Peralkaline and alkaline magmatism of the Ossa-Morena zone (SW Iberia): Age, source, and implications for the Paleozaic 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 Paleozaic and the collision of Gondwana and Laurussia in the late Paleozaic (Variscan orogeny). We present U-Pb zircon data from three alkaline to peralkaline syenites that intruded Neoproterozoic and Cambrian strata and give the opening of the Rheic Ocean in the early Paleozoic and the collision of Gondwana and Laurussia in the late Paleozoic (Variscan orogeny). The crustal section in this zone preserves the record of rifting that led to the opening of the Rheic Ocean in the early Paleozaic and the collision of Gondwana and Laurussia in the late Paleozaic (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 Paleozoaic peralkaline and alkaline magmas. The boundaries of microblocks represent zones of inherited crustal weakness that were later reactivated during the late Paleozoaic 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.

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—Pecceirollo 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; Pecceirollo 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;
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 (Eguzú 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; Stampfl 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; 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 paraautochthonous 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 rootless oceanic suture (ophiolitic complexes) separating the Cantabrian zone—West Asturian–Leonese zone—Central Iberian zone—Schistose domain ensemble (autochthonous and paraautochthonous) 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 Gondwana 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–Leones 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., 2008a, 2010). 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).

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 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 volcanic 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 to 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, peralcaline 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 Munná, 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 peralcaline 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–Leones 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, peralcaline and alkaline magmatism found along the different terrains that form the western European Variscan belt (Pin, 1990; Thieblemont and Cabanis, 1994; Crowley et al., 2000).

In NW Iberia (Fig. 2), the peralcaline 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 rift 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 successions; Alia, 1963; Carvallhos, 1965; Apalategui et al., 1990; Gonçalves and Carvallhos, 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, 2012a). 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 overlay 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 volcanioclastic rocks of calc-alkaline (peraluminous) affinity (Sánchez-García et al., 2003, 2008). Felsic rocks of this event were dated at ca. 530–526 Ma (Roméo 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 Chao–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
Peralkaline and alkaline magmatism of the Ossa-Morena zone (SW Iberia) | RESEARCH

COIMBRA-CÓRDOBA SHEAR ZONE

Postkinematic granitoids
Schists, lidades, graphito-bearing schists, quartzites (Ord. – Sil.)
Schists, metagraywackes, metaconglomerates, quartzites (early-mid. Camb.)
Metalinestones (marbles) (early Camb.)
Metaconglomerates (early Camb.)
Serie Negra Formation: metapelites, metagraywackes, black metacherts, metavolcanics (felsic and mafic) (Ediacar.)
Gneisses and amphibolites (Early Paleozoic protoliths)
Variscan migmatites (including high-pressure rocks) (Ediacaran and early Paleozoic protoliths)

CENTRAL IBERIAN ZONE

(Ordovician calc-alkaline, high-K magmatism; 494–488 Ma)
Schists and black schists
Quartzites, meta-arkoses, and metaconglomerates
Fine-grained metavolcanic-sedimentary rocks
Porphyritic coarse- to medium-grained felsic metavolcanics
Metagranitoids (granites, gabbros, and diorites)

OSSA-MORENA ZONE

Ultramafics (Ord.)
Alkaline mafic rocks: metagrabros, metadiorites, meta-anorthosites
Alkaline-Peralkaline felsic orthogneisses (hastingsite-riebeckite)
Schists, metagraywackes, metaconglomerates, quartzites (early-mid. Camb.)
Metalinestones (marbles) (early Camb.)
Metaconglomerates (early Camb.)
Serie Negra Formation: metapelites, metagraywackes, black metacherts, metavolcanics (felsic and mafic) (Ediacar.)
Gneisses and amphibolites (Early Paleozoic protoliths)
Variscan migmatites (including high-pressure rocks) (Ediacaran and early Paleozoic protoliths)

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

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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 the sample was decrепitated 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 $^{208}$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 $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ages <15%, and discordance between $^{206}\text{Pb}/^{238}\text{U}$ and $^{208}\text{Pb}/^{206}\text{Pb}$ ages <5%). Ratios and ages of the selected analyses (in bold) are presented in Tables DR1–DR3 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-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 $^{176}\text{Lu}/^{176}\text{Hf} = -24.5 \pm 1.6$ (2σ). The average value for the nonradiogenic $^{184}\text{Hf}/^{180}\text{Hf}$ for the same 600+ analyses deviates from the true value by 0.2%, which indicates the contribution from oxide and dimer isobars is negligible. Initial $^{187}\text{Hf}/^{177}\text{Hf}$ 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 $E_{\text{Hf}}$ 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

1 GSA Data Repository Item 2015027, Tables DR1–DR4, is available at www.geosociety.org/pubs/ft2015.htm, or on request from 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, dipyramidal prisms, elongated prisms, and multifaceted crystals. The size of the crystals ranges between 50 and 400 $\mu$m, but crystals are usually around 150 $\mu$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 $\mu$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 dipyramidal 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 $\mu$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.](https://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/7/1/73/3045711/73.pdf)
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 ± 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 $^{206}\text{Pb}/^{238}\text{U}$ 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 ± 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

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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.
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 $^{238}$U/$^{206}$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 $^{238}$U/$^{206}$Pb ages, 470 ± 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 $^{206}$Pb/$^{238}$U and $^{207}$Pb/$^{206}$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 ± 25 Ma (MSWD = 11.9). The most concordant grains (discordance between $^{206}$Pb/$^{238}$U and $^{207}$Pb/$^{206}$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 ± 9 Ma (MSWD = 0.79) in a Tera-Wasserburg concordia plot (Fig. 7C). The $^{238}$U/$^{206}$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 ± 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, Cevadas Lineament) has a limited range of $^{176}$Lu/$^{177}$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 $^{176}$Hf/$^{177}$Hf initial ratios, which range from 0.282616 to 0.282810 (average of 0.282659, scatter of 0.00004), and the highest $\epsilon_{Hf(t)}$ values, ranging from +4.6 to +11.5 ($t = 479$ Ma). The grains from sample PAL-2 ($n = 20$) are characterized by $^{176}$Hf/$^{177}$Hf initial ratios ranging from 0.282616 to 0.282810 (average of 0.282659, scatter of 0.00004), and $\epsilon_{Hf(t)}$ values from 0 to +3.2 ($t = 479$ Ma). Sample PAL-3 has similar isotopic values, with $^{176}$Hf/$^{177}$Hf initial ratios ranging from 0.282519 to 0.282650 (average of 0.282557, scatter of 0.00005), and $\epsilon_{Hf(t)}$ values from +4.0 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 $^{176}$Hf/$^{177}$Hf vs. $^{176}$Lu/$^{177}$Hf diagram. The dashed thick lines represent average values of $^{176}$Hf/$^{177}$Hf. The continuous thick lines show $^{176}$Lu/$^{177}$Hf variability. (B) Initial $\varepsilon_{\text{Hf}}$ 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 $^{176}$Hf/$^{177}$Hf = 0.283294 (Vervoort and Blichert-Toft, 1999) and $^{176}$Lu/$^{177}$Hf = 0.03933, and considering a straight evolution line with $\varepsilon_{\text{Hf(t)}} = +18$ and $\varepsilon_{\text{Hf(0)}} = 0$ (Blichert-Toft and Puchtel, 2010). Errors are provided in Tables DR1–DR3 (see text footnote 1).

**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; Diez 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 (Stampfl 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 intracratonic 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). Riffs tend to propagate where the minimum energy is required for lithospheric breakup (Vauclain 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; Ordoñez Casado, 1998; Egurrola 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. 9C) 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 Ordoñovic magmatism was widespread at sites in the Iberia sector of the Gondwanan platform (Bea et al., 2006; Solà 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 Ordoñovic 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–Leones 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-Gondwana 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 εNd(t) values of 3.39–4.91, and Lu-HF isotopic data (0 ≤ εHf(t) ≤ +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
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