Isotopic and igneous record of the Avalonian-Cadomian arc in NW Iberia

Registro isotópico y magmático del arco Avaloniense-Cadomiense en el NW de Iberia.

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Abstract: The upper allochthonous units of NW Iberian Massif contain an extensive Cambrian magmatism (c. 500 Ma), that generated large massifs of granitic rocks and gabbros with calc-alkaline and tholeiitic compositions, respectively. Petrological and geochemical features of these massifs are characteristic of volcanic arcs. The plutons intruded siliciclastic series deposited in the periphery of the West Africa Craton. U-Pb/Hf isotopic compositions of detrital zircon in the siliciclastic series, indicate arc activity between c. 750 Ma and c. 500 Ma. It was characterized by a large variety of isotopic sources, including from very old continental input, even Archean, to the addition of a significant amount of juvenile mafic material. These isotopic sources experienced an extensive mixing that explains the composition and isotopic features of the represented Cambrian plutons. The Cambrian igneous rocks of the upper units of NW Iberia can be related to the latest activity of the Avalonian-Cadomian arc. From Middle Cambrian times, arc activity in the periphery of Gondwana was replaced by pronounced extension associated with continental rifting, which finally led to separation of the microcontinent Avalonia. Subsequent drifting of Avalonia to the North caused progressive opening of one of the main Paleozoic ocean, the Rheic Ocean.

Key words: Cambrian magmatism, Avalonian-Cadomian arc, NW Iberian Massif, Variscan Orogen.

Resumen: *Las unidades alóctonas superiores del NW del Macizo Ibérico contienen un extenso magmatismo Cámbrico (c. 500 Ma), que generó grandes macizos de rocas graníticas y gabros, con composiciones calcoalcalinas y toleíticas, respectivamente. Las características petrológicas y geoquímicas de estos macizos son típicas de arcos volcánicos. Los plutones intruyen en series siliciclásticas depositadas en la periferia del Cratón del Oeste de África. Las relaciones isotópicas U-Pb/Hf de circones detríticos de las series siliciclásticas, indican que el arco fue activo entre c. 750 y c. 500 Ma. Originó una gran variedad de fuentes isotópicas, que incluyen desde fuentes continentales muy antiguas, incluso Arcaicas, hasta la participación de una gran cantidad de material máfico juvenil. Estas fuentes isotópicas experimentaron un amplio mixing que explica la composición y características isotópicas de los plutones Cámbricos investigados. El magmatismo Cámbrico del NW de Iberia puede relacionarse con la última actividad del arco Avaloniense-Cadomiense. A partir del Cámbrico medio, la actividad del margen activo peri-Gondwánico fue reemplazada por extensión asociada a un episodio de rifting continental, que finalmente dio lugar a la separación del microcontinente Avalonia. La deriva posterior de Avalonia hacia el norte originó la apertura progresiva de uno de los principales océanos Paleozoicos, el Océano Rheico.*

Palabras clave: *Magmatismo Cámbrico, arco Avaloniense-Cadomiense, NW del Macizo Ibérico, Orógeno Varisco.*

INTRODUCTION

The northern Gondwana margin did act as an active continental margin for a long period. The activity related to the peri-Gondwanan arc system ranges from Neoproterozoic to Early Paleozoic times, being frequently referred to as the Avalonian-Cadomian arc (Nance et al., 2002). Although the presence of the Avalonian-Cadomian arc in the northern Gondwanan margin is clear, the chronology of the igneous activity is poorly constrained in certain areas. This is because of the vast amount of geochronological data needed to make an accurate estimation of the timing of such activity. However, this information is more accessible using the isotopic record of magmatism preserved in the siliciclastic series derived from dismantling of the arc and surrounding continental regions. The Hf isotopic signature of detrital zircons, combined with U-Pb geochronology, has arisen as a key source of information to constrain both the age of magmatic activity and the isotopic sources involved in arc magma genesis (Gerdes and Zeh, 2006).

This manuscript presents a short review of geochemical data from two large massifs of Cambrian igneous rocks included in the upper allochthon (upper units) of the Órdenes Complex (Fig. 1), and isotopic data (Hf and U-Pb) of detrital zircons from the siliciclastic sedimentary series intruded by these plutons. Considered together, these data provide an integrated record of the activity in the Avalonian-Cadomian arc in this region.

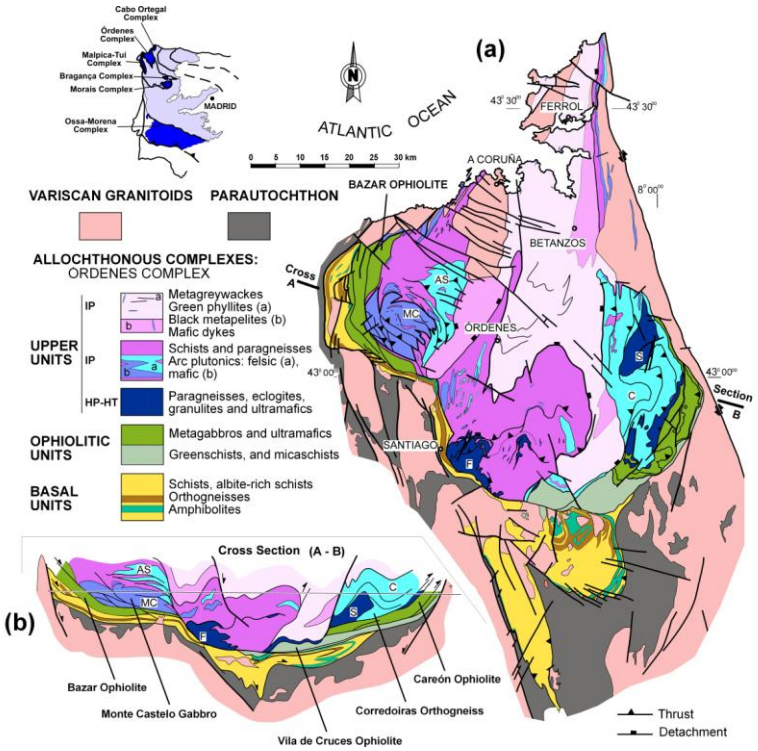

FIGURE 2. *(a) Geological map of the Órdenes Complex. (b) Representative cross-section. AS, A Silva Unit; C, Corredoiras Massif; F, Fornás Unit; MC, Monte Castelo Massif; S, Sobrado Unit.*

CAMBRIAN MAGMATIC ROCKS

The siliciclastic series of the upper allochthon are intruded by a variety of felsic to mafic igneous rocks including dikes, stocks and large massifs of gabbros and granitic rocks. The greywackic series of the upper structural levels is intruded by abundant dolerictic dykes (Fig. 1) dated at c. 510 Ma (Díaz García et al., 2010). The largest Cambrian igneous massifs that appear in the upper allochthon of NW Iberia are represented by the Monte Castelo Gabbro Massif (MCGM) and the Corredoiras Orthogneiss Massif (COM) (Fig. 1). Three major compositional types can be distinguished within the MCGM (Andonaegui et al., 2016): olivine gabbronorites, amphibole gabbronorites and biotite gabbronorites. The emplacement of the gabbro body has been dated at c. 499 Ma (Abati et al., 1999). Three main compositional types have been described in the COM by Andonaegui et al. (2012). The most abundant lithology is a coarse-grained, granular, hypidiomorphic granodiorite. Medium-grained, granular hypidiomorfic tonalitic orthogneisses appear in small volumes toward the NW part of the massif. Locally the tonalitic orthogneisses contain inclusions of medium-grained amphibole-rich orthogneisses, ranging in size from decimeters to meters. Finally, medium to fine-grained gabbronoritic rocks are found as scarce small stocks or lens-shaped bodies scattered between the orthogneisses. The COM has been dated at Cambrian (c. 492 Ma; Andonaegui et al., 2012).

GEOCHEMISTRY OF THE IGNEOUS BODIES

The plutonic rocks from the MCGM and COM show chemical compositions typical of magmatic arcs. The gabbroic terms have mafic-intermediate compositions, the tonalites range between intermediate and felsic (slightly peraluminous) and the granodiorites are felsic (peraluminous). In the AFM diagram, the gabbroic rocks occupy the tholeiitic field, the mafic rocks of the COM plotting closer to the boundary with the calc-alkaline series (Fig. 2a). In the same diagram, the tonalites and granodiorites plot on the calc-alkaline field. In the Th-Co diagram (Hastie et al., 2007; Fig. 2b), the lithologies of the MCGM plot on the field of island-arc tholeiites, whereas the rocks of the COM define a typical calc-alkaline series, with the most felsic terms laying in the high-K field. Such different composition between rocks of the MCGM and COM could indicate a different location in relation to the oceanic trench, the rocks of the COM being generated in a more distal position (Andonaegui et al., 2016).

The tectonic setting of the Cambrian magmatism can be investigated using the Hf-Th-Nb diagram, suitable for both mafic and felsic rocks (Wood, 1980; Fig. 2c). According to it, most of the igneous rocks were generated in a volcanic arc context, although some rocks of the MCGM are projected in a field that indicates more primitive compositions corresponding to MORB types. There are no additional geological arguments supporting the equivalence of the MCGM rocks with MORB lithologies, as the main gabbro body

intrudes a thick series of metasedimentary rocks. Moreover, the rocks of the MCGM are characterized by Hf/Th > 3, typical of island-arc tholeiites. On the contrary, the lithologies of the COM are in general characterized by Hf/Th < 3, typical of calc-alkaline series (Fig. 2a).

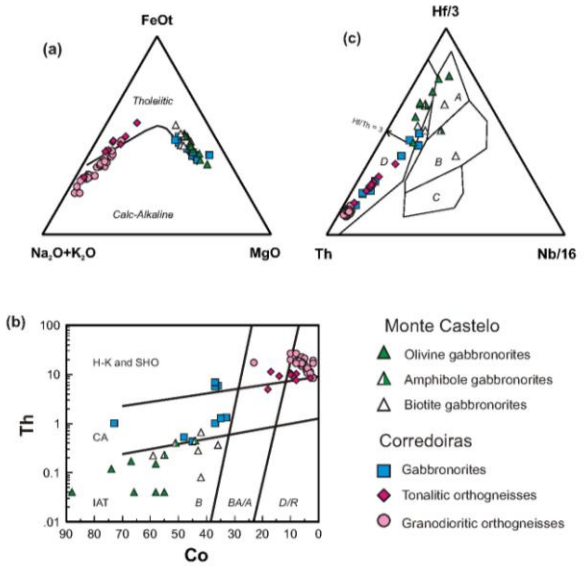

FIGURE 2. *(a) AFM diagram; tholeiitic and calc-alkaline fields after Irvine and Baragar (1971). (b) Th-Co discrimination diagram (Hastie et al., 2007). (c) Hf-Th-Nb diagram (Wood, 1980). A: N-MORB; B: E-MORB and within plate tholeiites; C: alkaline within plate basalt; D: volcanic arc basalt; Hf/Th > 3 island-arc tholeiites; Hf/Th < 3 calc-alkaline mafic and felsic rocks.*

ISOTOPIC RECORD OF THE MAGMATIC ARC

The provenance of the upper units of the allochthonous complexes of NW Iberia has been recently investigated, using U-Pb geochronology and Hf isotopic content of detrital zircons of siliciclastic metasedimentary series (Albert et al., 2015). These are the sedimentary series intruded by Cambrian granites and gabbros, both in Cabo Ortegal and Órdenes complexes. The zircon data can also be used to track episodes of crustal (zircon) growth over time and their relationship with the peri-Gondwanan arc system. Figure 3 shows a Hf isotope evolution diagram with zircon data from the amphibolite facies schists from the upper units of the Cabo Ortegal Complex. Data are from 5 samples of the Cariño Gneisses, a metaturbiditic series on which a total of 420 analysis were performed (Albert et al., 2015). The diagram shows three different episodes of zircon growth (Archean, Eburnean and Cadomian), which suggest that deposition of the siliciclastic series occurred in a sedimentary basin located in the periphery of the West Africa Craton. The most recent of these episodes resulted in a cycle of continuous zircon crystallization (likely accompanied by crustal growth) from about 750-500 Ma (Fig. 3). The proportion of zircons bearing crystallization ages between c. 750 Ma and c. 600 Ma is relatively small in these gneisses, but the proportion increases greatly for zircon grains formed between 600 and 500 Ma. The latter zircon age range is characterized by a large isotopic variety, ranging from grains formed after continental sources (Archean, Eburnean), to other cases indicating a large supply of juvenile material (Fig. 3). These sources reflect a rather continuous isotopic mixing, that explains both the continental sources recorded in the COM and the most primitive sources of the MCGM (Andonaegui et al., 2012, 2016). The great contribution of juvenile material deduced from the Hf isotope evolution diagram, and the extensive mixing line formed at 750-500 Ma, can only be explained in the context of a volcanic arc. This arc was generated in an active continental margin and it is characterized by the presence of extensive continental basement. The presence of rocks like those forming the MCGM and COM, characterized by two distinct mafic and felsic igneous end-members, with juvenile and continental isotopic sources, can be only explained in this context.

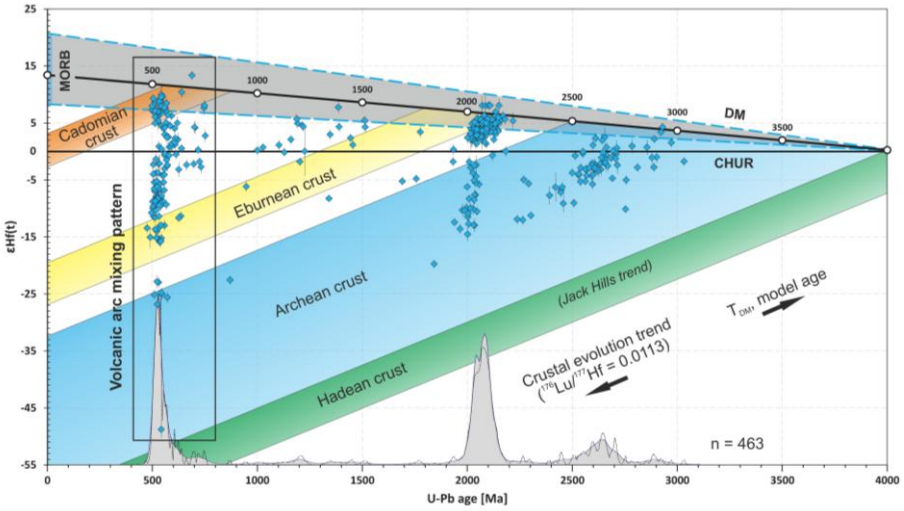

FIGURE 3. *Hf isotope evolution diagram showing zircon data of the siliciclastic rocks from the upper units of the Cabo Ortegal Complex (5 samples, 420 analyses). Each blue diamond is one analyses performed on one zircon core. Vertical rectangle shows the Lu-Hf vs. age mixing pattern of arc derived sediments. Kernel Density Estimation of analysed zircons with Lu-Hf systematics is represented in grey. CHUR: chondritic uniform reservoir; DM: depleted mantle; MORB: mid-ocean ridge basalt. Modified after Albert et al. (2015).*

DISCUSSION

The Cambrian magmatism recorded in the upper units of the allochthonous complexes of NW Iberian Massif shows significant compositional variety, ranging from granitic types to gabbroic rocks with juvenile character. According to Hf isotopic signature in detrital zircons, a rather continuous mixing of abundant juvenile material and varied continental sources (as old as Archean) characterized the magmatic event. The characteristics of the Cambrian magmatism and the provenance of its sedimentary host support that the Paleozoic sequences of the upper allochthonous units of NW Iberia were formed in a peri-Gondwanan volcanic arc. The igneous activity in this arc was intense between c. 600-500 Ma, and finished at c. 500 Ma, since younger arc-related igneous rocks have not been found in the upper allochthonous units. According to Hf systematics in zircon, the volcanic arc was also active between c. 750-600 Ma, although its record is scarce in the investigated metasedimentary series. Therefore, the generation of magmatic activity until c. 500 Ma cannot be interpreted as an isolated event limited to NW Iberia. Instead, the Cambrian magmatism was generated in the context of a volcanic arc active in the periphery of Gondwana over a long time period, at least between Neoproterozoic (Cryogenian) and Middle Cambrian times, the Avalonian-Cadomian arc (Fig. 3). The end of the activity in the Avalonian-Cadomian arc has been linked to the onset of a rifting event that affected the margin of Gondwana from Late Cambrian to Middle Ordovician times. This rifting is also well documented in other parts of the Variscan orogen and resulted in the opening of back-arc basins along the margin. The rifting event also caused the separation and drift of the microcontinent Avalonia from areas of the Gondwanan margin located further to the west of Iberia, as well as the opening of the Rheic Ocean.

Data compiled in this work allow documenting the end of the magmatic activity of the Avalonian-Cadomian arc in NW Iberia. This arc was active for a long period of time in the periphery of Gondwana, but in the north and northwestern part of the West African Craton it was progressively replaced by a period of rifting in Middle Cambrian times. The activity of this arc exerted a long-lasting influence on the peri-Gondwana magmatism and it likely ruled the development of sedimentary basins and the whole peri-continental dynamics.

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