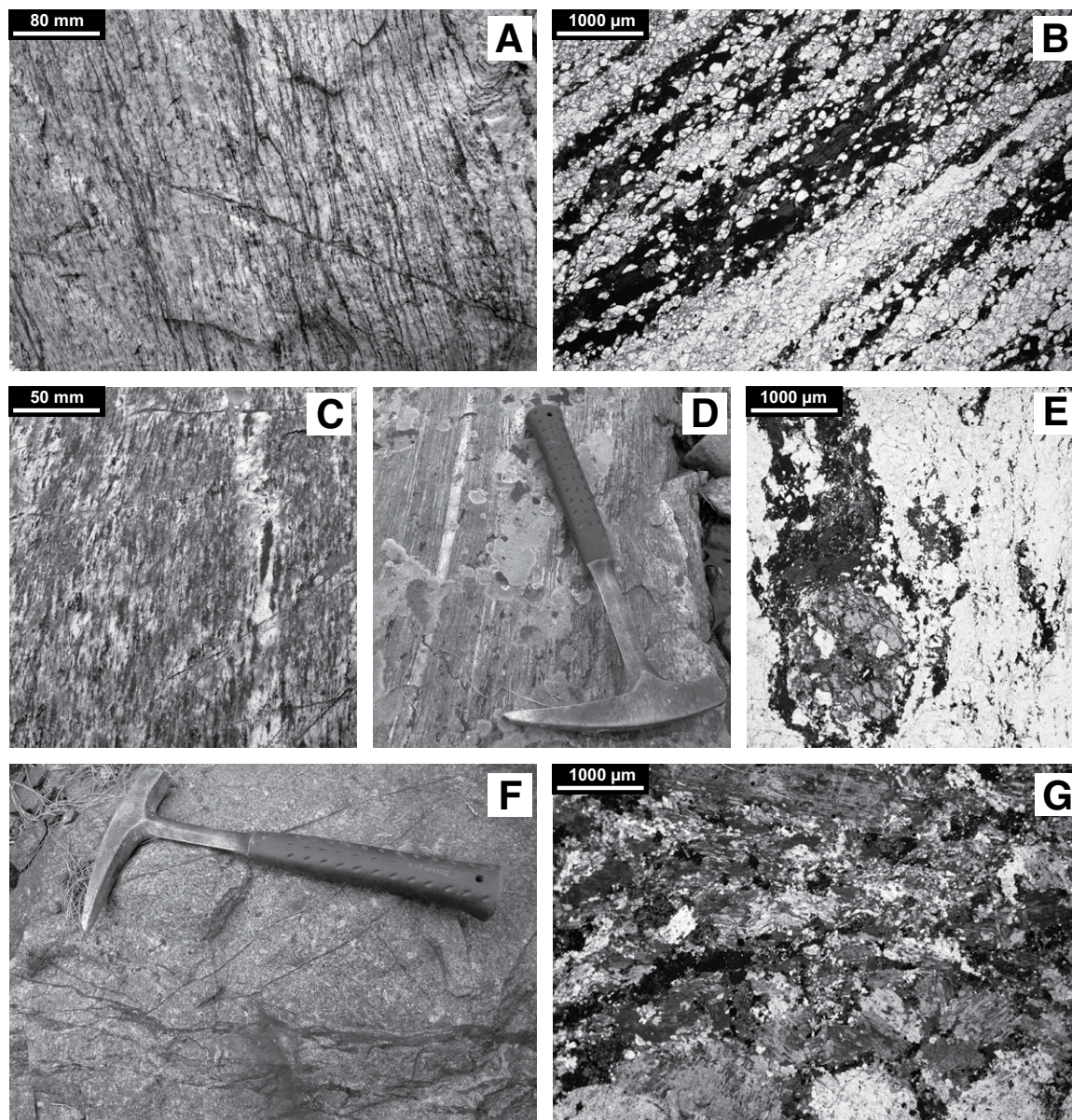


zone. Sample PAL-1 (Figueira de Cima, Cevadais Lineament; Assunção and Gonçalves, 1970; Gonçalves and Assunção, 1970) was located to the north of strongly sheared migmatites of the Coimbra-Córdoba shear zone (Pereira et al., 2008a), and sample PAL-2 (Arronches Lineament; Gonçalves, 1971) was located to the south of the migmatites. A third peralkaline syenite (sample PAL-3, Elvas pluton, Outeirão-Varche-Falcato Massif) was collected from the Elvas massif of the Alter do Chão sector, which is located at a more southerly position and shows spatial and chemical relationships with various bodies of mafic rocks (Carrilho Lopes et al., 1996).

Previous petrographic and chemical work classified the protoliths of these rocks as alkaline/peralkaline syenites, with riebeckite/aegirine or

hastingsite, and with more than 65% of the rock constituted by feldspar (Teixeira and Assunção, 1958; Gonçalves and Assunção, 1970; Coelho and Gonçalves, 1971; Carrilho Lopes et al., 1996). These rocks can be classified as subsolvus syenites due to the presence of two types of alkali feldspar: a K-rich type and a Na-rich type.

Sample PAL-1 (Figueira de Cima, Cevadais Lineament) is a peralkaline orthogneiss with riebeckite showing a near-vertical main foliation (N125°E/80°W) that crenulates a previous tectonic banding (Fig. 4A). The resulting crenulation lineation is parallel to a stretching lineation defined by the statistical orientation of elongate grains (N118°E/14°N). The main foliation is also a tectonic banding formed by domains rich in alkaline



**Figure 4.** (A) Field photograph of the main foliation in sample PAL-1 (note the crenulated banding in the upper-right corner); (B) tectonic banding of sample PAL-1 defined by melanocratic (riebeckite-rich) and felsic (feldspar-rich) layers (note the fine-grained texture); (C) subvertical crenulation cleavage of rocks close to sample PAL-2; (D) mylonitic tectonic banding of sample PAL-2, which is a: (E) garnet-bearing syenite with alkaline amphibole (riebeckite-arfvedsonite); (F) porphyritic alkaline-peralkaline syenite (PAL-3) exhibiting a complex network of amphibole-rich veins; and (G) perthitic and antiperthitic texture in weakly deformed feldspars of sample PAL-3 (a green-brown alkaline amphibole occupies the interstitial domains).

feldspar (albite-oligoclase + microcline) with minor quartz (absent in many layers) alternating with thinner lenticular aggregates of melanocratic minerals, mostly riebeckite and less commonly aegirine (Fig. 4B). Opaque minerals, titanite, zircon, biotite, fluorite, calcite, and allanite can be found as accessory phases. Most of the felsic mineralogy was fractured, granulated, and variably recrystallized during deformation (cataclastic flow). Feldspar is usually perthitized, and riebeckite is partly transformed into lepidomelane.

Sample PAL-2 (Arronches Lineament) is an alkaline orthogneiss with hastingsite and garnet. The main foliation in the sampling location is near vertical (N135°E/80°W) and ranges between a penetrative crenulation cleavage that affects a tectonic banding (Fig. 4C) and a mylonitic foliation (Fig. 4D). The crenulation lineation is parallel to a stretching lineation (N132°E/15°N). These gneisses show layers of very fine-grained feldspar (albite-oligoclase + microcline) and minor quartz. These minerals configure an intensively deformed matrix formed by fragmented, reoriented, and recrystallized grains that are also preserved as variably sized porphyroclasts. The felsic layers alternate with discontinuous lenses of mafic aggregates that consist of hastingsite and garnet, and may also include titanite, biotite, opaque minerals, allanite, zircon, calcite, apatite, and epidote (Fig. 4E). Mafic and accessory minerals can also be found in the quartz-feldspathic domains. Feldspar is frequently perthitized, and hastingsite can be partly replaced by garnet, although in most cases these two phases are in equilibrium. Transformation of hastingsite into lepidomelane is also observed.

Sample PAL-3 (Elvas pluton) is a weakly deformed, medium-grained porphyritic peralkaline syenite with riebeckite-arfvedsonite (Fig. 4F). The most abundant mineral phases are plagioclase (albite) and K-feldspar. The K-feldspar displays porphyritic and perthitic texture, whereas the Na-rich feldspar shows antiperthitic texture. Quartz is a minor constituent of this rock. Occupying the interstitial areas, the dominant mafic mineral is a green/brown alkaline amphibole (riebeckite-arfvedsonite), which may be accompanied by opaque minerals (magnetite, pyrite, arsenopyrite), zircon, titanite, and rare allanite and calcite (Fig. 4G). The mafic phases can also be found filling a complex set of veins (Fig. 4F), which were avoided during sampling.

## METHODS: ANALYTICAL TECHNIQUES

The samples were crushed, disk milled, sieved (300 µm), concentrated on a Wilfley table, and separated via heavy liquids (methylene iodide) at Universidad Complutense de Madrid. Care was taken to select representative grains from fractions using no magnetic discrimination. Zircon grains were hand-picked under a binocular microscope, selecting the most transparent to calculate protoliths crystallization ages and steeper grains to seek inheritance. At the Department of Geological Science, University of Florida, Gainesville, zircons were mounted on glass slides with a double-sided adhesive in parallel rows together with some grains of FC-1 zircon standard (Duluth Gabbro; Paces and Miller, 1993; Black et al., 2003) and set in epoxy resin. After the resin was cured, the mounts were ground down to expose their central portions by using sandpaper and polished with diamond abrasive on a lap wheel. The grains were photographed under a reflected light microscope, and, prior to analysis, their internal structure, inclusions, fractures, and physical defects were identified using backscattered electron (BSE) and cathodoluminescence imagery (CL) on a Carl Zeiss EVO MA10 XVP scanning electron microscope at University of Florida. The plugs were placed in an ultrasonic bath and cleaned in nitric acid to remove common-Pb surface contamination.

The U-Pb isotopic analyses were conducted at the University of Florida on a Nu Plasma multicollector plasma source mass spectrometer coupled to a New Wave 213 nm ultraviolet laser (LA-MC-ICP-MS). Zircon was ablated in He atmosphere. The laser was set at 4 Hz pulse

frequency, 40% power, and a laser spot diameter of 20–30 µm. The sample was decrepitated in a He stream and mixed with Ar gas (gas flows optimized daily) for sample transport into the mass spectrometer. On-peak background measurements (20 s) were performed before each analysis in order to subtract the gas blank, including  $^{204}\text{Hg}$  contribution. Actual ablation proceeded for 30 s in order to minimize ablation pit depth and hence elemental fractionation. The isotopic data were acquired using the Nu-Instruments Time Resolved Analysis software. Data calibration and drift corrections were based on multiple ablations of the FC-1 zircon standard bracketed between every 10 unknowns. Data were reduced with in-house software; however, crystallization ages and concordia plots were obtained using Isoplot (Ludwig, 2008). Representative age errors based on the long-term reproducibility of FC-1 were 2% for  $^{206}\text{Pb}/^{238}\text{U}$  (2σ) and 1% for  $^{207}\text{Pb}/^{206}\text{Pb}$  (2σ). Probability density distribution plots, kernel density estimators, and frequency diagrams of age populations were obtained using DensityPlotter 2.2 software (Vermeesch, 2012).

The most homogeneous part of the grain cores, free of defects, cracks, and inclusions, was analyzed. Some grains exhibited multiple and concentric layers of growth, some of which were analyzed. Only concordant or nearly concordant data were considered for interpretation of crystallization age (discordance between  $^{207}\text{Pb}/^{206}\text{Pb}$  and  $^{206}\text{Pb}/^{238}\text{U}$  ages <15%, and discordance between  $^{207}\text{Pb}/^{235}\text{U}$  and  $^{206}\text{Pb}/^{238}\text{U}$  ages <5%). Ratios and ages of the selected analyses (in bold) are presented in Tables DR1–DR3<sup>1</sup> and plotted in kernel density functions, probability density diagrams, age-frequency histograms, and Tera-Wasserburg and Wetherill concordia diagrams. Ages are reported based on  $^{206}\text{Pb}/^{238}\text{U}$  ratios, because they all are younger than 1 Ga. In the attribution of radiometric ages to igneous rocks, we followed the *International Chronostratigraphic Chart*, v2013/01 (www.stratigraphy.org).

The Lu-Hf isotopic analyses were conducted at the University of Florida on a Nu Plasma multicollector plasma source mass spectrometer coupled to a New Wave 213 nm ultraviolet laser (LA-MC-ICP-MS; e.g., Foster et al., 2012). Using cathodoluminescence imaging to guide spot selection, zircons were ablated with a 30-µm-diameter spot on, or as near as possible to, 30-µm-diameter spots previously analyzed for U-Pb geochronology in order to maximize the coherence for all data (Bickford et al., 2008). Analyses were performed using time-resolved analysis and real-time online mass bias and isobaric corrections for Yb and Lu after the methods of Mueller et al. (2008). Data from each ablation were reduced independently as described by Mueller et al. (2008) to ensure isotopic homogeneity of the ablated zircon volume. Age corrections were made using the decay constant of  $\lambda = 1.867 \times 10^{-11}$  (Söderlund et al., 2004) and measured Lu/Hf. Measured values for zircon standard FC-1 (uncorrected for its 1100 Ma age) during the period 2004–2011 yielded  $^{176}\text{Hf}/^{177}\text{Hf} = 0.28217 \pm 2$  (2σ,  $n > 600$ ) and  $\epsilon_{\text{Hf}(0)} = -24.5 \pm 1.6$  (2σ). The average value for the nonradiogenic  $^{180}\text{Hf}/^{177}\text{Hf}$  for the same 600+ analyses deviates from the true value by 0.2ε, which indicates the contribution from oxide and dimer isobars is negligible. Initial  $^{176}\text{Hf}/^{177}\text{Hf}$  values were calculated using Lu/Hf measured during ablation and U-Pb crystallization ages previously calculated for each sample (Tables DR1–DR3 [see footnote 1]). Precision of the final calculated initial isotopic ratios is based on replicate analyses of zircon standard FC-1 and propagation of errors associated with both U-Pb and Lu/Hf measurements. The  $\epsilon_{\text{Hf}(0)}$  values are based on bulk silicate earth with  $^{176}\text{Hf}/^{177}\text{Hf} = 0.282785$  and  $^{176}\text{Lu}/^{177}\text{Hf} = 0.0336$  (Bouvier et al., 2008). One-stage model ages ( $T_{\text{DM}}$ ) were calculated relative to the depleted mantle using values from Bouvier et al. (2008). Two-stage model ages ( $T_{\text{DM-2}}$ ) were calculated forcing a growth-curve

<sup>1</sup>GSA Data Repository Item 2015027, Tables DR1–DR4, is available at [www.geosociety.org/pubs/ft2015.htm](http://www.geosociety.org/pubs/ft2015.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org), Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.



through a zircon initial ratio with an assumed  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of 0.0115, corresponding to average continental crust (Rudnick and Gao, 2003).

## RESULTS FROM ZIRCON ANALYSIS

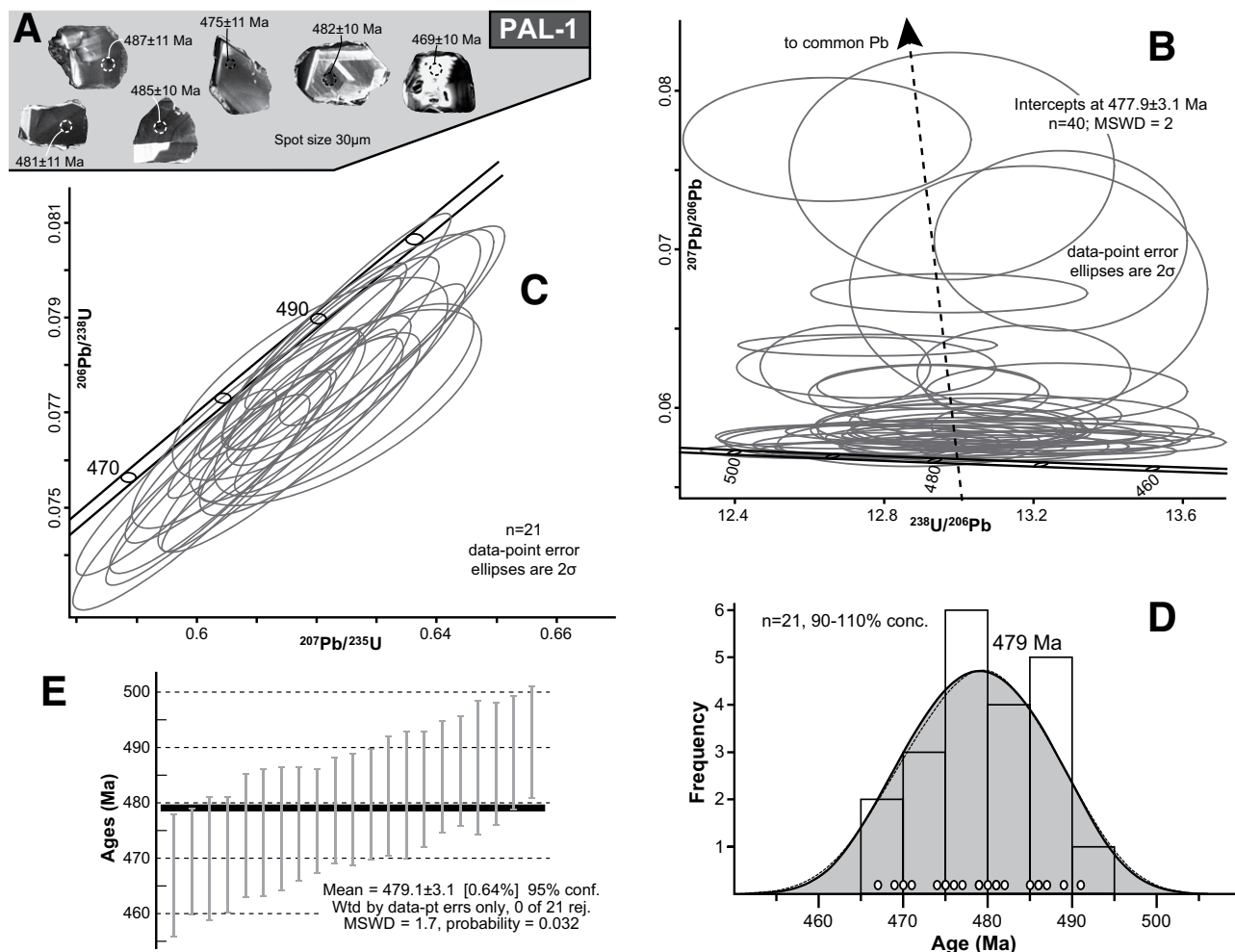
Supplementary data tables are available in the online Data Repository and summarize elemental and isotopic data for zircons; detailed U-Pb and Lu-Hf results are tabulated in Tables DR1–DR4 (see footnote 1).

### Zircon Description

Zircon yield in samples PAL-1 and PAL-2 is high. The grains show good preservation (few grains are broken) and range from colorless and transparent to faintly colored varieties (light brown, light pink, red, and yellow) with varied habits, including pyramids, dipyratid prisms, elongated prisms, and multifaceted crystals. The size of the crystals ranges between 50 and 400  $\mu\text{m}$ , but crystals are usually around 150  $\mu\text{m}$ . Almost all of zircons show dull surfaces and typical length-to-width ratios of 1:1 in the multifaceted grains and 3:1 in the other crystals. The crystals

exhibit well-developed surfaces (not rounded), and, although scarce, mineral inclusions are more abundant in the colored varieties. Conversely, zircon yield in sample PAL-3 is poor (only 18 grains were found), and the grain preservation is fair. Their size is smaller (30–200  $\mu\text{m}$ ) and they are dominantly colorless, with some faintly colored grains (brown and light pink). Zircon crystal habit in PAL-3 is mostly prismatic, although some pyramids and dipyratid prisms do exist. The crystals exhibit slightly rounded and lustrous surfaces (dominantly dull in the colored varieties) with a length-to-width ratio of 2:1–3:1.

CL images of zircon show that most of the grains have homogeneous central areas and a continuous growth between core and rim, with subordinate irregular or angular shapes, although there are also cores truncated by the zoning pattern of the rims (Figs. 5A, 6A, and 7A). Those cores have irregular to ellipsoidal shape and show an assortment of textures typical of inherited cores surrounded by poorly luminescent rims. Grains with and without xenocrystic cores are made up of several concentric zones with variable luminescence. The width of the zones ranges from less than 10  $\mu\text{m}$  up to occupying almost the entire exposed surface (in the CL image), giving an apparent unzoned texture to the grain. Zoning is mainly



**Figure 5.** PAL-1 U-Pb results. (A) Cathodoluminescence (CL) images with reference to analyzed spots; (B) Tera-Wasserburg plot including all analyses; (C) Wetherill concordia plot of the most concordant set of analyses; (D) age histogram, probability density diagram (dashed line), and kernel density function (ages used for calculation are shown as white circles); and (E) weighted average ages. MSWD—mean square of weighted deviates.



oscillatory, but there are also grains with faint oscillatory, homogeneous, sector, and soccer-ball zonation. With few exceptions, cores are less luminescent than rims, although the most external rim in each grain usually shows low luminescence or is even nonluminescent. Grains that developed large homogeneous zones are generally less luminescent, and those homogeneous zones are also the less luminescent areas of the grain.

### U-Pb Dating

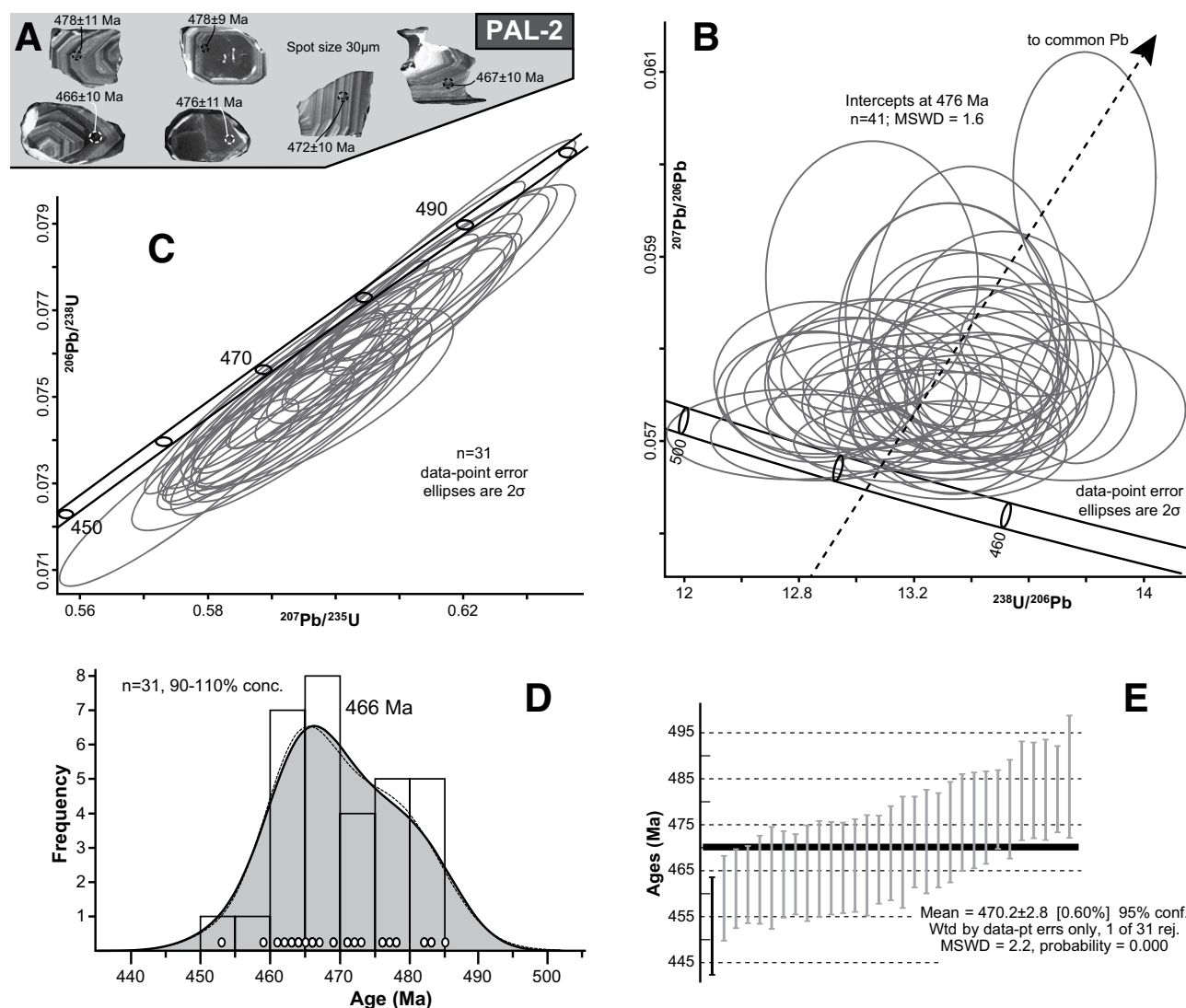
#### Peralkaline Orthogneiss with Riebeckite/Aegirine (PAL-1—Figueira de Cima, Cevadais Lineament)

Forty analyses were performed on 38 zircon grains from sample PAL-1 (Table DR1 [see footnote 1]). Altogether, these analyses define an apparent common-Pb discordia line that intercepts concordia at  $478 \pm 3$  Ma (mean square of weighted deviates [MSWD] = 2) in a Tera-Wasserburg concordia plot (Fig. 5B). Nineteen analyses were rejected due to either high common

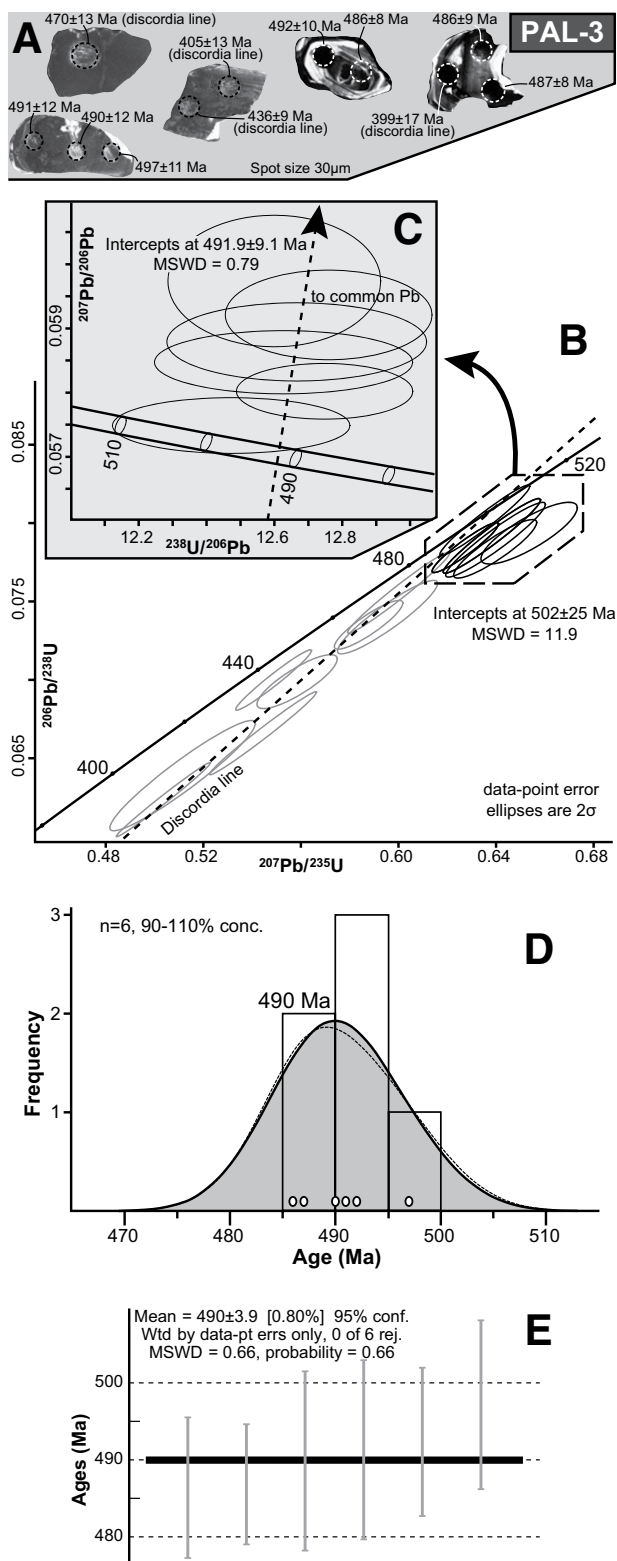
Pb (higher than the FC-1 reference zircons) or high discordance (>10%) and were considered no further. The remaining 21 analyses are shown in a Wetherill concordia plot (Fig. 5C), and their  $^{238}\text{U}/^{206}\text{Pb}$  ages span from ca. 467 to ca. 491 Ma, with a kernel density function maximum at ca. 479 Ma (Fig. 5D). The best estimate for the crystallization age of the igneous protolith of this sample is a weighted average  $^{206}\text{Pb}/^{238}\text{U}$  age of  $479 \pm 3$  Ma (MSWD = 1.7, Early Ordovician; Fig. 5E). This age is obtained by considering only the most concordant analyses (discordance between  $^{207}\text{Pb}/^{235}\text{U}$  and  $^{206}\text{Pb}/^{238}\text{U}$  ages <5%). This age is within error, and is in very good agreement with, the age determined by the common-Pb discordia line. No inherited zircon was found in this sample.

#### Alkaline Orthogneiss with Hastingsite and Garnet (PAL-2—Arronches Lineament)

Forty-one analyses performed on 40 zircon grains from sample PAL-2 (Table DR2 [see footnote 1]) reveal an array of points above the concordia



**Figure 6.** PAL-2 U-Pb results. (A) Cathodoluminescence (CL) images with reference to analyzed spots; (B) Tera-Wasserburg plot including all analyses; (C) Wetherill concordia plot of the most concordant set of analyses; (D) age histogram, probability density diagram (dashed line), and kernel density function (ages used for calculation are shown as white circles); and (E) weighted average ages. MSWD—mean square of weighted deviates.



**Figure 7.** PAL-3 U-Pb results. (A) Cathodoluminescence (CL) images with reference to analyzed spots; (B) Wetherill concordia plot including all analyses and a discordia line defined by the discordant points; (C) Tera-Wasserburg plot of the most concordant set of analyses; (D) age histogram, probability density diagram (dashed line), and kernel density function (ages used for calculation are shown as white circles); and (E) weighted average ages. MSWD—mean square of weighted deviates.

defining an apparent common-Pb discordia line yielding an intercept age of ca. 476 Ma in a Tera-Wasserburg concordia plot (Fig. 6B). Thirty-one grains were selected for calculating the crystallization age because of their low common-Pb content (much lower than the FC-1 reference zircons) and degree of concordance (>90%; Fig. 6C). The  $^{238}\text{U}/^{206}\text{Pb}$  ages of the selected analyses span from ca. 453 to ca. 485 Ma and pool together to define a kernel density function maximum at ca. 466 Ma (Fig. 6D). The weighted average of these  $^{238}\text{U}/^{206}\text{Pb}$  ages,  $470 \pm 3$  Ma (MSWD = 2.2, Early–Middle Ordovician, Fig. 6E), is considered the best estimate for the crystallization age, which was obtained by considering only the grains with the lowest common-Pb content and most concordant analyses (discordance between  $^{207}\text{Pb}/^{235}\text{U}$  and  $^{206}\text{Pb}/^{238}\text{U}$  ages <5%). The age is in good agreement with the age determined by the common-Pb discordia line. No inherited zircon was observed in this sample.

#### Peralkaline Syenite with Riebeckite-Arfvedsonite (PAL-3—Elvas Pluton)

Among a total of 19 analyses performed on sample PAL-3 (Table DR3 [see footnote 1]), five were rejected for calculation of the crystallization age of its protolith because of high common Pb (much higher than the FC-1 reference zircons). The remaining analyses are divided into eight discordant and six concordant grains (Fig. 7B). The discordant analyses define a discordia line that (upper) intercepts the concordia at  $502 \pm 25$  Ma (MSWD = 11.9). The most concordant grains (discordance between  $^{207}\text{Pb}/^{235}\text{U}$  and  $^{206}\text{Pb}/^{238}\text{U}$  ages <4%) are grouped near that intercept age and also constitute an array of points defining an apparent common-Pb discordia line that intercepts the concordia at  $492 \pm 9$  Ma (MSWD = 0.79) in a Tera-Wasserburg concordia plot (Fig. 7C). The  $^{238}\text{U}/^{206}\text{Pb}$  ages of the concordant analyses range from ca. 486 to ca. 497 Ma, with a kernel density function maximum at ca. 490 Ma (Fig. 7D) and a similar weighted average age of  $490 \pm 4$  Ma (MSWD = 0.66, Furongian; Fig. 7E). The latter is considered the best estimate for the crystallization age of the protolith, which is within error of the age determined by the common-Pb discordia line. No inherited components were found in this sample, although one highly discordant grain might account for a Paleoproterozoic input.

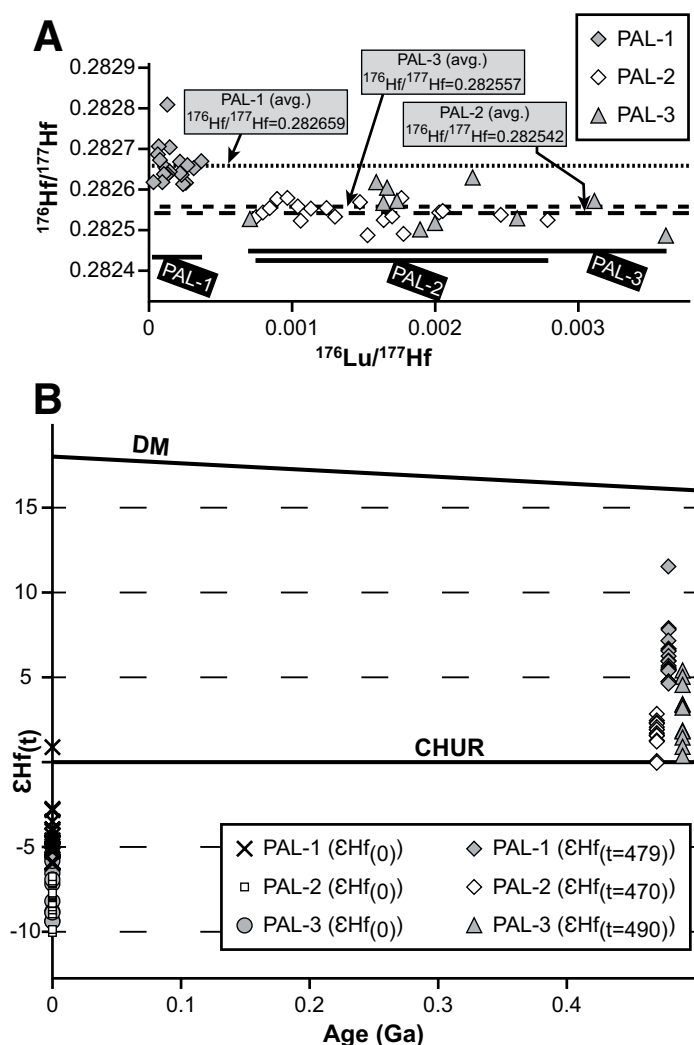
#### Lu-Hf Systematics

Fifty-one dated zircon grains were selected for Lu-Hf isotope analysis (Table DR4 [see footnote 1]), and the results are plotted in Figure 8. Sample PAL-1 (Figueira de Cima, Cevadais Lineament) has a limited range of  $^{176}\text{Lu}/^{177}\text{Hf}$  values, whereas samples PAL-2 (Arronches Lineament) and PAL-3 (Elvas pluton) display a much wider range. Zircon grains from sample PAL-1 ( $n = 20$ ) have the highest  $^{176}\text{Hf}/^{177}\text{Hf}$  initial ratios, which range from 0.282616 to 0.282810 (average of 0.282659, scatter of 0.00004), and the highest  $\epsilon_{\text{Hf}(t)}$  values, ranging from +4.6 to +11.5 ( $t = 479$  Ma). The grains from sample PAL-2 ( $n = 20$ ) are characterized by  $^{176}\text{Hf}/^{177}\text{Hf}$  initial ratios ranging from 0.282501 to 0.282594 (average of 0.282542, scatter of 0.00003), and  $\epsilon_{\text{Hf}(t)}$  values from 0 to +3.2 ( $t = 470$  Ma). Sample PAL-3 has similar isotopic values, with  $^{176}\text{Hf}/^{177}\text{Hf}$  initial ratios ranging from 0.282519 to 0.282650 (average of 0.282557, scatter of 0.00005), and  $\epsilon_{\text{Hf}(t)}$  values from +0.4 to +5.4 ( $t = 490$  Ma).

#### DISCUSSION

##### Age and Source of the Peralkaline and Alkaline Magmatism

Previous geochronological work performed in the alkaline suites of the Ossa-Morena zone suggested an ~20–35 m.y. gap between the first (ca. 505–500 Ma; Galindo et al., 1990; Ochsner, 1993; Montero et al., 2000)



**Figure 8. Results of Lu-Hf spot analyses of zircons from samples PAL-1, PAL-2, and PAL-3. (A) Initial  $^{176}\text{Hf}/^{177}\text{Hf}$  vs.  $^{176}\text{Lu}/^{177}\text{Hf}$  diagram. The dashed thick lines represent average values of  $^{176}\text{Hf}/^{177}\text{Hf}$ . The continuous thick lines show  $^{176}\text{Lu}/^{177}\text{Hf}$  variability. (B) Initial  $\epsilon_{\text{Hf}}$  vs. apparent age diagram. Chondritic uniform reservoir (CHUR) line represents the isotope evolution of the chondritic uniform reservoir through time. The depleted mantle growth line (DM) has been calculated using present values of  $^{176}\text{Hf}/^{177}\text{Hf} = 0.283294$  (Vervoort and Blichert-Toft, 1999) and  $^{176}\text{Lu}/^{177}\text{Hf} = 0.03933$ , and considering a straight evolution line with  $\epsilon_{\text{Hf}}(0) = +18$  and  $\epsilon_{\text{Hf}}(4.558 \text{ Ga}) = 0$  (Blichert-Toft and Puchtel, 2010). Errors are provided in Tables DR1–DR3 (see text footnote 1).**

and later (ca. 480–470 Ma; Galindo and Portugal Ferreira, 1989; Ochsner, 1993) pulses of peralkaline and alkaline magmatism. The crystallization ages of the syenites obtained in this work span a minimum of ~20 m.y., from ca. 490 Ma (sample PAL-3, Elvas pluton) to ca. 470 Ma (PAL-2, Arronches Lineament), and show an apparent return period of ~10 m.y. (ca. 479 Ma, sample PAL-1, Figueira de Cima, Cevadais Lineament).

Despite the compositional differences between the different rock bodies, the ages of the peralkaline and alkaline magmatism in the Ossa-Morena zone as a whole are compatible with a persistent tensional regime during the Cambrian-Ordovician transition. Moreover, such magmatism appears to follow a period of continental extension that started at ca. 530–526 Ma (Romeo et al., 2006; Chichorro et al., 2008; Sánchez-García et al., 2008, 2014; Pereira et al., 2011, 2012d). Consequently, the Ossa-Morena

zone was subjected to long-lived crustal extension since the cessation of the subduction-related magmatic activity of the Cadomian arc system (i.e., for a minimum of ~60 m.y. from ca. 530 to ca. 470 Ma).

The Lu-Hf isotopic data from this study suggest a significant mantle-derived component in the three samples of peralkaline and alkaline syenites. The initial  $\epsilon_{\text{Hf}}$  values for PAL-1 are all positive and approach the model values for depleted mantle at ca. 480 Ma ( $+4.6 \leq \epsilon_{\text{Hf}(t)} \leq +11.5$ ). PAL-2 and PAL-3 give initial  $\epsilon_{\text{Hf}(t)}$  values that range from zero to +3 and +5, respectively, which indicate a significant component of juvenile material in the magma sources. These isotopic data are consistent with either magma sources in the mantle or relatively recently emplaced mafic material in the deep crust. Very limited mixing with crustal magmas is indicated for PAL-1 and perhaps slightly greater mixing/assimilation for PAL-2 and PAL-3. Based on an assumed age of ca. 480 Ma (Carrilho Lopes et al., 1993), this magmatic suite of alkaline and peralkaline rocks has  $^{87}\text{Sr}/^{86}\text{Sr}_{(480)}$  ratios of 0.7040–0.7544, and  $\epsilon_{\text{Nd}(480)}$  values of 3.39–4.91, indicating mantle derivation and involvement of some crustal contamination (Carrilho Lopes, 2004).

The variation of the  $^{176}\text{Lu}/^{177}\text{Hf}$  ratios in zircon from samples PAL-2 and PAL-3 suggests the occurrence of incomplete mixing during rock genesis, whereas the narrower  $^{176}\text{Lu}/^{177}\text{Hf}$  range of sample PAL-1 suggests a more homogeneous source, or greater mixing. Overall, the inhomogeneity of the zircon Hf isotope signatures (span of values for each sample, and among the three samples) may reflect open-system melting of deeper fertile crust, with extraction of the melt to higher crustal levels.

### Structuring of the Gondwana Lithosphere during Early Paleozoic Extension

Assuming that protracted attenuation of the lithosphere commonly leads to the formation of marine basins, the opening of the Rheic Ocean is considered to be the major consequence of persistent extension in Iberia during the early Paleozoic (Crowley et al., 2000; Bozkurt et al., 2008; Nance et al., 2010).

Two contrasting geodynamic models have been proposed to explain the source of tensional forces needed to individualize and/or rift apart the Gondwanan continental terranes exposed in Iberia. In the NW Iberia model, rifting and associated magmatism are interpreted as related to construction of a Cambrian arc system and a back-arc basin that was active until the Ordovician (Arenas et al., 2007; Díez Fernández et al., 2010; Fuenlabrada et al., 2010; Andonaegui et al., 2012). In that model, protracted subduction and subduction roll-back on the northern Gondwana margin produced extension in the back-arc region (Japan Sea model), leading to opening of marine basins (Abati et al., 2010). The alternative model for the Rheic Ocean opening in SW Iberia (Sánchez-García et al., 2003; Linnemann et al., 2008) suggests that oblique ridge/trench collision caused a thermal anomaly and subsequent rifting (analogous to the Cenozoic transfer of Baja California by the Pacific plate).

The differences between extant models for the formation of ocean basins along the Gondwana periphery may be because the continental blocks were laterally separated from each other prior to rifting (Stampfli et al., 2002). The development of discrete faults through the extending crust that facilitated the intrusion of deeply sourced fluids and juvenile magmas up to upper-crust levels (i.e., the peralkaline and alkaline suites), however, indicates that a significant portion of the northern margin of West Gondwana was affected by intracontinental rifting after ca. 500–490 Ma, forming narrow rifts. Early Paleozoic magmatism in the Bohemian Massif (Central Europe) indicates that attenuation of the continental lithosphere was accompanied by the emplacement of crustal- and mantle-derived bimodal magmatism (e.g., Floyd et al., 2000).

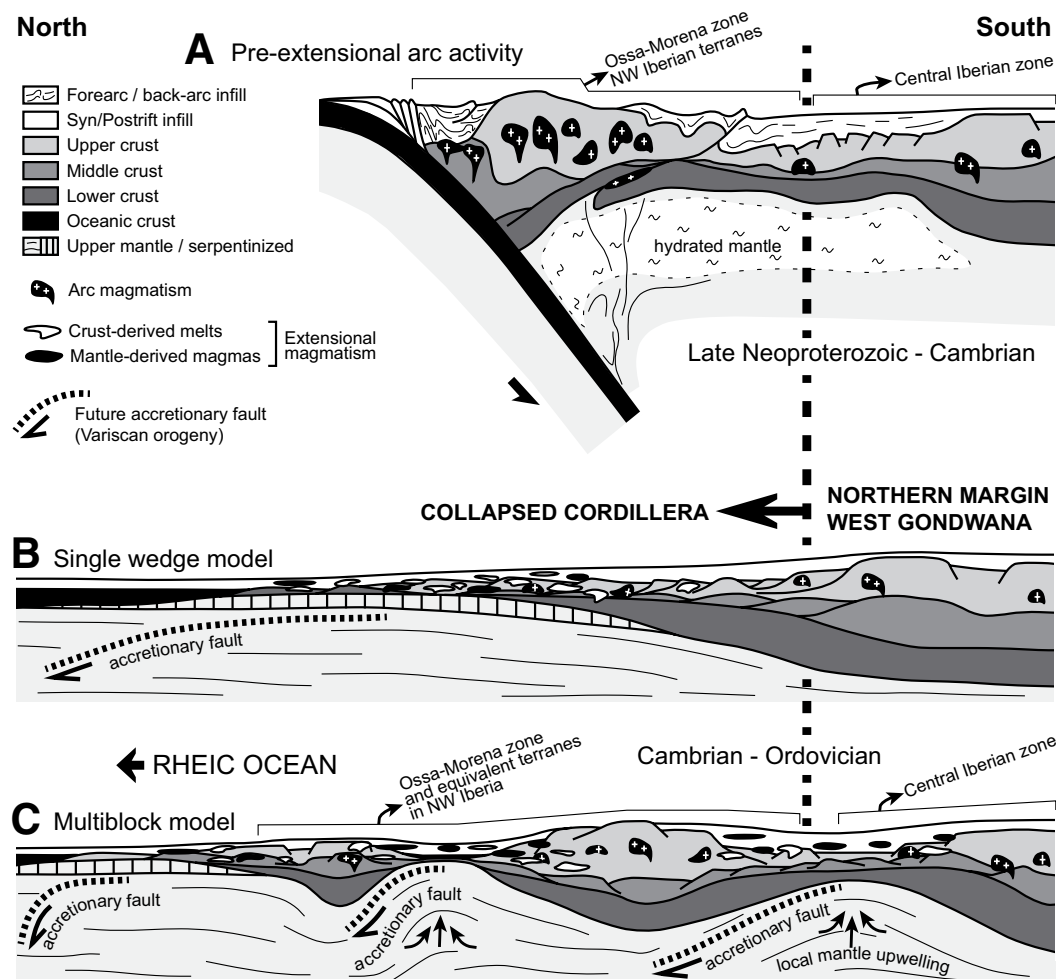


Recent modeling of Cordilleran-type orogens suggests that the presence of buoyant mantle wedges (formed after prolonged subduction) may promote volume forces acting on the orogenic crust and trigger horizontal extension and boudinaging of the upper plate (Rey and Müller, 2010). The Iberian sections of the margin were part of a long-lived Cordilleran-type orogen up to the Neoproterozoic-Cambrian transition (Fig. 9A), with renewed Cambrian arc activity for the case of NW Iberia. Therefore, a buoyant (highly hydrated, molten) mantle under the peri-Gondwanan lithosphere likely existed in the Cambrian and Ordovician (Pin et al., 2007). As a consequence, no large excess temperatures (e.g., plume-generated) would have been required for a passive rifting of lithosphere underlain by fertile mantle. However, effective ridge-push stresses, frictional stresses, and viscous stresses tend to produce an overall compressive crustal stress and sustain Cordilleran-type orogens, thus preventing passive rifting.

Models proposed for the Ossa-Morena zone and NW Iberia favor a ridge-subduction event by the Cambrian or Cambrian-Ordovician (Sánchez-García et al., 2003; Sánchez Martínez et al., 2012). Large buoyant slab segments (e.g., oceanic crust surrounding ridge zones) sink more slowly into the asthenosphere, so their subduction lowers the plate subduction velocity (Martinod et al., 2005) and, consequently, reduces/eliminates the ridge-push and frictional stresses affecting the subduction boundary. Following ridge subduction, increasingly older, denser, and thicker oceanic crust would reach the trench, increasing the effective slab-pull stress. These processes in combination favor trench retreat, causing

the buoyancy and gravitational stresses to overcome the forces sustaining orogenic topography, which ultimately leads to collapse and extension.

Extensional processes can lead to different crustal configurations, depending on lithospheric composition, thermal structure, extension rate, and the existence of previous heterogeneities (Buck, 1991; Benes and Davy, 1996; Corti et al., 2003; Rosenbaum et al., 2008). Rifts tend to propagate where the minimum energy is required for lithosphere breakup (Vauchez et al., 1997). In NW Iberia, the Ordovician peralkaline and alkaline magmatic suites developed in the back-arc region that separated the Gondwana mainland from a Cambrian arc system (Díez Fernández et al., 2010, 2012a). In SW Iberia, the Cambrian-Ordovician peralkaline and alkaline rocks of the Ossa-Morena zone were mostly located near its northern boundary with the Central Iberian zone, where there was a late Neoproterozoic arc system (Dallmeyer and Quesada, 1992; Ordóñez Casado, 1998; Eguíluz et al., 2001, 2013; Bandrés et al., 2004) that was later subjected to extension and voluminous magmatism during the Cambrian-Ordovician (Sánchez-García et al., 2008, 2010). Therefore, the intrusion of the peralkaline and alkaline suites in Iberia was not random but preferentially located either in previously attenuated crust and/or along the boundaries of formerly active belts (Ediacaran and Cambrian). These domains of inherited crustal weakness were probably characterized by the presence of strong competence contrasts, either lithological contrasts (granitoids vs. sedimentary rocks vs. metamorphic rocks) or the presence of preexisting fault zones, suture zones, failed rifts, or spreading centers.



**Figure 9. Contrasting models for the formation of wide continental platforms following the collapse of a Cordilleran-type margin along the northern margin of West Gondwana. (A) Cordilleran-style evolution during the late Neoproterozoic-Cambrian. (B) Single-wedge model versus (C) multiblock model for lithospheric extension during the Cambrian-Ordovician. Locations of major zones of the Iberian Massif are indicated.**

Seismic activity and peralkaline and alkaline intrusion were probably controlled by deep fractures that penetrated the entire lithosphere to tap magma sources deep in the crust or in the mantle. Once present, these melts probably modified the thermal field, produced new rheological heterogeneities, and influenced the dynamics of extension by enhancing deformation and strain localization (e.g., Buck, 2006). For these reasons, we favor an alternative to the classical single wedge-shaped passive margin with gradual transition from normal continental to normal oceanic crust (single wedge model; Fig. 9B) that has been generally suggested for the Gondwanan flank of the Rheic Ocean (Linnemann et al., 2007, 2008; Murphy et al., 2008; Nance et al., 2010). We propose that feedbacks among magmatism, deformation, and the existence of various inherited weak zones across the peri-Gondwanan domain eventually led to a horizontal crustal profile characterized by a series of continental blocks separated by variably thinned continental crust, or transitional continental-oceanic crust in the most attenuated areas (multiblock model; Fig. 9C). According to the similar age of the peralkaline and alkaline magmatism in NW and SW Iberia, it is likely that at least part of the crustal block compartmentalization occurred simultaneously across the margin.

The simultaneous formation of alkaline and calc-alkaline magmatic rocks in Iberia can be understood as a direct result of the cessation of the arc activity in Cambrian times (ca. 530–495 Ma) followed by extension over the formerly overriding plate. Such compositional variations indicate contribution of multiple magma sources, initially formed in active-margin settings (e.g., metasomatized mantle wedge, underplated mafic material, uplifted asthenosphere) and then extracted from the subcontinental mantle lithosphere under a high-heat-flow regime via lithosphere necks (Black and Liégeois, 1993; Liégeois et al., 1998; Bonin, 2004; Oyhantçabal et al., 2007).

### Variscan Reactivation of Inherited Crustal Weakness Zones

Preexisting crustal-scale faults and strong lithological contrasts may control the geometry, orientation, and precise location of faults that accommodate reactivation (Holdsworth et al., 2001). The multiblock model for Gondwana rifting proposed here implies the formation of a number of crustal-scale rheological weaknesses across a rather irregular, yet fairly continuous, continental lithosphere. The structure of this broad area of Iberia had implications for the geodynamic evolution several tens of millions of years later, during the Variscan orogeny. Although Ordovician magmatism was widespread at sites in the Iberia sector of the Gondwanan platform (Bea et al., 2006; Solá et al., 2008; Díez Montes et al., 2010; Rubio-Ordóñez et al., 2012), we would like to draw attention to the spatial association between the peralkaline and alkaline magmatic suites and the location of some Variscan metamorphic belts with high-pressure rocks (eclogites, granulites, and blueschists; Fig. 1).

Eclogite lenses and high-pressure mineral assemblages consistently indicate that Ordovician peralkaline and alkaline suites of NW Iberia are part of a continental section that experienced deep subduction during the Variscan orogeny (ca. 370 Ma; Martínez Catalán et al., 1996; Rubio Pascual et al., 2002; Rodríguez et al., 2003; Díez Fernández et al., 2011). Significant numbers of the peralkaline and alkaline rocks of the Ossa-Morena zone (this study) are aligned with a heterogeneous Variscan metamorphic belt with high-pressure rocks that marks the transition to the continental block defined by the Cantabrian zone–West Asturian–Leonese zone–Central Iberian zone–Schistose domain (Figs. 1 and 3; Coimbra-Córdoba shear zone; Burg et al., 1981; Apalategui et al., 1990; Ábalos et al., 1991). Eclogitic rocks form at subcontinental depths, and many authors agree that evidence of a Variscan continental subduction zone is preserved along the Coimbra-Córdoba shear zone (Azor et al., 1994; Ordóñez Casado, 1998; Simancas et al., 2001; Pereira et al., 2010). In the southern part of the Ossa-

Morena zone, there is evidence for high-pressure metamorphism related to the Variscan orogeny (De Jong et al., 1991; Leal, 2001; Booth-Rea et al., 2005; Rubio Pascual et al., 2013), but the relationship with early Paleozoic peralkaline and alkaline rocks is not known.

Subduction processes affecting continental crust in Iberia were active from ca. 400 Ma to ca. 340 Ma, as documented by high-pressure crustal rocks exposed in the European Variscan belt (Kroner and Romer, 2013, and references therein). Consequently, those sections of continental crust that experienced larger attenuation during the early Paleozoic would be mechanically weaker and therefore more prone to mechanical failure under compressive forces. In this scenario, these preexisting zones of weakness would become reactivated as major accretionary faults during subsequent orogeny.

Following Kroner and Romer (2013), we suggest that the development of several Variscan metamorphic belts with high-pressure rocks (NW Iberian belts and Coimbra-Córdoba belt), which today separate terranes that belonged to the Gondwana margin, is one of the ultimate consequences of Ordovician lithosphere necking. The set of relatively buoyant microblocks separated by readily subductable (thinner) crust was subjected to late Paleozoic plate convergence (multiblock model; Fig. 9C). After the closure of the Rheic Ocean, multiple Variscan high-pressure metamorphic belts formed, as opposed to the single belt predicted by a single wedge-shaped margin. The onset of high-pressure metamorphism was sequential, with high-pressure metamorphism in the Upper Allochthon of NW Iberia and in the Lower Allochthon of NW Iberia dated at ca. 400–390 Ma (Ordóñez Casado et al., 2001; Fernández-Suárez et al., 2007) and ca. 380–370 Ma (Rodríguez et al., 2003; Abati et al., 2010), respectively. The obtained ages in NW Iberia are older than those of ca. 340 Ma determined for high-pressure rocks of the Coimbra-Córdoba shear zone (Ordóñez Casado, 1998; Pereira et al., 2010) and from the Central Iberian zone (Villaseca et al., 2015). According to our model, the earliest onset of high-pressure metamorphism is recorded at margins of crustal blocks that were in more external positions in the continental margin.

### CONCLUSIONS

The Ossa-Morena zone represents a section of the northern margin of West Gondwana that was subjected to long-lived crustal extension and abundant magmatism after the cessation of peri-Gondwanan magmatic arc activity during the late Neoproterozoic–Early Cambrian transition (Cadomian orogeny). U-Pb zircon dating of peralkaline and alkaline syenites from the Ossa-Morena zone indicates that this particular type of magmatism occurred in the Furongian–Middle Ordovician transition (ca. 490–470 Ma). These ages overlap those obtained for peralkaline and alkaline granitoids in other sections of Gondwana (e.g., those exposed in the basal allochthonous terranes of NW Iberia at ca. 485–470 Ma). Together, these magmatic events depict a stage of narrow intracontinental rifting that is traceable along the boundaries of the continental blocks that today make up Iberia.

The  $^{87}\text{Sr}/^{86}\text{Sr}_{(480)}$  ratios of 0.7040–0.7544,  $\epsilon_{\text{Nd}(480)}$  values of 3.39–4.91, and Lu-Hf isotopic data ( $0 \leq \epsilon_{\text{Hf}(t)} \leq +11.5$ ) extracted from zircon support a significant mantle-derived component for the peralkaline and alkaline magmas, which were tapped from deep sources, probably in the lower crust or the upper mantle.

We propose that the arrival of peralkaline and alkaline magmas during intracontinental rifting was coeval with a necking process affecting the Gondwanan lithosphere, thus shaping it into a series of variably connected continental microblocks, even transitional continental-oceanic crust in the most attenuated areas. These inherited (early Paleozoic) zones of crustal

weakness were subsequently reactivated by Variscan tectonism during late Paleozoic time as Gondwana and Laurussia collided to form Pangea.

Our observations suggest that Cordilleran-type orogens that are subjected to extension after long-lived subduction can develop wide continental platforms featuring multiple continental blocks. Such a setting favors an inhomogeneous record of geological events across the same continental margin following block segregation. In addition, the formation of sequenced high-pressure belts in collisional orogens can be explained as the ultimate result of multiple necking events of continental lithosphere during precollisional collapse of a Cordilleran-type orogen.

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## REFERENCES CITED

- Ábalos, B., 1990, *Cinemática y Mecanismos de la Deformación en Régimen de Transpresión: Evolución Estructural y Metamórfica de la Zona de Cizalla Dúctil de Badajoz-Córdoba* [Ph.D. thesis]: Bilbao, Spain, Universidad del País Vasco, 430 p.
- Ábalos, B., Gil Ibarguchi, J.I., and Eguiluz, L., 1991, Cadomian subduction, collision and Variscan transpression in the Badajoz-Córdoba shear belt, southwest Spain: *Tectonophysics*, v. 199, p. 51–72, doi:10.1016/0040-1951(91)90118-C.
- Abati, J., Castineiras, P., Arenas, R., Fernández-Suárez, J., and Gómez Barreiro, J., 2007, Using SHRIMP zircon dating to unravel tectonothermal events in arc environments. The early Palaeozoic arc of NW Iberia revisited: *Terra Nova*, v. 19, p. 432–439, doi:10.1111/j.1365-3121.2007.00768.x.
- Abati, J., Dunning, G.R., Arenas, R., Díaz García, F., González Cuadra, P., Martínez Catalán, J.R., and Andonaegui, P., 1999, Early Ordovician orogenic event in Galicia (NW Spain): Evidence from U–Pb ages in the uppermost unit of the Ordenes complex: *Earth and Planetary Science Letters*, v. 165, p. 213–228, doi:10.1016/S0012-821X(98)00268-4.
- Abati, J., Gerdes, A., Fernández-Suárez, J., Arenas, R., Whitehouse, M.J., and Díez Fernández, R., 2010, Magmatism and early-Variscan continental subduction in the northern Gondwana margin recorded in zircons from the basal units of Galicia, NW Spain: *Geological Society of America Bulletin*, v. 122, p. 219–235, doi:10.1130/B26572.1.
- Alia, M., 1963, Rasgos estructurales de la Baja Extremadura: *Boletín Real Sociedad Española: Histoire et Nature*, v. 61, p. 247–262.
- Ancochea, E., Arenas, R., Brandle, J.L., Peinado, M., and Sagredo, J., 1988, Caracterización de las rocas metavolcánicas silúricas del NO del Macizo Ibérico: *Geociencias, Aveiro*, v. 3, p. 23–34.
- Anderson, E.M., 1936, The dynamics of the formation of cone-sheets, ring dykes, and cauldron-subsidence: *Proceedings of the Royal Society of Edinburgh*, v. 56, p. 128–163.
- Andonaegui, P., Castineiras, P., González Cuadra, P., Arenas, R., Sánchez Martínez, S., Abati, J., Díaz García, F., and Martínez Catalán, J.R., 2012, The Corredoiras orthogneiss (NW Iberian Massif): Geochemistry and geochronology of the Paleozoic magmatic suite developed in a peri-Gondwanan arc: *Lithos*, v. 128–131, p. 84–99, doi:10.1016/j.lithos.2011.11.005.
- Apalategui, O., Eguiluz, L., and Quesada, C., 1990, Ossa-Morena zone: Structure, in Dalmeyer, R.D., and Martínez García, E., eds., *Pre-Mesozoic Geology of Iberia*: Berlin, Germany, Springer-Verlag, p. 280–292.
- Araújo, A., Fonseca, P.E., Munhá, J.M., Moita, P., Pedro, J., and Ribeiro, A., 2005, The Moura phyllonitic complex: An accretionary complex related with obduction in the southern Iberia Variscan suture: *Geodinamica Acta*, v. 18, p. 375–388, doi:10.3166/ga.18.375-388.
- Arenas, R., Gil Ibarguchi, J.I., González Lodeiro, F., Klein, E., Martínez Catalán, J.R., Ortega Gironés, E., de Pablo Maciá, J.G., and Peinado, M., 1986, Tectonostratigraphic units in the complexes with mafic and related rocks of the NW of the Iberian Massif: *Hercynica*, v. 2, p. 87–110.
- Arenas, R., Martínez Catalán, J.R., Sánchez Martínez, S., Fernández-Suárez, J., Andonaegui, P., Pearce, J.A., and Corfú, F., 2007, The Vila de Cruces ophiolite: A remnant of the early Rhee Ocean in the Variscan suture of Galicia (northwest Iberian Massif): *The Journal of Geology*, v. 115, p. 129–148, doi:10.1086/510645.
- Arenas, R., Sánchez Martínez, S., Castineiras, P., Jeffries, T.E., Díez Fernández, R., and Andonaegui, P., 2009, The basal tectonic melange of the Cabo Ortegal complex (NW Iberian Massif): A key unit in the suture of Pangea: *Journal of Iberian Geology*, v. 35, p. 85–125.
- Arenas, R., Díez Fernández, R., Sánchez Martínez, S., Gerdes, A., Fernández-Suárez, J., and Albert, R., 2014, Two-stage collision: Exploring the birth of Pangea in the Variscan terranes: *Gondwana Research*, v. 25, p. 756–763, doi:10.1016/j.gr.2013.08.009.
- Arps, C.E.S., 1970, Petrology of a part of the western Galicia basement between the Río Jallas and the Río de Arosa (NW Spain) with emphasis on zircon investigations: *Leidse Geologische Mededelingen*, v. 46, p. 57–155.
- Assunção, C.F.T., 1956a, Notas de mineralogia e petrografia portuguesa. X. Um anortositó (bytownitito) do Alto Alentejo (Campo Maior): *Boletim do Museu e Laboratório Mineralógico e Geológico da Faculdade de Ciências, Universidade de Lisboa*, v. 24, p. 141–145.
- Assunção, C.F.T., 1956b, Rochas gabróicas e anortositicas do Alto Alentejo (Alguns elementos para o seu estudo), in *Actas do XXIII Congresso Luso-Espanhol para o Progresso das Ciências*, v. 5, 4a Seção, Ciências Naturais, Coimbra, Portugal, p. 23–28.
- Assunção, C.F.T., and Gonçalves, F., 1970, Contribuição para o conhecimento das rochas hipercalcinicas e alcalinas (gnaisse hastingsíticos) do Alto Alentejo (Portugal): *Boletim da Sociedade Geológica de Portugal*, v. 17, p. 187–228.
- Azor, A., Lodeiro, F.G., and Simancas, J.F., 1994, Tectonic evolution of the boundary between the Central Iberian and Ossa-Morena zones (Variscan belt, southwest Spain): *Tectonics*, v. 13, p. 45–61, doi:10.1029/93TC02724.
- Ballèvre, M., Bosse, V., Ducassou, C., and Pitra, P., 2009, Palaeozoic history of the Armorican Massif: Models for the tectonic evolution of the suture zones: *Comptes Rendus Geoscience*, v. 341, p. 174–201, doi:10.1016/j.crte.2008.11.009.
- Bandrés, A., Eguiluz, L., Pin, C., Paquette, J.L., Ordóñez, B., Le Fèvre, B., Ortega, L.A., and Gil Ibarguchi, J.I., 2004, The northern Ossa-Morena Cadomian batholith (Iberian Massif): Magmatic arc origin and early evolution: *International Journal of Earth Sciences*, v. 93, p. 860–885, doi:10.1007/s00531-004-0423-6.
- Barberi, F., Ferrara, G., Santacroce, R., Treuil, M., and Varet, J., 1975, A transitional basalt-pantellerite sequence of fractional crystallization, the Boina centre (Afar Rift, Ethiopia): *Journal of Petrology*, v. 16, p. 22–56, doi:10.1093/petrology/16.1.22.
- Barker, D.S., 1987, Tertiary alkaline magmatism in Trans-Pecos Texas, in Fitton, J.G., and Upton, B.G.J., eds., *Alkaline Igneous Rocks: Geological Society of London Special Publication* 30, p. 415–431, doi:10.1144/GSL.SP.1987.030.01.20.
- Bea, F., Montero, P., Talavera, C., and 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*, v. 4, p. 395–401.
- Benes, V., and Davy, P., 1996, Modes of continental lithospheric extension: Experimental verification of strain localization processes: *Tectonophysics*, v. 254, p. 69–87, doi:10.1016/0040-1951(95)00076-3.
- Bickford, M.E., Mueller, P.A., Kamenov, G.D., and Hill, B.M., 2008, Crustal evolution of southern Laurentia during the Paleoproterozoic: Insights from zircon Hf isotopic studies of ca. 1.75 Ga rocks in central Colorado: *Geology*, v. 36, p. 555–558, doi:10.1130/G24700A.1.
- Black, L.P., Kamo, S.L., Williams, I.S., Mundil, R., Davis, D.W., Korsch, R.J., and Foudoulis, C., 2003, The application of SHRIMP to Phanerozoic geochronology: a critical appraisal of four zircon standards: *Chemical Geology*, v. 200, p. 171–188, doi:10.1016/S0009-2541(03)00166-9.
- Black, R., and Liégeois, J.P., 1993, Cratons, mobile belts, alkaline rocks and continental lithospheric mantle—The Pan-African testimony: *Journal of the Geological Society of London*, v. 150, p. 89–98, doi:10.1144/gsjgs.150.1.0088.
- Black, S., MacDonald, R., and Kelly, M.R., 1997, Crustal origin for peralkaline rhyolites from Kenya: Evidence from U-series disequilibrium and Th-isotopes: *Journal of Petrology*, v. 38, p. 277–297, doi:10.1093/ptro/38.2.277.
- Blichert-Toft, J., and Puchtel, I.S., 2010, Depleted mantle sources through time: Evidence from Lu–Hf and Sm–Nd isotope systematics of Archean komatiites: *Earth and Planetary Science Letters*, v. 297, p. 598–606, doi:10.1016/j.epsl.2010.07.012.
- Bonin, B., 2004, Do coeval mafic and felsic magmas in post-collisional to within-plate regimes necessarily imply two contrasting, mantle and crustal, sources? A review: *Lithos*, v. 78, p. 1–24, doi:10.1016/j.lithos.2004.04.042.
- Bonin, B., 2007, A-type granites and related rocks: Evolution of a concept, problems and prospects: *Lithos*, v. 97, p. 1–29, doi:10.1016/j.lithos.2006.12.007.
- Booth-Rea, G., Azañón, J.M., Martínez-Martínez, J.M., Vidal, O., and García-Dueñas, V., 2005, Contrasting structural and *P–T* evolution of tectonic units in the southeastern Betics: Key for understanding the exhumation of the Alboran domain HP/LT crustal rocks (western Mediterranean): *Tectonics*, v. 24, TC2009, doi:10.1029/2004TC001640.
- Bouvier, A., Vervoort, J.D., and Patchett, P.J., 2008, The Lu–Hf and Sm–Nd isotopic composition of CHUR: Constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets: *Earth and Planetary Science Letters*, v. 273, p. 48–57, doi:10.1016/j.epsl.2008.06.010.
- Bozkurt, E., Pereira, M.F., Strachan, R.A., and Quesada, C., 2008, Evolution of the Rhee Ocean: *Tectonophysics*, v. 461, p. 1–8, doi:10.1016/j.tecto.2008.08.015.
- Braid, J.A., Murphy, J.B., Quesada, C., and Mortensen, J., 2011, Tectonic escape of a crustal fragment during the closure of the Rhee Ocean: U–Pb detrital zircon data from the late Palaeozoic Pulo do Lobo and South Portuguese zones, southern Iberia: *Journal of the Geological Society of London*, v. 168, p. 383–392, doi:10.1144/0016-76492010-104.
- Buck, W.R., 1991, Modes of continental lithospheric extension: *Journal of Geophysical Research—Solid Earth*, v. 96, p. 20,161–20,178, doi:10.1029/91JB01485.
- Buck, W.R., 2006, The role of magma in the development of the Afro-Arabian Rift System, in Yirgu, G., Ebinger, C.J., and Maguire, P.K.H., eds., *The Afar Volcanic Province within the East African Rift System: Geological Society of London Special Publication* 259, p. 43–54, doi:10.1144/GSL.SP.2006.259.01.05.
- Burg, J.P., Iglesias, M., Laurent, P., Matte, P., and Ribeiro, A., 1981, Variscan intracontinental deformation: The Coimbra-Córdoba shear zone (SW Iberian Peninsula): *Tectonophysics*, v. 78, p. 161–177, doi:10.1016/0040-1951(81)90012-3.
- Canilho, M.H., 1973, Complexo plutónico básico e ultrabásico de Alter do Chão (Alentejo): *Boletim da Sociedade Geológica de Portugal*, v. 18, p. 155–170.
- Carrilho Lopes, J.M., 2004, *Petrologia e Geoquímica de Complexos Plutónicos do Nordeste Alentejano (Portugal Central): Província Alcalino e Maciço de Campo Maior* [Ph.D. thesis]: Évora, Portugal, Universidade de Évora, 505 p.
- Carrilho Lopes, J.M., Portugal Ferreira, M., and Munhá, J., 1993, Geochronological relationships between the Alter do Chão–Cabeço de Vide basic/ultrabasic massif and associated



- peralkaline rocks in NE Alentejo (central Portugal), in XII Western Peninsula Meeting Abstracts: Bilbao, Spain, Terra Nova, v. 5, supplement 6, p. 10.
- Carrilho Lopes, J.M., Munhá, J.M., and Gonçalves, F., 1996, Química mineral dos complexos Gabro-Sieníticos de Alter do Chão e de Elvas (NE-Alentejo, Portugal Central), in Araújo, A., and Pereira, M.F., eds., Estudos sobre a Geologia da Zona de Ossa-Morena (Macico Ibérico): Évora, Portugal, Livro de Homen, Prof Francisco Gonçalves, p. 57–90.
- Carvalho, A., 1965, Contribuição para o conhecimento geológico da região entre Portel e Ficalho (Alentejo): Memórias dos Serviços Geológicos de Portugal, v. 11, p. 1–130.
- Castiñeiras, P., Díaz García, F., and Gómez Barreiro, J., 2010, REE-assisted U-Pb zircon age (SHRIMP) of an anatectic granodiorite: Constraints on the evolution of the A Silva granodiorite, Iberian allochthonous complexes: Lithos, v. 116, p. 153–166, doi:10.1016/j.lithos.2010.01.013.
- Chacón, J., 1979, Estudio Geológico del Sector Central del Anticlinorio Portalegre-Badajoz-Córdoba (Macizo Ibérico Meridional) [Ph.D. thesis]: Granada, Spain, Universidad de Granada, 728 p.
- Chichorro, M., Pereira, M.F., Díaz-Azpiroz, M., Williams, I.S., Fernández, C., Pin, C., and Silva, J.B., 2008, Cambrian ensialic rift-related magmatism in the Ossa-Morena zone (Évora-Aracena metamorphic belt, SW Iberian Massif): Sm-Nd isotopes and SHRIMP zircon U-Th-Pb geochronology: Tectonophysics, v. 461, p. 91–113, doi:10.1016/j.tecto.2008.01.008.
- Civetta, L., D'Antonio, M., Orsi, G., and Tilton, G.R., 1998, The geochemistry of volcanic rocks from Pantelleria Island, Sicily Channel: Petrogenesis and characteristics of the mantle source region: Journal of Petrology, v. 39, p. 1453–1491, doi:10.1093/ptro/39.8.1453.
- Clague, D.A., 1987, Hawaiian alkaline volcanism, in Fitton, J.G., and Upton, B.G.J., eds., Alkaline Igneous Rocks: Geological Society of London Special Publication 30, p. 227–252, doi:10.1144/GSL.SP.1987.030.01.10.
- Coelho, A.V.P., and Gonçalves, F., 1971, Novos elementos sobre gnaisses nefeliníticos e rochas hipercalcínicas albiticas do alto Alentejo: Boletim da Sociedade Geológica de Portugal, v. 18, p. 105–117.
- Collins, W.J., 2002, Hot orogens, tectonic switching, and creation of continental crust: Geology, v. 30, p. 535–538, doi:10.1130/0091-7613(2002)030<0535:HOTSAC>2.0.CO;2.
- Collins, W.J., Beams, S.D., White, A.J.R., and Chappell, B.W., 1982, Nature and origin of A-type granites with particular reference to southeastern Australia: Contributions to Mineralogy and Petrology, v. 80, p. 189–200, doi:10.1007/BF00374895.
- Corti, G., Bonini, M., Conticelli, S., Innocenti, F., Manetti, P., and Sokoutis, D., 2003, Analogue modelling of continental extension: A review focused on the relations between the patterns of deformation and the presence of magma: Earth-Science Reviews, v. 63, p. 169–247, doi:10.1016/S0012-8252(03)00035-7.
- Crespo-Blanc, A., 1992, Structure and kinematics of a sinistral transpressive suture between the Ossa-Morena and the South Portuguese zones, South Iberian Massif: Journal of the Geological Society of London, v. 149, p. 401–411, doi:10.1144/gsjgs.149.3.0401.
- Crespo-Blanc, A., and Orozco, M., 1988, The southern Iberian shear zone: A major boundary in the Hercynian folded belt: Tectonophysics, v. 148, p. 221–227, doi:10.1016/0040-1951(88)90130-8.
- Crowley, Q.G., Floyd, P.A., Winchester, J.A., Franke, W., and Holland, J.G., 2000, Early Palaeozoic rift-related magmatism in Variscan Europe: Fragmentation of the Armorican terrane assemblage: Terra Nova, v. 12, p. 171–180, doi:10.1046/j.1365-3121.2000.00290.x.
- Dallmeyer, R.D., and Quesada, C., 1992, Cadomian vs. Variscan evolution of the Ossa-Morena zone (SW Iberia): Field and  $^{40}\text{Ar}/^{39}\text{Ar}$  mineral age constraints: Tectonophysics, v. 216, p. 339–364, doi:10.1016/0040-1951(92)09405-U.
- Davies, G.R., and MacDonald, R., 1987, Crustal influences in the petrogenesis of the Naivasha basalt-comendite complex: Combined trace element and Sr-Nd-Pb isotope constraints: Journal of Petrology, v. 28, p. 1009–1031, doi:10.1093/petrology/28.6.1009.
- De Jong, G., Dalstra, H., De Boorder, H., and Savage, J.F., 1991, Blue amphiboles, Variscan deformation and plate tectonics in the Beja Massif, south Portugal: Comunicações Serviços Geológicos de Portugal, v. 77, p. 59–64.
- Dias da Silva, I., Valverde-Vaquero, P., González Clavijo, E., Díez Montes, A., and Martínez Catalán, J.R., 2014, Structural and stratigraphical significance of U-Pb ages from the Mora and Saldanha volcanic complexes (NE Portugal, Iberian Variscides), in Schulmann, K., Martínez Catalán, J.R., Lardeaux, J.M., Janousek, V., and Oggiano, G. eds., The Variscan Orogeny: Extent, Timescale and the Formation of the European Crust: Geological Society of London Special Publication 405, doi:10.1144/SP405.3.
- Díaz Azpiroz, M., Castro, A., Fernández, C., López, S., Fernández Caliani, J.C., and Moreno-Ventas, I., 2004, The contact between the Ossa-Morena and the South Portuguese zones. Characteristics and significance of the Aracena metamorphic belt, in its central sector between Aroche and Aracena (Huelva): Journal of Iberian Geology, v. 30, p. 23–51.
- Díaz Azpiroz, M., Fernández, C., Castro, A., and El-Biad, M., 2006, Tectonometamorphic evolution of the Aracena metamorphic belt (SW Spain) resulting from ridge-trench interaction during Variscan plate convergence: Tectonics, v. 25, TC1001, doi:10.1029/2004TC001742.
- Díez Fernández, R., and Martínez Catalán, J.R., 2009, 3D analysis of an Ordovician igneous ensemble: A complex magmatic structure hidden in a polydeformed allochthonous Variscan unit: Journal of Structural Geology, v. 31, p. 222–236, doi:10.1016/j.jsg.2008.11.017.
- Díez Fernández, R., Martínez Catalán, J.R., Gerdes, A., Abati, J., Arenas, R., and Fernández-Suárez, J., 2010, U-Pb ages of detrital zircons from the basal allochthonous units of NW Iberia: Provenance and paleoposition on the northern margin of Gondwana during the Neoproterozoic and Paleozoic: Gondwana Research, v. 18, p. 385–399, doi:10.1016/j.gr.2009.12.006.
- Díez Fernández, R., Martínez Catalán, J.R., Arenas, R., and Abati, J., 2011, Tectonic evolution of a continental subduction-exhumation channel: Variscan structure of the basal allochthonous units in NW Spain: Tectonics, v. 30, TC3009, doi:10.1029/2010TC002850.
- Díez Fernández, R., Castiñeiras, P., and Gómez Barreiro, J., 2012a, Age constraints on Lower Paleozoic convection system: Magmatic events in the NW Iberian Gondwana margin: Gondwana Research, v. 21, p. 1066–1079, doi:10.1016/j.gr.2011.07.028.
- Díez Fernández, R., Martínez Catalán, J.R., Arenas, R., Abati, J., Gerdes, A., and Fernández-Suárez, J., 2012b, U-Pb detrital zircon analysis of the lower allochthon of NW Iberia: Age constraints, provenance and links with the Variscan mobile belt and Gondwanan cratons: Journal of the Geological Society of London, v. 169, p. 655–665, doi:10.1144/jgs2011-146.
- Díez Fernández, R., Martínez Catalán, J.R., Gómez Barreiro, J., and Arenas, R., 2012c, Extensional flow during gravitational collapse: A tool for setting plate convergence (Padrón migmatitic dome, Variscan belt, NW Iberia): The Journal of Geology, v. 120, p. 83–103, doi:10.1086/662735.
- Díez Montes, A., Martínez Catalán, J.R., and Bellido Mulas, F., 2010, Role of the Ollo de Sapo massive felsic volcanism of NW Iberia in the Early Ordovician dynamics of northern Gondwana: Gondwana Research, v. 17, p. 363–376, doi:10.1016/j.gr.2009.09.001.
- Eby, G.N., 1992, Chemical subdivision of the A-type granitoids: Petrogenetic and tectonic implications: Geology, v. 20, p. 641–644, doi:10.1130/0091-7613(1992)020<0641:CSOTAT>2.3.CO;2.
- Eguiluz, L., and Ábalos, B., 1992, Tectonic setting of Cadomian low-pressure metamorphism in the central Ossa-Morena zone (Iberian massif, SW Spain): Precambrian Research, v. 56, p. 113–137, doi:10.1016/0301-9268(92)90087-5.
- Eguiluz, L., Ábalos, B., and Gil Ibarguchi, J.I., 1990, Eclogitas de la banda de Cizalla Badajoz-Córdoba (Suroeste de España). Datos petrográficos y significado geodinámico: Geogaceta, v. 7, p. 28–31.
- Eguiluz, L., Gil Ibarguchi, J.I., Ábalos, B., and Apraiz, A., 2000, Superposed Hercynian and Cadomian orogenic cycles in the Ossa-Morena zone and related areas of the Iberian Massif: Geological Society of America Bulletin, v. 112, p. 1398–1413, doi:10.1130/0016-7606(2000)112<1398:SHACOC>2.0.CO;2.
- Eguiluz, L., Bandrés, A., Ortega, J.L., Gil Ibarguchi, J.I., Garcés, M., Paquette, J.L., and Pin, C., 2001, New evidence on the Cadomian evolution of northern Ossa-Morena zone (SW Spain), in Abstracts: Sion, Switzerland, IGCP 453 International Meeting on Collisional Orogens, p. 67–68.
- Eguiluz, L., Iriondo, A., and Martínez-Torres, L.M., 2013, Edad  $^{40}\text{Ar}/^{39}\text{Ar}$  (539.06 ± 3 Ma) de los anfíboles del Granitoide del Escribano: Arco volcánico cadomiense (zona de Ossa-Morena): Geogaceta, v. 54, p. 51–54.
- Expósito, I., Simancas, J.F., González Lodeiro, F., Bea, F., Montero, P., and Salman, K., 2003, Metamorphic and deformational imprint of Cambrian–Lower Ordovician rifting in the Ossa-Morena zone (Iberian Massif, Spain): Journal of Structural Geology, v. 25, p. 2077–2087, doi:10.1016/S0191-8141(03)00075-0.
- Fernández-Suárez, J., Arenas, R., Abati, J., Martínez Catalán, J.R., Whitehouse, M.J., and Jeffries, T.E., 2007, U-Pb chronometry of polymetamorphic high-pressure granulites: An example from the allochthonous terranes of the NW Iberian Variscan belt: Geological Society of America, v. 200, p. 469–488, doi:10.1130/2007.1200(24).
- Fernández-Suárez, J., Díaz García, F., Jeffries, T.E., Arenas, R., and Abati, J., 2003, Constraints on the provenance of the uppermost allochthonous terrane of the NW Iberian Massif: inferences from detrital zircon U-Pb ages: Terra Nova, v. 15, p. 138–144, doi:10.1046/j.1365-3121.2003.00479.x.
- Fernández-Suárez, J., Gutiérrez-Alonso, G., Jenner, G.A., and Tubrett, M.N., 2000, New ideas on the Proterozoic–early Palaeozoic evolution of NW Iberia: Insights from U-Pb detrital zircon ages: Precambrian Research, v. 102, p. 185–206, doi:10.1016/S0301-9268(00)00065-6.
- Fernández-Suárez, J., Gutiérrez-Alonso, G., and Jeffries, T.E., 2002, The importance of along-margin terrane transport in northern Gondwana: Insights from detrital zircon parentage in Neoproterozoic rocks from Iberia and Brittany: Earth and Planetary Science Letters, v. 204, p. 75–88, doi:10.1016/S0012-821X(02)00963-9.
- Fitton, J.G., 1987, The Cameroon line, West Africa: A comparison between oceanic and continental alkaline volcanism, in Fitton, J.G., and Upton, B.G.J., eds., Alkaline Igneous Rocks: Geological Society of London Special Publication 30, p. 273–291, doi:10.1144/GSL.SP.1987.030.01.13.
- Fitton, J.G., and Upton, B.G.J., eds., 1987, Alkaline Igneous Rocks: Geological Society of London Special Publication 30, 568 p.
- Floor, P., 1966, Petrology of an aegirine-riebeckite gneiss-bearing part of the Hesperian Massif: The Galiñeiro and surrounding areas, Vigo, Spain: Leidse Geologische Mededelingen, v. 36, p. 204.
- Floyd, P.A., Winchester, J.A., Seston, R., Kryza, R., and Crowley, Q.G., 2000, Review of geochemical variation in Lower Palaeozoic metabasites from the NE Bohemian Massif: Intracratonic rifting and plume-ridge interaction, in Franke, W., Haak, V., Oncken, O., and Tanner, D., Orogenic Processes: Quantification and Modelling in the Variscan Belt: Geological Society of London Special Publication 179, p. 155–174, doi:10.1144/GSL.SP.2000.179.01.11.
- Foster, D.A., Mueller, P.A., Heatherington, A., Gifford, J.N., and Kalakay, T.J., 2012, Lu-Hf systematics of magmatic zircons reveal a Proterozoic crustal boundary under the Cretaceous Pioneer batholith, Montana: Lithos, v. 142–143, p. 216–225, doi:10.1016/j.lithos.2012.03.005.
- Franke, W., 2000, The mid-European segment of the Variscides: Tectonostratigraphic units, terrane boundaries and plate tectonic evolution, in Franke, W., Haak, V., Oncken, O., and Tanner, D. eds., Orogenic Processes: Quantification and Modelling in the Variscan Belt: Geological Society of London Special Publication 179, p. 35–61, doi:10.1144/GSL.SP.2000.179.01.05.
- Fuenlabrada, J.M., Arenas, R., Sánchez Martínez, S., Díaz García, F., and Castiñeiras, P., 2010, A peri-Gondwanan arc in NW Iberia: Isotopic and geochemical constraints on the origin of the arc—A sedimentary approach: Gondwana Research, v. 17, p. 338–351, doi:10.1016/j.gr.2009.09.007.
- Galindo, C., 1989, Petrología y Geocronología del Complejo Plutónico Tálaga-Barcarrota (Badajoz) [Ph.D. thesis]: Madrid, Spain, Universidad Complutense de Madrid, 377 p.
- Galindo, C., and Casquet, C., 2004, El magmatismo prevarisco de la zona de Ossa-Morena, in Vera, J.A., ed., Geología de España: Madrid, Spain, SGE-IGME, p. 190–194.

- Galindo, C., and Portugal Ferreira, M.R., 1989, Petrology and chronology of the San Amaro peralkaline orthogneisses (Badajoz, Ossa-Morena zone): Memórias e notícias. Publicações do Museu e Laboratório Mineralógico e Geológico da Universidade de Coimbra, v. 108, p. 45–67.
- Galindo, C., Portugal Ferreira, M.R., Casquet, C., and Priem, H.N.A., 1990, Dataciones Rb/Sr en el complejo plutónico Tálga Barcarrota (CPTB) (Badajoz): Geogaceta, v. 8, p. 7–10.
- Gómez Barreiro, J., Martínez Catalán, J.R., Díez Fernández, R., Arenas, R., and Díaz García, F., 2010, Upper crust reworking during gravitational collapse: The Bembibre–Pico Sacro detachment system (NW Iberia): Journal of the Geological Society of London, v. 167, p. 769–784, doi:10.1144/0016-76492009-160.
- Gómez-Pugnaire, M.T., Azor, A., Fernández-Soler, J.M., and Sánchez-Vizcaino, V.L., 2003, The amphibolites from the Ossa–Morena/Central Iberian Variscan suture (southwestern Iberian Massif): Geochemistry and tectonic interpretation: Lithos, v. 68, p. 23–42, doi:10.1016/S0024-4937(03)00018-5.
- Gonçalves, F., 1971, Subsídios para o Conhecimento Geológico do Nordeste Alentejano: Serviços Geológicos de Portugal [Nova Série] Memória, v. 18, 62 p.
- Gonçalves, F., and Assunção, C.F.T., 1970, Carta Geológica de Portugal na escala 1:50,000. Notícia Explicativa da Folha 37-A, Elvas: Lisboa, Portugal, Serviços Geológicos de Portugal, 50 p.
- Gonçalves, F., and Carvalho, A., 1994, O Proterozoico da zona de Ossa-Morena no Alentejo. Síntese e atualização de conhecimentos: Memórias da Academia das Ciências de Lisboa, Classe de Ciências, v. 34, p. 141–173.
- Gonçalves, F., and Fernandes, A.P., 1973, Carta Geológica de Portugal na escala 1:50000. Notícia Explicativa da Folha 32-B, Portalegre: Lisboa, Portugal, Serviços Geológicos de Portugal, 45 p.
- Gonçalves, F., Zbyszewski, G., and Coelho, A.V.P., 1975, Carta Geológica de Portugal na escala 1:50000. Notícia Explicativa da Folha 32-D, Sousel: Lisboa, Portugal, Serviços Geológicos de Portugal, 49 p.
- Hawkesworth, C., and Kemp, A., 2006, Using hafnium and oxygen isotopes in zircons to unravel the record of crustal evolution: Chemical Geology, v. 226, p. 144–162, doi:10.1016/j.chemgeo.2005.09.018.
- Holdsworth, R.E., Handa, M., Miller, J.A., and Buick, I.S., 2001, Continental reactivation and reworking: An introduction, in Miller, J.A., Holdsworth, R.E., Buick, I.S., and Hand, M., eds., Continental Reactivation and Reworking: Geological Society of London Special Publication 184, p. 1–12, doi:10.1144/GSL.SP2001.184.01.01.
- Houghton, B.F., Weaver, S.D., Wilson, C.J.N., and Lanphere, M.A., 1992, Evolution of a Quaternary peralkaline volcano: Mayor Island, New Zealand: Journal of Volcanology and Geothermal Research, v. 51, p. 217–236, doi:10.1016/0377-0273(92)90124-V.
- James, E.W., and Henry, C.D., 1991, Compositional changes in Trans-Pecos Texas magmatism coincident with Cenozoic stress realignment: Journal of Geophysical Research–Solid Earth, v. 96, p. 13,561–13,575, doi:10.1029/91JB00203.
- Johnson, S.E., Schmidt, K.L., and Tate, M.C., 2002, Ring complexes in the Peninsular Ranges Batholith, Mexico and the USA: Magma plumbing systems in the middle and upper crust: Lithos, v. 61, p. 187–208, doi:10.1016/S0024-4937(02)00079-8.
- Julivert, M., Martínez, F.J., and Ribeiro, A., 1980, The Iberian segment of the European Hercynian foldbelt, in Cogne, J., and Slansky, M., eds., Geology of Europe: From Pre-Cambrian to the Post-Hercynian Sedimentary Basins: Mémoires du BRGM, Société Géologique du Nord (Villeneuve-d'Ascq), p. 132–158.
- Kemp, A.I.S., Wormald, R.J., Whitehouse, M.J., and Price, R.C., 2005, Hf isotopes in zircon reveal contrasting sources and crystallization histories for alkaline to peralkaline granites of Temora, southeastern Australia: Geology, v. 33, p. 797–800, doi:10.1130/G21706.1.
- Kemp, A.I.S., Hawkesworth, C.J., Foster, G.L., Paterson, B.A., Woodhead, J.D., Hergt, J.M., Gray, C.M., and Whitehouse, M.J., 2007, Magmatic and crustal differentiation history of granitic rocks from Hf–O isotopes in zircon: Science, v. 315, p. 980–983, doi:10.1126/science.1136154.
- Kroner, U., and Romer, R.L., 2013, Two plates—Many subduction zones: The Variscan orogeny reconsidered: Gondwana Research, v. 24, p. 298–329, doi:10.1016/j.gr.2013.03.001.
- Lancelot, J.R., and Allegret, A., 1982, Radiochronologie U/Pb de l'ortogneiss de Alter Pedroso (Alto Alentejo) et évolution anté-hercynienne de l'Europe occidentale: Neues Jahrbuch für Mineralogie Monatshefte, v. 9, p. 305–394.
- Leal, N., 2001, Estudo Petrológico e Geoquímico de Rochas Metamórficas Máficas de Alta Pressão das Regiões do Alívito–Viana do Alentejo e de Safira (Zona de Ossa-Morena, Maciço Ibérico) [Ph.D. thesis]: Lisboa, Portugal, Universidade de Lisboa, 401 p.
- Liégeois, J.P., Navez, J., Hertogen, J., and Black, R., 1998, Contrasting origin of post-collisional high-K calc-alkaline and shoshonitic versus alkaline and peralkaline granitoids. The use of sliding normalization: Lithos, v. 45, p. 1–28, doi:10.1016/S0024-4937(98)00023-1.
- Liñán, E., and Quesada, C., 1990, Ossa-Morena zone: 2. Stratigraphy, in Dallmeyer, R.D., and Martínez García, E., eds., Pre-Mesozoic Geology of Iberia: Berlin, Germany, Springer-Verlag, p. 229–266.
- Linnemann, U., Gerdes, A., Drost, K., and Buschmann, B., 2007, The continuum between Cadomian orogenesis and opening of the Rheic Ocean: Constraints from LA-ICP-MS U-Pb zircon dating and analysis of plate-tectonic setting (Saxo-Thuringian zone, northeastern Bohemian Massif, Germany), in Linnemann, U., Nance, R.D., Kraft, P., and Zulauf, G., eds., The Evolution of the Rheic Ocean: From Avalonian-Cadomian Active Margin to Alleghenian-Variscan Collision: Geological Society of America Special Paper 423, p. 61–96, doi:10.1130/2007.2423(03).
- Linnemann, U., Pereira, F., Jeffries, T.E., Drost, K., and Gerdes, A., 2008, The Cadomian orogeny and the opening of the Rheic Ocean: The diachrony of geotectonic processes constrained by LA-ICP-MS U-Pb zircon dating (Ossa-Morena and Saxo-Thuringian zones, Iberian and Bohemian Massifs): Tectonophysics, v. 461, p. 21–43, doi:10.1016/j.tecto.2008.05.002.
- Lipman, P.W., 1997, Subsidence of ash-flow calderas: Relation to caldera size and magma-chamber geometry: Bulletin of Volcanology, v. 59, p. 198–218, doi:10.1007/s004450050186.
- López-Guijarro, R., Armendariz, M., Quesada, C., Fernández-Suárez, J., Murphy, J.B., Pin, C., and Bellido, F., 2008, Ediacaran–Palaeozoic tectonic evolution of the Ossa Morena and Central Iberian zones (SW Iberia) as revealed by Sm–Nd isotope systematics: Tectonophysics, v. 461, p. 202–214, doi:10.1016/j.tecto.2008.06.006.
- López-Munguira, A., and Nieto García, F., 2004, Low-grade metamorphism in the central sector of the Ossa-Morena zone: Journal of Iberian Geology, v. 30, p. 109–118.
- Ludwig, K.R., 2008, Isoplot 3.6: Berkeley Geochronology Center Special Publication 4, 77 p.
- Macdonald, R., 2012, Evolution of peralkaline silicic complexes: Lessons from the extrusive rocks: Lithos, v. 152, p. 11–22, doi:10.1016/j.lithos.2012.01.014.
- MacDonald, R., Davies, G.R., Bliss, C.M., Leat, P.T., Bailey, D.K., and Smith, R.L., 1987, Geochemistry of high-silica peralkaline rhyolites, Naivasha, Kenya Rift Valley: Journal of Petrology, v. 28, p. 979–1008, doi:10.1093/petrology/28.6.979.
- Machado, G., Hladil, J., Koptikova, L., Fonseca, P., Rocha, F., and Galle, A., 2009, The Odivelas Limestone: Evidence for a Middle Devonian reef system in western Ossa-Morena zone (Portugal): Geologica Carpathica, v. 60, p. 121–137, doi:10.2478/v10096-009-0008-1.
- Martínez Catalán, J.R., Arenas, R., Díaz García, F., Rubio Pascual, F.J., Abati, J., and Marquín García, J., 1996, Variscan exhumation of a subducted Paleozoic continental margin: The basal units of the Ordenes complex, Galicia, NW Spain: Tectonics, v. 15, p. 106–121, doi:10.1029/95TC02617.
- Martínez Catalán, J.R., Díaz García, F., Arenas, R., Abati, J., Castineiras, P., González Cuadra, P., Gómez Barreiro, J., and Rubio Pascual, F.J., 2002, Thrust and detachment systems in the Ordenes complex (northwestern Spain): Implications for the Variscan–Appalachian geodynamics, in Martínez Catalán, J.R., Hatcher, R.D., Arenas, R., and Díaz García, F., eds., Variscan–Appalachian Dynamics: The Building of the Late Paleozoic Basement: Geological Society of America Special Paper 364, p. 163–182, doi:10.1130/0-8137-2364-7.163.
- Martínez Catalán, J.R., Fernández-Suárez, J., Jenner, G.A., Belousova, E., and Díez Montes, A., 2004, Provenance constraints from detrital zircon U–Pb ages in the NW Iberian Massif: Implications for Palaeozoic plate configuration and Variscan evolution: Journal of the Geological Society of London, v. 161, p. 463–476, doi:10.1144/0016-764903-054.
- Martínez Catalán, J.R., Arenas, R., Díaz García, F., Gómez Barreiro, J., González Cuadra, P., Abati, J., Castiñeiras, P., Fernández-Suárez, J., Sánchez Martínez, S., Andonaegui, P., González Clavijo, E., Díez Montes, A., Rubio Pascual, F.J., and Valle Aguado, B., 2007, Space and time in the tectonic evolution of the northwestern Iberian Massif. Implications for the Variscan belt, in Hatcher, R.D., Carlson, M.P., McBride, J.H., and Martínez Catalán, J.R., eds., 4-D Framework of Continental Crust: Geological Society of America Memoir 200, p. 403–423.
- Martínez Catalán, J.R., Arenas, R., Abati, J., Sánchez Martínez, S., Díaz García, F., Fernández-Suárez, J., González Cuadra, P., Castiñeiras, P., Gómez Barreiro, J., Díez Montes, A., González Clavijo, E., Rubio Pascual, F.J., Andonaegui, P., Jeffries, T.E., et al., 2009, A rootless suture and the loss of the roots of a mountain chain: The Variscan belt of NW Iberia: Comptes Rendus Geoscience, v. 341, p. 114–126, doi:10.1016/j.crte.2008.11.004.
- Martinod, J., Funicello, F., Faccenna, C., Labanieh, S., and Regard, V., 2005, Dynamical effects of subducting ridges: Insights from 3-D laboratory models: Geophysical Journal International, v. 163, p. 1137–1150, doi:10.1111/j.1365-246X.2005.02797x.
- Mata, J., and Munhá, J., 1986, Geochemistry of Cambrian metavolcanic rocks from the Córdoba-Elvas domain (Ossa-Morena zone): Maleo, v. 2, p. 27.
- Mata, J., and Munhá, J., 1990, Magmatogénese de metavulcanitos Câmbricos do nordeste Alentejano: Os stádios iniciais de rifting continental: Comunicações dos Serviços Geológicos de Portugal, v. 76, p. 61–89.
- Mata, J., Ribeiro, M.L., and Piçarra, J.M., 1993, S. Marcos do Campo volcanic complex: Geochemical evidence for a volcanic arc in the Ossa-Morena zone (Ordovician?), in XII Western Peninsula Meeting Abstracts: Terra Nova, v. 5, supplement 6, p. 2.
- Matte, P., 2001, The Variscan collage and orogeny (480–290 Ma) and the tectonic definition of the Armorica microplate: A review: Terra Nova, v. 13, p. 122–128, doi:10.1046/j.1365-3121.2001.00327.x.
- Montero, P., and Floor, P., 2004, Los complejos alcalinos prevariscos (magmatismo del Paleozoico Inferior en las unidades basales), in Vera, J.A., ed., Geología de España: Madrid, Spain, SGE-IGME, p. 149–150.
- Montero, P., Salman, K., Bea, F., Azor, A., Expósito Ramos, I., González Lodeiro, F., Martínez Poyatos, D., and Simancas, J.F., 2000, New data on the geochronology of the Ossa-Morena zone, Iberian Massif, in Martínez Catalán, J.R., Hatcher, R.D., Arenas, R., and Díaz García, F., eds., Variscan–Appalachian Dynamics: The Building of the Upper Paleozoic Basement: Basement Tectonics 15. Galicia 2000 Abstracts: A Coruña, Spain, p. 136–138.
- Montero, P., Bea, F., Corretge, L.G., Floor, P., and Whitehouse, M.J., 2009, U–Pb ion microprobe dating and Sr and Nd isotope geology of the Galifeiro igneous complex: A model for the peraluminous/peralkaline duality of the Cambro-Ordovician magmatism of Iberia: Lithos, v. 107, p. 227–238, doi:10.1016/j.lithos.2008.10.009.
- Mueller, P.A., Kamenov, G.D., Heatherington, A.L., and Richards, J., 2008, Crustal evolution in the southern Appalachian orogen: Evidence from Hf isotopes in detrital zircons: The Journal of Geology, v. 116, p. 414–422, doi:10.1086/589311.
- Murphy, J.B., and Nance, R.D., 1991, Supercontinent model for the contrasting character of late Proterozoic orogenic belts: Geology, v. 19, p. 469–472, doi:10.1130/0091-7613(1991)019<0469:SMFTCC>2.3.CO;2.
- Murphy, J.B., Gutiérrez-Alonso, G., Fernández-Suárez, J., and Braid, J.A., 2008, Probing crustal and mantle lithosphere origin through Ordovician volcanic rocks along the Iberian passive margin of Gondwana: Tectonophysics, v. 461, p. 166–180, doi:10.1016/j.tecto.2008.03.013.
- Nance, R.D., Murphy, J.B., and Keppie, J.D., 2002, A Cordilleran model for the evolution of Avalonia: Tectonophysics, v. 352, p. 11–31, doi:10.1016/S0040-1951(02)00187-7.
- Nance, R.D., Murphy, J.B., Strachan, R.A., Keppie, J.D., Gutiérrez-Alonso, G., Fernández-Suárez, J., Quesada, C., Linnemann, U., D'Imos, R., and Pisarevsky, S.A., 2008, Neoproterozoic–early Palaeozoic tectonostratigraphy and palaeogeography of the peri-Gondwanan terranes: Amazonian v. West African connections, in Ennih, N., and Liégeois,

- J.P., eds., The Boundaries of the West African Craton: Geological Society of London Special Publication 297, p. 345–383, doi:10.1144/SP297.17.
- Nance, R.D., Gutiérrez-Alonso, G., Keppie, J.D., Linnemann, U., Murphy, J.B., Quesada, C., Strachan, R.A., and Woodcock, N.H., 2010, Evolution of the Rheic Ocean: *Gondwana Research*, v. 17, p. 194–222, doi:10.1016/j.gr.2009.08.001.
- Ochsner, A., 1993, U-Pb Geochronology of the Upper Proterozoic–Lower Paleozoic Geodynamic Evolution in the Ossa-Morena Zone (SW Iberia): Constraints on the Timing of the Cadomian Orogeny [Ph.D. thesis]: Zürich, ETH Zürich Unterstützen, 249 p.
- Oliveira, D.P.S., Poujol, M., and Robb, L.J., 2002, U-Pb geochronology for the Barreiros tectonised granitoids and Arronches migmatitic gneisses: Tomar-Córdoba shear zone, east-central Portugal: *Revista de la Sociedad Geológica de España*, v. 15, p. 105–112.
- Oliveira, J.T., Oliveira, V., and Piçarra, J.M., 1991, Traços gerais da evolução tectonostratigráfica da zona de Ossa Morena, em Portugal: Síntese crítica do estado actual dos conhecimentos: *Comunicações dos Serviços Geológicos de Portugal*, v. 77, p. 3–26.
- Ordóñez Casado, B., 1998, Geochronological Studies of the Pre-Mesozoic Basement of the Iberian Massif: The Ossa Morena Zone and the Allochthonous Complexes within the Central Iberian Zone [Ph.D. thesis]: Zürich, Swiss Federal Institute of Technology, 235 p.
- Ordóñez Casado, B., Gebauer, D., Schafer, H.J., Gil Ibarra, J.I., and Peucat, J.J., 2001, A single Devonian subduction event for the HP/HT metamorphism of the Cabo Ortegal complex within the Iberian Massif: *Tectonophysics*, v. 332, p. 359–385, doi:10.1016/S0040-1951(00)00210-9.
- Oyhantçabal, P., Siegesmund, S., Wemmer, K., Frei, R., and Layer, P., 2007, Post-collisional transition from calc-alkaline to alkaline magmatism during transcurrent deformation in the southernmost Dom Feliciano belt (Braziliano-Pan-African, Uruguay): *Lithos*, v. 98, p. 141–159, doi:10.1016/j.lithos.2007.03.001.
- Paces, J.B., and Miller, J.D., 1993, Precise U-Pb ages of Duluth complex and related mafic intrusions, northeastern Minnesota: Geochronological insights to physical, petrogenetic, paleomagnetic, and tectonomagmatic processes associated with the 1.1 Ga Midcontinent rift system: *Journal of Geophysical Research*, v. 98, p. 13,997–14,013, doi:10.1029/93JB01159.
- Pastor-Galán, D., Gutiérrez-Alonso, G., Murphy, J.B., Fernández-Suárez, J., Hofmann, M., and Linnemann, U., 2013, Provenance analysis of the Paleozoic sequences of the northern Gondwana margin in NW Iberia: Passive margin to Variscan collision and oroclinal development: *Gondwana Research*, v. 23, p. 1089–1103, doi:10.1016/j.gr.2012.06.015.
- Peccerillo, A., Barberio, M.R., Yirgu, G., Ayalew, D., Barbieri, M., and Wu, T.W., 2003, Relationships between mafic and peralkaline silicic magmatism in continental rift settings: A petrological, geochemical and isotopic study of the Gedemsa volcano, central Ethiopian Rift: *Journal of Petrology*, v. 44, p. 2003–2032, doi:10.1093/petrology/egg068.
- Peccerillo, A., Donati, C., Santo, A.P., Orlando, A., Yirgu, G., and Ayalew, D., 2007, Petrogenesis of silicic peralkaline rocks in the Ethiopian Rift: Geochemical evidence and volcanological implications: *Journal of African Earth Sciences*, v. 48, p. 161–173, doi:10.1016/j.jafrearsci.2006.06.010.
- Pereira, M.F., and Quesada, C., 2006, Ediacaran to Visean crustal growth processes in the Ossa-Morena zone (SW Iberia), International Geoscience Programme 497 Evora Meeting 2006: Conference Abstracts and Field Trip Guide: Madrid, Spain, Publicaciones IGME, 115 p.
- Pereira, M.F., Chichorro, M., Santos, J.F., Moita, P., and Silva, J.B., 2004, Geochemistry of Lower Paleozoic anorogenic basic rocks from the Evora Massif (western Ossa-Morena zone): *Geogaceta*, v. 35, p. 87–90.
- Pereira, M.F., Chichorro, M., Linnemann, U., Equiluz, L., and Silva, J.B., 2006, Inherited arc signature in Ediacaran and Early Cambrian basins of the Ossa-Morena zone (Iberian Massif, Portugal): Paleogeographic link with European and North African Cadomian correlatives: *Precambrian Research*, v. 144, p. 297–315, doi:10.1016/j.precamres.2005.11.011.
- Pereira, M.F., Silva, J.B., Chichorro, M., Moita, P., Santos, J.F., Apraiz, A., and Ribeiro, C., 2007, Crustal growth and deformational processes in the northern Gondwana margin: Constraints from the Evora Massif (Ossa-Morena zone, southwest Iberia, Portugal), in Linnemann, U., Nance, R.D., Kraft, P., and Zulauf, G., eds., The Evolution of the Rheic Ocean: From Avalonian-Cadomian Active Margin to Alleghenian-Variscan Collision: Geological Society of America Special Paper 423, p. 333–358, doi:10.1130/2007.2423(16).
- Pereira, M.F., Apraiz, A., Silva, J.B., and Chichorro, M., 2008a, Tectono-thermal analysis of high-temperature mylonitization in the Coimbra-Cordoba shear zone (SW Iberian Massif, Ouguela tectonic unit, Portugal): Evidence of intra-continental transcurrent transport during the amalgamation of Pangea: *Tectonophysics*, v. 461, p. 378–394, doi:10.1016/j.tecto.2007.11.042.
- Pereira, M.F., Chichorro, M., Williams, I.S., and Silva, J.B., 2008b, Zircon U-Pb geochronology of paragneisses and biotite granites from the SW Iberian Massif (Portugal): Evidence for a palaeogeographical link between the Ossa-Morena Ediacaran basins and the West African craton, in Ennhi, N., and Liégeois, J.P., eds., The Boundaries of the West African Craton: Geological Society of London Special Publication 297, p. 385–408, doi:10.1144/SP297.18.
- Pereira, M.F., Chichorro, M., Williams, I.S., Silva, J.B., Fernández, C., Díaz-Azpiroz, M., Apraiz, A., and Castro, A., 2009a, Variscan intra-orogenic extensional tectonics in the Ossa-Morena zone (Évora-Aracena-Lora del Río metamorphic belt, SW Iberian Massif): SHRIMP zircon U-Th-Pb geochronology, in Murphy, J.B., Keppie, J.D., and Hynes, A.J., eds., Ancient Orogens and Modern Analogues: Geological Society of London Special Publication 327, p. 215–237, doi:10.1144/SP327.11.
- Pereira, M.F., Silva, J.B., and Chichorro, M., 2009b, Comment on “Geodynamic evolution of the SW Ossa-Variscides” by António Ribeiro et al.: *Tectonics*, v. 28, TC4009, doi:10.1029/2008TC002430.
- Pereira, M.F., Apraiz, A., Chichorro, M., Silva, J.B., and Armstrong, R.A., 2010, Exhumation of high-pressure rocks in northern Gondwana during the early Carboniferous (Coimbra-Cordoba shear zone, SW Iberian Massif): Tectono-thermal analysis and U-Th-Pb SHRIMP in-situ zircon geochronology: *Gondwana Research*, v. 17, p. 440–460, doi:10.1016/j.gr.2009.10.001.
- Pereira, M.F., Chichorro, M., Solá, A.R., Silva, J.B., Sánchez-García, T., and Bellido, F., 2011, Tracing the Cadomian magmatism with detrital/inherited zircon ages by in-situ U-Pb SHRIMP geochronology (Ossa-Morena zone, SW Iberian Massif): *Lithos*, v. 123, p. 204–217, doi:10.1016/j.lithos.2010.11.008.
- Pereira, M.F., Chichorro, M., Johnston, S.T., Gutiérrez-Alonso, G., Silva, J.B., Linnemann, U., Hofmann, M., and Drost, K., 2012a, The missing Rheic Ocean magmatic arcs: Provenance analysis of late Paleozoic sedimentary clastic rocks of SW Iberia: *Gondwana Research*, v. 22, p. 882–891, doi:10.1016/j.gr.2012.03.010.
- Pereira, M.F., Chichorro, M., Silva, J.B., Ordóñez-Casado, B., Lee, J.K.W., and Williams, I.S., 2012b, Early Carboniferous wrenching, exhumation of high-grade metamorphic rocks and basin instability in SW Iberia: Constraints derived from structural geology and U-Pb and <sup>40</sup>Ar-<sup>39</sup>Ar geochronology: *Tectonophysics*, v. 558–559, p. 28–44, doi:10.1016/j.tecto.2012.06.020.
- Pereira, M.F., Linnemann, U., Hofmann, M., Chichorro, M., Solá, A.R., Medina, J., and Silva, J.B., 2012c, The provenance of Late Ediacaran and Early Ordovician siliciclastic rocks in the southwest Central Iberian zone: Constraints from detrital zircon data on northern Gondwana margin evolution during the late Neoproterozoic: *Precambrian Research*, v. 192–195, p. 166–189, doi:10.1016/j.precamres.2011.10.019.
- Pereira, M.F., Solá, A.R., Chichorro, M., Lopes, L., Gerdes, A., and Silva, J.B., 2012d, North-Gondwana assembly, break-up and paleogeography: U-Pb isotope evidence from detrital and igneous zircons of Ediacaran and Cambrian rocks of SW Iberia: *Gondwana Research*, v. 22, p. 866–881, doi:10.1016/j.gr.2012.02.010.
- Pin, C., 1990, Variscan oceans—Ages, origins and geodynamic implications inferred from geochemical and radiometric data: *Tectonophysics*, v. 177, p. 215–227, doi:10.1016/0040-1951(90)90282-D.
- Pin, C., Cuesta, L.A.O., and Gil Ibarra, J.I., 1992, Mantle-derived, early Paleozoic A-type metagranitoids from the NW Iberian Massif—Nd isotope and trace-element constraints: *Bulletin de la Société Géologique de France*, v. 163, p. 483–494.
- Pin, C., Kryza, R., Ober-Dziedzic, T., Mazur, S., Turniak, K., and Waldausrova, J., 2007, The diversity and geodynamic significance of Late Cambrian (ca. 500 Ma) felsic anorogenic magmatism in the northern part of the Bohemian Massif: A review based on Sm-Nd isotope and geochemical data, in Linnemann, U., Nance, R.D., Kraft, P., and Zulauf, G., eds., The Evolution of the Rheic Ocean: From Avalonian-Cadomian Active Margin to Alleghenian-Variscan Collision: Geological Society of America Special Paper 423, p. 209–229, doi:10.1130/2007.2423(09).
- Quesada, C., 1990, Ossa-Morena zone: Introduction, in Dallmeyer, R.D., and Martínez García, E., eds., Pre-Mesozoic Geology of Iberia: Berlin, Germany, Springer-Verlag, p. 249–251.
- Quesada, C., 1991, Geological constraints on the Paleozoic tectonic evolution of tectonostratigraphic terranes in the Iberian Massif: *Tectonophysics*, v. 185, p. 225–245, doi:10.1016/0040-1951(91)90446-Y.
- Quesada, C., Bellido, F., Dallmeyer, R.D., Gil-Ibarra, J.I., Oliveira, J.T., Perez-Estaun, A., Ribeiro, A., Robardet, M., and Silva, J.B., 1991, Terranes within the Iberian Massif: Correlations with West African sequences, in Dallmeyer, R.D., and Lécroché, J.P., eds., The West African Orogens and Circum-Atlantic Correlatives: IGCP-Project 233: Berlin, Springer, p. 267–293.
- Quesada, C., Fonseca, P.E., Munhá, J.M., Oliveira, J.T., and Ribeiro, A., 1994, The Beja-Acebuches Ophiolite (southern Iberia Variscan fold belt): Geological characterization and geodynamic significance: *Boletín Geológico y Minero (IGME)*, v. 105, p. 3–49.
- Rey, P.F., and Müller, R.D., 2010, Fragmentation of active continental plate margins owing to the buoyancy of the mantle wedge: *Nature Geoscience*, v. 3, p. 257–261, doi:10.1038/ngeo825.
- Ribeiro, A., Pereira, E., and Dias, R., 1990, Structure in the northwest of the Iberian Peninsula, in Dallmeyer, R.D., and Martínez García, E., eds., Pre-Mesozoic Geology of Iberia: Berlin, Germany, Springer-Verlag, p. 220–236.
- Ribeiro, A., Munhá, J., Dias, R., Mateus, A., Pereira, E., Ribeiro, L., Fonseca, P., Araújo, A., Oliveira, T., Romão, J., Chaminé, H., Coke, C., and Pedro, J., 2007, Geodynamic evolution of the SW Ossa-Variscides: *Tectonics*, v. 26, TC6009, doi:10.1029/2006TC002058.
- Ribeiro, A., Munhá, J., Fonseca, P.E., Araújo, A., Pedro, J.C., Mateus, A., Tassinari, C., Machado, G., and Jesus, A., 2010, Variscan ophiolite belts in the Ossa-Morena zone (southwest Iberia): Geological characterization and geodynamic significance: *Gondwana Research*, v. 17, p. 408–421, doi:10.1016/j.gr.2009.09.005.
- Ribeiro, M.L., 1987, Petrogenesis of early Paleozoic peralkaline rhyolites from the Macedo de Cavaleiros region (NW de Portugal): *Geologische Rundschau*, v. 76, p. 147–168, doi:10.1007/BF01820579.
- Ribeiro, M.L., and Floor, P., 1987, Magmatismo peralcalino no Macico Hespérico: Sua distribuição e significado geodinâmico, geologia de los granitoides y rocas asociadas del Macizo Hespérico, in Bea, F.C., ed., Geología de los Granitoides y Rocas Asociadas del Macizo Hespérico: Libro Homenaje a L.C. García de Figuerola: Madrid, Ediciones Rueda, p. 211–222.
- Ribeiro, M.L., Mata, J., and Munhá, J.M., 1992, Magmatismo do Paleozóico Inferior em Portugal, in Gutiérrez Marco, J.C., Saavedra, J., and Rábano, I., eds., Paleozoico Inferior de Ibero-América: Badajoz, Spain, Universidad de Extremadura, p. 378–394.
- Ribeiro, M.L., Munhá, J.M., Mata, J., and Palácios, T., 1997, Vulcanismo na Zona de Ossa Morena e seu enquadramento geodinâmico, in Araújo, A., and Pereira, M.F., eds., Estudo sobre a geologia de Ossa-Morena (Maciço Ibérico). Homenagem ao Prof. Francisco Gonçalves, Évora, Universidade de Évora, p. 37–55.
- Robardet, M., and Gutiérrez Marco, J.C., 1990, Sedimentary and faunal domains in the Iberian Peninsula during Lower Paleozoic times, in Dallmeyer, R.D., and Martínez García, E., eds., Pre-Mesozoic Geology of Iberia: Berlin, Germany, Springer-Verlag, p. 383–395.
- Robardet, M., and Gutiérrez Marco, J.C., 2002, Chapter 5: Silurian, in Gibbons, W., and Moreno, T., eds., The Geology of Spain: London, Geological Society of London, p. 51–66.
- Robardet, M., and Gutiérrez Marco, J.C., 2004, The Ordovician, Silurian and Devonian sedimentary rocks of the Ossa-Morena zone (SW Iberian Peninsula, Spain): *Journal of Iberian Geology*, v. 30, p. 73–92.



- Robardet, M., Piçarra, J.M., Storch, P., Gutiérrez Marco, J.C., and Sarmiento, G.N., 1998, Ordovician and Silurian stratigraphy and faunas (graptolites and conodonts) in the Ossa Morena zone of SW Iberian Peninsula (Portugal and Spain): *Temas Geológicos-Mineros Instituto Geológico y Minero de España*, v. 23, p. 289–318.
- Rodríguez, J., Cosca, M.A., Gil Ibarguchi, J.I., and Dallmeyer, R.D., 2003, Strain partitioning and preservation of  $^{40}\text{Ar}/^{39}\text{Ar}$  ages during Variscan exhumation of a subducted crust (Malpica-Tui complex, NW Spain): *Lithos*, v. 70, p. 111–139, doi:10.1016/S0024-4937(03)00095-1.
- Rodríguez, J., Paquette, J.L., and Gil Ibarguchi, J.I., 2007, U-Pb dating of Lower Ordovician alkaline magmatism in the Gondwana margin (Malpica-Tui complex, Iberian Massif): Latest continental events before oceanic spreading, in Arenas, R., Martínez Catalán, J.R., Abati, J., and Sánchez Martínez, S., eds., *IGCP 497—The Rheic Ocean: Its Origin, Evolution and Correlatives. The Rootless Variscan Suture of NW Iberia (Galicia, Spain). Field Trip Guide & Conference Abstracts: A Coruña, Spain, Instituto Geológico y Minero de España*, p. 163–164.
- Romeo, I., Lunar, R., Capote, R., Quesada, C., Piña, R., Dunning, G.R., and Ortega, L., 2006, U-Pb age constraints on Variscan magmatism and Ni-Cu-PGE metallogeny in the Ossa-Morena zone (SW Iberia): *Journal of the Geological Society of London*, v. 163, p. 837–846, doi:10.1144/0016-76492005-065.
- Rosas, F.M., Marques, F.O., Ballèvre, M., and Tassinari, C., 2008, Geodynamic evolution of the SW Variscides: Orogenic collapse shown by new tectonometamorphic and isotopic data from western Ossa-Morena zone, SW Iberia: *Tectonics*, v. 27, TC6008, doi:10.1029/2008TC002333.
- Rosenbaum, G., Weinberg, R.F., and Regenauer-Lieb, K., 2008, The geodynamics of lithospheric extension: *Tectonophysics*, v. 458, p. 1–8, doi:10.1016/j.tecto.2008.07.016.
- Rubio-Ordóñez, A., Valverde Vaquero, P., Corrette, L.G., Cuesta-Fernández, A., Gallastegui, G., Fernández-González, M., and Gerdes, A., 2012, An Early Ordovician tonalitic-granodioritic belt along the Schistose-Greywacke Domain of the Central Iberian zone (Iberian Massif, Variscan belt): *Geological Magazine*, v. 149, p. 927–939, doi:10.1017/S0016756811001129.
- Rubio-Ordóñez, A., Gutiérrez-Alonso, G., Valverde-Vaquero, P., Cuesta, A., Gallastegui, G., Gerdes, A., and Cárdenas, V., 2015, Arc-related Ediacaran magmatism along the northern margin of Gondwana: Geochronology and isotopic geochemistry from northern Iberia: *Gondwana Research*, v. 27, no. 1, p. 216–227, doi:10.1016/j.gr.2013.09.016.
- Rubio Pascual, F., Arenas, R., Díaz García, F., Martínez Catalán, J.R., and Abati, J., 2002, Contrasting high-pressure metabasites from the Santiago unit (Ordones complex, northwestern Iberian massif, Spain), in Martínez Catalán, J.R., Hatcher, R.D., Arenas, R., and Díaz García, F., eds., *Variscan-Appalachian Dynamics: The Building of the Late Paleozoic Basement: Geological Society of America Special Paper 364*, p. 105–124, doi:10.1130/0-8137-2364-7.105.
- Rubio Pascual, F.J., Matas, J., and Martín Parra, L.M., 2013, High-pressure metamorphism in the early Variscan subduction complex of the SW Iberian Massif: *Tectonophysics*, v. 592, p. 187–199, doi:10.1016/j.tecto.2013.02.022.
- Rudnick, R.L., and Gao, S., 2003, Composition of the continental crust, in Rudnick, R.L., ed., *The Crust: Treatise in Geochemistry: Oxford, Elsevier*, p. 1–64.
- Sagredo, J., and Peinado, M., 1992, Vulcanismo Cámbrico d la zona de Ossa Morena, in Gutiérrez Marco, J.C., Saavedra, J., and Rábano, I., eds., *Paleozoico Inferior de Ibero-America: Badajoz, Spain, Universidad de Extremadura*, p. 567–576.
- Salman, K., 2002, Estudio Petroológico, Geoquímico y Geocronológico de los Granitoides del Área Monasterio-Cala, Zona de Ossa-Morena (Macizo Ibérico) [Ph.D. thesis]: Granada, Spain, Universidad de Granada, 232 p.
- Salman, K., 2004, The timing of the Cadomian and Variscan cycles in the Ossa-Morena zone, SW Iberia: Granitic magmatism from subduction to extension: *Journal of Iberian Geology*, v. 30, p. 119–132.
- Sánchez-García, T., Bellido, F., and Quesada, C., 2003, Geodynamic setting and geochemical signatures of Cambrian–Ordovician rift-related igneous rocks (Ossa-Morena zone, SW Iberia): *Tectonophysics*, v. 365, p. 233–255, doi:10.1016/S0040-1951(03)00024-6.
- Sánchez-García, T., Quesada, C., Bellido, F., Dunning, G.R., and González del Tánago, J., 2008, Two-step magma flooding of the upper crust during rifting: The early Paleozoic of the Ossa Morena zone (SW Iberia): *Tectonophysics*, v. 461, p. 72–90, doi:10.1016/j.tecto.2008.03.006.
- Sánchez-García, T., Pereira, M.F., Chichorro, M., Quesada, C., Pin, C., and Silva, J.B., 2010, Rift-related volcanism predating the birth of the Rheic Ocean (Ossa-Morena zone, SW Iberia): *Gondwana Research*, v. 17, p. 392–407, doi:10.1016/j.gr.2009.10.005.
- Sánchez-García, T., Pereira, M.F., Bellido, F., Chichorro, M., Silva, J.B., Valverde-Vaquero, P., Pin, C., and Solá, A.R., 2014, Early Cambrian granitoids of North Gondwana margin in the transition from a convergent setting to intra-continental rifting (Ossa-Morena zone, SW Iberia): *International Journal of Earth Sciences*, v. 103, p. 1203–1218, doi:10.1007/s00531-013-0939-8.
- Sánchez Martínez, S., Arenas, R., Fernández-Suárez, J., and Jeffries, T.E., 2009, From Rodinia to Pangaea: Ophiolites from NW Iberia as witness for a long-lived continental margin, in Murphy, J.B., Keppie, J.D., and Hynes, A.J., eds., *Ancient Orogens and Modern Analogues: Geological Society of London Special Publication 327*, p. 317–341, doi:10.1144/SP327.14.
- Sánchez Martínez, S., Gerdes, A., Arenas, R., and Abati, J., 2012, The Bazar ophiolite of NW Iberia: A relic of the Iapetus-Tornquist Ocean in the Variscan suture: *Terra Nova*, v. 24, p. 283–294, doi:10.1111/j.1365-3121.2012.01061.x.
- Santos, J.F., Schärer, U., Gil Ibarguchi, J.I., and Girardeau, J., 2002, Genesis of pyroxenite-rich peridotite at Cabo Ortegal (NW Spain): Geochemical and Pb-Sr-Nd isotope data: *Journal of Petrology*, v. 43, p. 17–43, doi:10.1093/petrology/43.1.17.
- Simancas, J.F., Poyatos, D.M., Expósito, I., Azor, A., and Lodeiro, F.G., 2001, The structure of a major suture zone in the SW Iberian Massif: The Ossa-Morena/Central Iberian contact: *Tectonophysics*, v. 332, p. 295–308, doi:10.1016/S0040-1951(00)00262-6.
- Simancas, J.F., Tahiri, A., Azor, A., Lodeiro, F.G., Poyatos, D.J.M., and Hadi, H.E., 2005, The tectonic frame of the Variscan-Alleghanian orogen in southern Europe and northern Africa: *Tectonophysics*, v. 398, p. 181–198, doi:10.1016/j.tecto.2005.02.006.
- Simancas, J.F., Azor, A., Martínez-Poyatos, D., Tahiri, A., El Hadi, H., González-Lodeiro, F., Pérez-Estaún, A., and Carbonell, R., 2009, Tectonic relationships of southwest Iberia with the allochthons of northwest Iberia and the Moroccan Variscides: *Comptes Rendus Geoscience*, v. 341, p. 103–113, doi:10.1016/j.crte.2008.11.003.
- Söderlund, U., Patchett, P.J., Vervoort, J.D., and Isachsen, C.E., 2004, The 176-Lu decay constant determined by Lu-Hf and U-Pb isotope systematics of Precambrian mafic intrusions: *Earth and Planetary Science Letters*, v. 219, p. 311–324, doi:10.1016/S0012-821X(04)00012-3.
- Solá, A.R., Pereira, M.F., Williams, I.S., Ribeiro, M.L., Neiva, A.M.R., Montero, P., Bea, F., and Zinger, T., 2008, New insights from U-Pb zircon dating of Early Ordovician magmatism on the northern Gondwana margin: The Urta Formation (SW Iberian Massif, Portugal): *Tectonophysics*, v. 461, p. 114–129, doi:10.1016/j.tecto.2008.01.011.
- Stampfli, G.A., Von Raumer, J.F., and Borel, G., 2002, Paleozoic evolution of pre-Variscan terranes: From Gondwana to the Variscan collision, in Martínez Catalán, J.R., Hatcher, J.R.D., Arenas, R., and Díaz García, F., eds., *Variscan-Appalachian Dynamics: The Building of the Late Paleozoic Basement: Geological Society of America Special Paper 364*, p. 263–280, doi:10.1130/0-8137-2364-7.263.
- Sumner, J.M., and Wolff, J., 2003, Petrogenesis of mixed-magma, high-grade, peralkaline ignimbrite “TL” (Gran Canaria): Diverse styles of mixing in a replenished, zoned magma chamber: *Journal of Volcanology and Geothermal Research*, v. 126, p. 109–126, doi:10.1016/S0377-0273(03)00121-5.
- Talavera, C., Montero, P., Bea, F., González Lodeiro, F., and Whitehouse, M., 2013, U-Pb zircon geochronology of the Cambro-Ordovician metagranites and metavolcanic rocks of central and NW Iberia: *International Journal of Earth Sciences*, v. 102, p. 1–23, doi:10.1007/s00531-012-0788-x.
- Teixeira, C., and Assunção, C.F.T., 1958, Sur la géologie et la pétrographie des gneiss à riebeckite et aegyrine et des syénites à néphéline et sodalite de Cevadais, près d’Ougela (Campo Maior), Portugal: *Comunicações dos Serviços Geológicos de Portugal*, v. 42, p. 31–56.
- Thiéblemont, D., and Cabisan, B., 1994, Magmatic record of the geodynamic evolution of Brittany and Vendée during Paleozoic times: Trace element constraints, in Keppie, J.D., ed., *Pre-Mesozoic Geology in France: Berlin, Germany, Springer-Verlag*, p. 220–230.
- Touil, A., Hafid, A., Moutte, J., and Boukhari, A.E., 2008, Petrology and geochemistry of the Neoproterozoic Siroua granitoids (central Anti-Atlas, Morocco): Evolution from subduction-related to within-plate magmatism, in Ennih, N., and Liégeois, J.P., eds., *The Boundaries of the West African Craton: Geological Society of London Special Publication 297*, p. 265–283, doi:10.1144/SP297.13.
- Trua, T., Deniel, C., and Mazzuoli, R., 1999, Crustal control in the genesis of Plio-Quaternary bimodal magmatism of the Main Ethiopian Rift (MER): Geochemical and isotopic (Sr, Nd, Pb) evidence: *Chemical Geology*, v. 155, p. 201–231, doi:10.1016/S0009-2541(98)00174-0.
- Valverde-Vaquero, P., Marcos, A., Farias, P., and Gallastegui, G., 2005, U-Pb dating of Ordovician felsic volcanism in the Schistose domain of the Galicia-Trás-os-Montes zone near Cabo Ortegal (NW Spain): *Geologica Acta*, v. 3, p. 27–37.
- Vauchez, A., Barruol, G., and Tommasi, A., 1997, Why do continents break-up parallel to ancient orogenic belts?: *Terra Nova*, v. 9, p. 62–66, doi:10.1111/j.1365-3121.1997.tb00003.x.
- Vermeesch, P., 2012, On the visualisation of detrital age distributions: *Chemical Geology*, v. 312–313, p. 190–194, doi:10.1016/j.chemgeo.2012.04.021.
- Vervoort, J.D., and Blüchert-Toft, J., 1999, Evolution of the depleted mantle: Hf isotope evidence from juvenile rocks through time: *Geochimica et Cosmochimica Acta*, v. 63, p. 533–556, doi:10.1016/S0016-7037(98)00274-9.
- Villaseca, C., Castiñeiras, P., and Orejana, D., 2015, Early Ordovician metabasites from the Spanish Central System: A remnant of intraplate HP rocks in the Central Iberian zone: *Gondwana Research*, v. 27, no. 1, p. 392–409, doi:10.1016/j.gr.2013.10.007.
- von Raumer, J.F., and Stampfli, G.M., 2008, The birth of the Rheic Ocean—Early Palaeozoic subsidence patterns and subsequent tectonic plate scenarios: *Tectonophysics*, v. 461, p. 9–20, doi:10.1016/j.tecto.2008.04.012.
- Whalen, J.B., Currie, K.L., and Chappell, B.W., 1987, A-type granites—Geochemical characteristics, discrimination and petrogenesis: Contributions to Mineralogy and Petrology, v. 95, p. 407–419, doi:10.1007/BF00402202.
- Zirakparvar, N.A., Baldwin, S.L., and Vervoort, J.D., 2013, The origin and geochemical evolution of the Woodlark Rift of Papua New Guinea: *Gondwana Research*, v. 23, p. 931–943, doi:10.1016/j.gr.2012.06.013.

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