Evolution of a Neoproterozoic suture in the Iberian Massif, Central Portugal: new U-Pb ages of igneous and metamorphic events at the contact between the Ossa Morena Zone and Central Iberian Zone

Journal Article**Author(s):**

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Publication date:

2015-04

Permanent link:

<https://doi.org/10.3929/ethz-a-010739433>

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Originally published in:

Lithos 220-223, <https://doi.org/10.1016/j.lithos.2015.02.001>

Funding acknowledgement:

335577 - Interplay between metamorphism and deformation in the Earth's lithosphere (EC)

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18 **Keywords:** Northern Gondwana margin, Cadomian magmatism, *P-T* thermodynamic
19 modelling, ID-TIMS U-Pb geochronology, Sr-Nd isotopes.
20

21 **Abstract:** A Neoproterozoic suture is exposed at the contact between the Ossa Morena Zone
22 and the Central Iberian Zone, in the Iberian Massif (Central Portugal), the westernmost
23 segment of the European Variscides. Although, the Cadomian magmatic and
24 tectonometamorphic events have been previously documented, their timing is still poorly
25 constrained, particularly in the inner zones of the suture. We used geochronological (ID-
26 TIMS U-Pb) data to establish the sequence of events, isotopic (Rb-Sr, Sm-Nd) data to

characterize the magmatic sources and thermodynamic modelling to determine the maximum P - T conditions attained during the Cadomian metamorphism. The first event, in the future Ossa Morena Zone, is the onset of island arc magmatism represented mainly by tholeiites with a MORB signature. Their igneous crystallization age is unknown, but they are older than ca. 539 Ma. This magmatic activity was accompanied by deposition of fine-grained sediments in a Neoproterozoic basin. The second event is the evolution of the Cadomian magmatic arc in different stages. The earliest magmatic stage occurs at ca. 692 Ma, which is the oldest igneous age known in the Ossa Morena Zone. It is followed by the generation of subalkaline and peraluminous protoliths at ca. 569 Ma, with the isotopic signature of old crustal sources. The final phase of the arc magmatism (ca. 548-544 Ma) involved mainly partial melting of continental crust. The range of the main magmatic activity must have been between ca. 569 Ma and ca. 544 Ma as mentioned for other areas in the Ossa Morena Zone. A major metamorphic event, recorded in metamorphic monazite, zircon and titanite at ca. 540 Ma, attained upper amphibolite facies conditions close to the transition to granulite facies (7–8 kbar and 640-660°C). It represents the continental arc accretion of the Ossa Morena Zone with the Iberian Autochthon passive margin (future Central Iberian Zone). The Early Ordovician rocks (ca. 483-477 Ma) were generated from depleted and juvenile sources. These rocks are strongly deformed and with melting features, display metamorphism at amphibolite facies conditions. They are interpreted as related with the Rheic Ocean.

1. Introduction

The recognition of Neoproterozoic sutures and the knowledge of their early history are crucial to understanding Gondwana assembly and its dynamics, allowing us to constrain the timing of collisional events. Gondwana assembly constitutes a significant part of Neoproterozoic

geologic history. Fragments of this evolution are documented in different areas of the Appalachian–Variscan orogen of North America and southern Europe where a major Neoproterozoic suture has been recognized (e.g. Murphy et al., 2006 and references therein). In the Iberian Massif, Western Europe, this suture is preserved within the Tomar-Badajoz-Córdoba Shear Zone (Fig. 1a), at the contact between the Ossa Morena and Central Iberian Zones (e.g. Eguíluz et al., 2000; Ribeiro et al., 1990). Several authors have recognized a complex evolution, as a result of the superposed Cadomian and Variscan orogenic cycles (e.g. Eguíluz et al., 2000; Quesada and Munhá, 1990; Ribeiro et al., 2009). The age of the amalgamation and suturing process is controversial owing to very intense structural and metamorphic overprinting together with still scarce geochronological data (López-Guijarro et al., 2008). Previous studies of the area include geological sketch maps (Conde, 1984; Gonçalves in Teixeira, 1981; Pereira et al., 1998; Ribeiro et al., 2013) and 1: 50 000 geological maps published by the Portuguese Geological Survey (Romão and Esperancinha, 2000; Romão, 2006; Zbyszewski et al., 1981, 1983). The tectonostratigraphic sequence has been established. These authors recognized the occurrence of a Precambrian basement based on field evidence without geochronological data. This study establishes a new tectonostratigraphic sequence based on detailed mapping, petrography, ID-TIMS U-Pb geochronology and whole rock isotopic (Rb-Sr, Sm-Nd) data. These data are used to constrain the timing of the magmatic and tectonometamorphic events at the northern margin of Gondwana, providing important information for the understanding of Gondwana assembly and the constraints they imposed on the subsequent events that led to the assembly of Pangea.

2. Geological setting and petrography

The Iberian Massif represents the westernmost segment of the European Variscides. It was first subdivided into different tectonostratigraphic units by Lotze (1945) and later modified by several authors (e.g. Julivert et al., 1972; Ribeiro et al., 2010a). The studied area is located at the contact between the Ossa Morena Zone and the Central Iberian Zone, within the Tomar-Badajoz-Córdoba Shear Zone (Fig. 1a). The Ossa Morena Zone was formed along the West African craton margin by recycling of ancient West African crust whereas the Central Iberian Zone, was formed either along the Amazonian margin of Gondwana by recycling of Avalonian and older Amazonian basement (Nance et al., 2008) or near north-east Africa zones by recycling of Saharan metacraton or Arabian-Nubian shield basement (Bea et al., 2010; Villaseca et al., 2011).

The tectonostratigraphic sequence established in this study corresponds to a lower limb of an overturned fold (Fig. 1c). It comprises the following units from bottom to top: the Série Negra Unit, the Sardoal Complex and the Mouriscas Complex. They have a NW-SE direction and are bounded by thrust faults (Fig. 1b). These units belong to the Ossa-Morena zone and were transported towards the NE, on top of the (low-grade and relatively autochthonous) Central-Iberian Zone during the Variscan orogeny (Fig. 1c). The amount of the Variscan NE thrust displacement is at least 5 to 10 km (Ribeiro et al., 2010b).

2.1. Série Negra Unit

The Série Negra Unit is a volcano-sedimentary succession, deformed and metamorphosed under variable *P-T* conditions (Alía, 1963; Carvalhosa, 1965; Eguíluz et al., 2000). It is recognized in southern Portugal and in Spain (e.g. Eguíluz et al., 2000; Pereira et al., 2006) and it has an equivalent in the Bohemian Massif (Linnemann et al., 2008). It is considered to have been deposited in a back arc basin of Ediacaran age (ca. 590-550 Ma) (e.g. Linnemann et

al., 2008 and references therein). In Spain (Monesterio Antiform) two different sequences were distinguished within the Série Negra: a lower one, the Montemolín succession and an upper one, the Tentudía succession (Eguíluz, 1987). Quesada (1990a, 1990b, 1997, 2006) interpreted the Montemolín succession as a passive margin sequence, whereas the Tentudía succession would represent the infill of a back arc basin.

In the studied area, the Série Negra comprises metavolcanic rocks, metavolcaniclastic rocks, metagreywacke, phyllite, quartz-phyllite, schists (micaschist, quartz-mica schist, quartzofeldspathic schist) with interbedded black chert, greenschist and amphibolite and rhyodacite intrusions (Fig. 1b). The greenschists and amphibolites occur as lenticular bodies oriented parallel to the host rock foliation planes. They are dark-green and fine-grained. The protoliths of the amphibolite have a tholeiitic character with island arc affinity and transitional-alkalic character with an intra-plate signature (Henriques, 2013). The metamorphism and mostly the intense deformation of the lithologies make difficult any stratigraphic linear correlation with the successions established in the southeastern part of the Ossa Morena Zone.

2.2. Sardoa Complex

The Sardoa Complex consists of deformed metamorphic rocks mostly of igneous origin: quartzofeldspathic schist, felsic orthogneiss, migmatite, gneissic granite, interbedded amphibolite and amphibolitic gneiss (Fig. 1b). Minor Carboniferous rhyodacites have intruded these lithologies (Fig. 1b). The quartzofeldspathic schist shows a pronounced foliation and locally contains coarser and light colored interbedded layers resembling gneissic banding. It contains medium- to coarse-grained porphyroclasts of oligoclase and rare K-feldspar in a foliated matrix of quartz, oligoclase, biotite and muscovite. Muscovite is overgrowing fibrolitic sillimanite. Accessories are almandine, tourmaline, ilmenite, rutile,

zircon, monazite and apatite. Secondary phases include albite and epidote. Mylonitic fabric and folded foliation are common. Sardoal Complex orthogneisses were grouped according to location and field relationships. All orthogneisses exhibit intensive deformation features like folded foliation and mylonite. In thin section, porphyroclastic textures are observed and deformation features are common. They include mylonitic fabric, S-C fabrics, ribbon quartz, porphyroclast granulation, rounded porphyroclasts, grain-size reduction and kink-band folds (Fig. 2a). Orthogneisses have variable K-feldspar abundances and different accessory mineral contents (Appendix 1). The Souto orthogneiss is located in the northwest area of the reservoir (Fig. 1b) and is associated with the quartzo-feldspathic schist. It is medium- to coarse-grained and contains quartz, oligoclase, biotite, muscovite and rarely K-feldspar. Accessory minerals include almandine, fibrolitic sillimanite, zircon, tourmaline, ilmenite, rutile, monazite and apatite. The Carvalhal orthogneiss is observed in the Tagus river banks, in the southeast of the area (Fig. 1b). It has a well- defined banded structure, where dark-colored biotite-muscovite layers are deflected around light-colored quartzo-feldspathic layers (Fig. 2b). This orthogneiss is in close association with migmatite, which displays a wide range of structures like schollen structures, biotite schlieren and stromatic structures usually folded (Fig. 2c). The Carvalhal orthogneiss is fine-grained and contains quartz, oligoclase, andesine, orthoclase, perthitic microcline, biotite and muscovite. Accessory minerals include almandine, tourmaline, zircon, ilmenite, apatite, monazite, rutile and magnetite. Chlorite occurs as a secondary mineral. The Sardoal orthogneiss crops out in the area located southeast of the reservoir (Fig. 1b) and frequently exhibits augen textures. It is associated with gneissic granite that contains abundant relict lithoclasts, biotite restites and quartz rods. The Sardoal orthogneiss is coarse-grained and consists of quartz, oligoclase, K-feldspar, biotite and muscovite. Accessory minerals are fibrolite (Fig. 2d), tourmaline, zircon, apatite, ilmenite, magnetite, rutile and pyrite. Chlorite results from the alteration of biotite. The Olalhas orthogneiss occurs in the Olalhas klippe

(Ribeiro et al., 2013), located in the northwest of the area (Fig. 1b). It is fine- to medium-grained and comprises quartz, oligoclase, biotite, muscovite and rare K-feldspar. Accessory minerals include sillimanite, staurolite, almandine, tourmaline, zircon, ilmenite, apatite and pyrite. Staurolite and sillimanite are enclosed in muscovite (Fig. 2e). The minerals of the orthogneiss were reequilibrated, particularly biotite and muscovite, whereas the plagioclase reequilibration was less intense (Henriques, 2013). The protoliths of the orthogneiss were calc-alkaline, peraluminous and had granitic and granodioritic compositions. They were generated in an active continental margin as indicated by their chemical compositions: enrichments in LILE compared to HFSE; high $Nb_N/Yb_N=3.98$ to 17.91; negative anomalies in P_2O_5 and TiO_2 (e.g. Wilson, 1989) and Th/Ta ratios (5.96 to 17.23) and Yb values (0.96), that fall in the range of values for active continental margins from Gorton and Schandl (2000) (Henriques et al., 2006; Henriques et al., 2010a; Henriques, 2013). Thermodynamic modelling indicates metamorphism at amphibolitic facies conditions (4-4.5 kb and 570-590° C) (Henriques et al., 2013).

In the Sardoal Complex, elongate metre-size bodies of amphibolite and amphibolitic gneiss occur interbedded in the orthogneiss. The Cabeço da Moura amphibolite, located in the Olalhas klippe (Fig. 1b), is dark and fine-grained. In thin section, it displays foliated granoblastic to nematoblastic textures and consists of magnesiohornblende, labradorite rimmed by andesine, diopside with subordinate ilmenite, zircon, titanite, apatite, quartz, magnetite and pyrite. Locally, ferrohornblende, labradorite rimmed by bytownite, augite and rarely ferroedenite are present. The mineralogical association indicates upper amphibolite facies conditions (e.g. Bucher and Frey, 2002). Retrograde minerals include actinolite and epidote. The Vila Nova amphibolite occurs in the remaining Sardoal Complex area (Fig. 1b). It is fine-grained and shows an incipient gneissic banding, where dark layers are enriched in amphibole and light layers are enriched in plagioclase, epidote and carbonate. In thin section,

foliated granoblastic to nematoblastic textures are observed. The mineral content consists of magnesiohornblende, labradorite rimmed by andesine, diopside with subordinate ilmenite, titanite, apatite, quartz, and pyrite. Actinolite and epidote are retrograde minerals. The Vila Nova amphibolite locally contains pargasite and ferropargasite. The Cabeço da Moura amphibolite shows N and E-MORB affinities and the Vila Nova amphibolite shows E-MORB affinities in Wood (1980) diagram (Henriques, 2013). Both are mainly tholeiites, according to the ratios established by Pearce (1983), $Th/Yb=0.02$ to 0.28 and $Ta/Yb=0.06$ to 0.26 . They were generated in an island-arc setting as indicated by the MORB- normalized spider diagram of Pearce (1983), that shows enrichment of LILE relatively to HFSE ($Nb_N/Yb_N=0.98$ to 3.57) and a depletion of HFSE relatively to MORB (Henriques et al., 2010b; Henriques, 2013).

2.3. Mouriscas Complex

The Mouriscas Complex is a deformed and metamorphosed predominantly mafic igneous complex that consists of amphibolite, protomylonite trondhjemite, garnet amphibolite, metatexite and diatexite. Bodies of amphibolite are fine- to coarse-grained and comprise most of the Complex area. Deformation features, like folded foliation and mylonite, are common. Metamorphic segregation appears as incipient gneissic banding. Rarely relic igneous textures are preserved in some outcrops. Thin sections show preserved igneous texture (Fig. 2f), porphyroclastic texture and mylonitic fabric (Fig. 2g). Amphibolite consists of plagioclase, amphibole and less abundant quartz, biotite, titanite, zircon, tourmaline, apatite, ilmenite, rutile, magnetite and pyrite. Actinolite, epidote and chlorite are retrograde phases. Amphibole is usually zoned: magnesiohornblende rimmed by cummingtonite, ferrotschermakite, tschermakite, and less frequently ferrohornblende. Cummingtonite rimmed by ferrotschermakite and tschermakite is also present. The protoliths of the amphibolites, which

are plutonic, have basic to intermediate compositions and show calc-alkaline character and intra-plate and continental arc affinities (Henriques, 2013; Ribeiro et al., 1995).

The protomylonite trondhjemite occurs as dykes and massive outcrops. The dykes of metric dimension intruded the Neoproterozoic amphibolites. Protomylonite trondhjemite shows porphyroclastic and cataclastic textures and mylonitic fabric. It consists of porphyroclasts of quartz, oligoclase, muscovite, biotite, almandine, fibrolitic sillimanite and staurolite. The main constituents of the matrix are quartz, oligoclase, biotite, almandine and small amounts of zircon, rutile, ilmenite, monazite, apatite and rare K-feldspar. Secondary minerals are chlorite and muscovite. Estimated P - T conditions using thermodynamic modelling are in the range of 4.5-6.2 kb and 590-650° C (Henriques et al., 2013).

Garnet amphibolite crops out as a massive heterogeneous outcrop of decametric dimension. The most distinctive feature is the occurrence of large garnet grains surrounded by light-colored halos (Fig. 2h). Garnet amphibolite is medium- to coarse-grained and contains plagioclase, amphibole and less abundant almandine, biotite, quartz, epidote, zircon, apatite and ilmenite. Plagioclase is andesine rimmed by oligoclase. Amphibole is grunerite rimmed by ferrotschermakite. Almandine occurs as large irregular porphyroblasts surrounded by quartz, andesine and oligoclase, that cross cut the foliation, indicating post-kinematic recrystallization. The whole rock data indicate protoliths with MORB signatures and crustal contamination (Henriques, 2013; Ribeiro et al., 1995). The garnet amphibolite P - T conditions were estimated using thermodynamic modelling at 6.5 kb and 550° C (Henriques et al., 2013).

3. Analytical methods

3.1. ID-TIMS U-Pb geochronology

The analytical procedures were performed at the Earth Sciences Department of Memorial University of Newfoundland. A total of 12 rock samples representative of the geological units were collected for ID-TIMS U-Pb analyses (Fig. 1b). The samples (20-30 kg each) were crushed, pulverized and sieved to dimensions < 40 mesh. Heavy mineral fractions were separated using the Wifley table, heavy liquids and the Frantz magnetic separator. The final fractions were observed under a binocular microscope and the best quality zircon, monazite and titanite were picked for analysis. Cathodo-luminescence images of zircon were obtained on a FEI Quanta 400 SEM. Some of the selected zircon and coarse monazite and titanite crystals were abraded using the Krogh (1982) technique. Zircon from some samples was subjected to annealing, followed by chemical abrasion using the technique of Mattinson (2005). After these procedures a second selection of the best crystals was done to assure the quality of the analyses. Mineral fractions were washed and weighed. Zircon fractions were mixed with a ^{205}Pb - ^{238}U spike (Parrish and Krogh, 1987) and dissolved with distilled HF and distilled 8N HNO_3 in Krogh-type Teflon® dissolution bombs, that were kept in the oven at a temperature of 220°C for 5 days (after Krogh, 1973). Monazite fractions were mixed with a ^{205}Pb - ^{238}U spike and dissolved with distilled 6.2N HCl in a savillex® Teflon container which was heated on a hot plate for 5 days at 120°C (Parrish, 1990). Titanite fractions were mixed with a ^{205}Pb - ^{238}U spike and dissolved with distilled HF and distilled 8N HNO_3 in a savillex® Teflon container which was heated on a hot plate for 5 days at 120°C. U and Pb were separated through ion exchange chemistry according to modified procedures for zircon chemistry after Krogh (1973), reducing the volume of the columns and the reagents in a ratio of 1/10, and HBr chemistry after Manhés et al. (1978) for titanite and monazite. The isotopic ratios were measured in a Finningan MAT 262 thermal ionization mass spectrometer, which includes an ion counting secondary electron multiplier (SEM) detector. U and Pb were loaded together on a previously outgassed Re filament with silica gel and dilute H_3PO_4 using the

technique of Cameron et al. (1969). The mass spectrometer faraday cups were calibrated using a NBS 981 Pb standard and the SEM was calibrated against a faraday cup by measuring a known isotopic ratio. The isotopic ages were calculated using the decay constants of Jaffey et al. (1977) and an unpublished program. The uncertainties of the isotopic ratios were calculated at 2σ using the same software and taking into account the uncertainties of the isotopic ratio measurements, the U and Pb fractionation, the laboratory procedure blanks (1-10 pg Pb) and the initial common Pb, which was corrected following the model of Stacey and Kramers (1975). The ages were calculated using ISOPLOT (Ludwig, 2003) and uncertainties are reported at the 95% confidence level. Upper intercept ages for discordia lines were calculated after Davis (1982).

3.2. Rb-Sr and Sm-Nd isotopes

A total of 21 samples were analysed at the Earth Sciences Department of the Memorial University of Newfoundland, St. John's, Canada. For Sm-Nd and Sr analyses approximately 0.05 to 0.2 g of rock powder was dissolved in Savilex© Teflon beakers using a mixture of concentrate HF - HNO₃ acids. A mixed ¹⁵⁰Nd/¹⁴⁹Sm spike was added to each sample prior to acid digestion. Both sample and spike were weighed on a high-precision balance. After five days of digestion, the solution was evaporated to dryness and then taken up in 6 N HCl acid for two days. The solution was then dried and taken up in 2.5N HCl and loaded on cationic exchange AG50W - X8 resin to separate the REE and Sr fractions. The Sm and Nd were then separated using a secondary column loaded with Eichrom© Ln resin, while Sr was purified and recuperated using a 1 mL column filled with Eichrom© Sr spec. resin. All reagents were distilled and blank levels are ca. 100 -200 pg for Nd. All isotopic ratios were obtained using a multicollector Finnigan Mat 262 mass spectrometer in static mode. The Nd and Sr isotopic ratios were normalized to ¹⁴⁶Nd/¹⁴⁴Nd=0.721903 and ⁸⁸Sr/⁸⁶Sr=8.375209 respectively. The

reported $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were corrected for the deviation from repeated measurements of the JNdi-1 ($^{143}\text{Nd}/^{144}\text{Nd} = 0.512115$, Tanaka et al., 2000) and NBS 987 ($^{87}\text{Sr}/^{86}\text{Sr}=0.710340$) standards. During the course of data acquisition, replicates of the standards gave a mean value of $^{143}\text{Nd}/^{144}\text{Nd}=0.512137 \pm 19$ (Stedv, n=112) for JNdi-1 and $^{87}\text{Sr}/^{86}\text{Sr}=0.710291 \pm 25$ (Stedv, n=46) for NBS 987. In-run precisions on all isotopic ratios are given at 95% confidence level. Errors on Nd and Sr isotopic compositions are $<0.002\%$ and errors on the $^{147}\text{Sm}/^{144}\text{Nd}$ ratio are estimated to be less than 0.1%. The ϵNd values were calculated using values of $^{147}\text{Sm}/^{144}\text{Nd}=0.1967$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$ for the present day chondrite uniform reservoir (CHUR). ^{147}Sm decay constant is $6.54 \times 10^{-12} \text{ y}^{-1}$ (Steiger and Jäger, 1977). T_{DM} is calculated with respect to the DePaolo (1981a) mantle model and also using a linear evolution for a mantle separated from the CHUR at 4.55 Ga and having a present day ϵNd value of +10 ($T_{\text{DM}2}$).

3.3. Electron microprobe analyses

Mineral analyses were performed on an electronic microprobe CAMECA SX-100, at Oviedo University, Spain, with a 15 kV accelerating voltage, 15 nA beam current, 5 μm beam diameter and peak counting times of 10 s for most elements except for V (20 s), Co and Ni (5 s). Some of the mineral analyses were carried out on an electron microprobe Jeol 8500-F at Laboratório Nacional de Energia e Geologia (LNEG), Portugal, with a 15 kV accelerating voltage, 15 nA beam current, 5 μm beam diameter and 15 s peak counting times. The detection limit is variable according to the element, but generally higher than 200 ppm and the accuracy is better than 2%. ZAF corrections were applied.

4. ID-TIMS U-Pb geochronology

4.1. Sardaoal Complex

Sample 321-140 is from a quartzo-feldspathic schist (Appendix 1). This sample contains flat euhedral medium to large yellow monazite and euhedral, clear, colorless, medium to large (2:1) zircon prisms. The oldest monazite fraction (M1) provided a $^{207}\text{Pb}/^{235}\text{U}$ age of 540 ± 3 Ma (95%CI) and the weighted average $^{207}\text{Pb}/^{235}\text{U}$ age of M1 and M2 is 538 ± 2 Ma (MSWD=0.92, 95%CI), which is interpreted as the age of the metamorphic event (Fig. 4b, Table 1a). M3 is younger and also overlaps Concordia. It is interpreted likely to have a thin rim of Variscan age. The CL images show zoned zircon (Fig. 3a, b) that in some cases present dissolution surfaces and evidence of late metamorphism in the rim (Fig. 3b). Six zircon analyses (Z1-Z3 and Z6-Z8) define a discordia line anchored at a lower intercept at 540 ± 3 Ma age and giving an upper intercept age of $692 + 77/-60$ Ma, with a probability of fit of 8% (Fig. 4b, Table 1a). The isotopic systematics of this group of zircon analyses suggests that the age of 692 Ma is the age of the protolith which was likely an igneous rock. Two zircon analyses (Z4 and Z5) are highly discordant indicating an inherited component in these grains (Fig. 4a, Table 1a).

Sample gn is from a Carvalhal orthogneiss (Appendix 1). This sample contains subhedral, medium yellow monazite and euhedral, clear, sharp, colorless, medium to large (2:1) zircon prisms. Four monazite analyses provided four concordant data points that show some scatter along the Concordia curve, the oldest one (M2) has a $^{207}\text{Pb}/^{235}\text{U}$ age of 540 ± 5 Ma (95%CI) which is interpreted as the age of metamorphism (Fig. 4d, Table 1a). Younger monazite fractions (M1, M3, M4) all overlap the Concordia but are interpreted to be composite and on a mixing line to a Variscan metamorphic overprint (Fig. 4d). The CL images show growth

zoning in euhedral zircon (Fig. 3c), some of which contain subrounded cores (Fig. 3d). Triplicate concordant analyses of zircon prisms (Z6, Z10, Z12) yield a weighted average $^{206}\text{Pb}/^{238}\text{U}$ age of 569 ± 3 Ma (MSWD=0.33, 95% CI), which is interpreted as the igneous crystallization age of the protolith granite (Fig. 4d, Table 1a). Analyses Z7, Z8, Z13 and Z14, which are concordant or near concordant at older ages, are interpreted to represent composite grains with igneous rims and older cores (Fig. 4d, Table 1a). There are also inherited Neoproterozoic zircons, with $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 2801 Ma (Z11) and of 2755 Ma (Z5) and several analyses with inherited Proterozoic zircon (Z1-Z4) defining a line with a lower intercept age at 569 ± 3 Ma (the most likely age of the rims) and an upper intercept at 1905 ± 85 Ma (Fig. 4c, Table 1a). This might be the age of a significant amount of material in the source region, either just detrital zircons, or perhaps actual basement orthogneiss of this age.

Sample 10 is from a Sardoal orthogneiss (Appendix 1). This sample contains clear, sharp, colorless, euhedral (3:1) large zircon prisms. The CL images show well preserved concentric oscillatory growth zoning (Fig. 3e, f). Four analyses (Z2, Z4, Z6, Z7) are slightly discordant and have a weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 548 ± 4 Ma (MSWD=0.08, 95%CI), which is interpreted as the age of igneous crystallization of the protolith (Fig. 4e, Table 1a). Fractions Z1, Z3 and Z5 are discordant and interpreted to contain inherited older zircon components (Fig. 4e, Table 1a).

Sample 311-56 is from a Souto orthogneiss (Appendix 1). This sample contains subhedral medium to large monazite and subhedral to euhedral, clear, colorless, medium to large zircon prisms (2:1) with tapered ends. The oldest monazite fraction (M2) provides a $^{207}\text{Pb}/^{235}\text{U}$ age of 539 ± 2 Ma (95%CI) (Fig. 4g, Table 1a) and is interpreted as the age of metamorphic event. The monazite data points are slightly “reversely” discordant (Fig. 4g) which is related

to the incorporation during crystallization of excess amounts of ^{230}Th (Parrish, 1990; Schärer, 1984). The zircon CL images show zoned zircon (Fig. 3g) around cores (Fig. 3h). One zircon fraction (Z3) is slightly discordant and two zircon fractions (Z1 and Z2) are highly discordant indicating the presence of inheritance (Fig. 4f, g, Table 1a).

Sample 311-30 is from a Olalhas orthogneiss (Appendix 1). This sample contains euhedral, colorless, medium to large (3:1) zircon prisms with tapered ends. The CL images show igneous and inherited zircons with evidence of late recrystallization (Fig. 3i, j). Four zircon multigrain fractions provided discordant data points (Fig. 4h, Table 1a) interpreted to reflect inheritance, also supported by CL images. Analysis Z3 is close to the Concordia curve with a $^{206}\text{Pb}/^{238}\text{U}$ age of 597 Ma (Fig. 4h, Table 1a) whereas Z1 contains a component with $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1696 Ma (Fig. 4h, Table 1a).

Sample 311-1 is from a Cabeço da Moura amphibolite (Appendix 1). This sample contains two zircon populations. The first one consists of clear, colorless, small equant multi-faceted «soccer-ball» zircon. The other one consists of clear, colorless, subhedral, long prisms with rounded ends. The «soccer-ball» zircon CL images (Fig. 3k, l) show fir-tree type and radial sector zoning. The external morphology of «soccer-ball» zircons and their internal texture indicate they are metamorphic zircon that crystallized at upper amphibolite/granulite grades (e.g. Hoskin and Schaltegger, 2003 and references therein). Three multi-grain zircon fractions of small equant multi-faceted «soccer-ball» provided three data points (Z1, Z2, Z4) with a weighted average $^{206}\text{Pb}/^{238}\text{U}$ age of 539 ± 3 Ma (MSWD=0.20, 95%CI), which is interpreted as the age of the peak of metamorphism (Fig. 4i, Table 1a). One single long zircon prism

provided a slightly discordant data point (Z3) that probably reflects some inheritance of Pb (Fig. 4i, Table 1a).

Sample 311-62 is from a Vila Nova amphibolite (Appendix 1). This sample contains a population of medium clear subhedral brown titanite. Two titanite fractions provided a weighted average $^{206}\text{Pb}/^{238}\text{U}$ age of 529 ± 5 Ma (MSWD=0.018, 95%CI), which is interpreted as the age of cooling through the blocking temperature for titanite after the ca. 539 Ma peak of metamorphism (Fig. 4j, Table 1a).

4.2. Mouriscas Complex

Sample 321-138 is from an amphibolite that shows relic igneous texture (Appendix 1). Zircon in this sample consists of medium to large square cross-section prism fragments plus prisms and large cross-section (3:1) prisms. The CL images show banded zoning common in mafic rocks such as hornblende gabbro or diorite (Hoskin, 2000) (Fig. 3m). Three zircon fractions provided overlapping concordant data points, with a weighted average $^{206}\text{Pb}/^{238}\text{U}$ age of 544.2 ± 1.7 Ma (MSWD=0.66, 95% CI), which is interpreted to be the time of igneous crystallization (Fig. 5a, Table 1b).

Sample 58A is amphibolite that shows granofelsic texture (Fig. 2f, Appendix 1). This sample contains two populations of zircon: one euhedral, clear, sharp, colorless, needle prisms and another euhedral to subhedral, colorless, medium to large (2:1) prisms. The CL images of both zircon populations show a banded zoning pattern (Fig. 3n). Evidence for a late metamorphic event is suggested by subrounded contours. Three multi-grain fractions containing medium-large (2:1) prisms provide overlapping concordant data points with a

weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 544.3 ± 2.5 Ma (MSWD=0.054; 95%CI), which is interpreted to be the time of igneous crystallization (Fig. 5b, Table 1b).

Sample 321-M is from an amphibolite that shows porphyroclastic texture and mylonitic fabric (Fig. 2g, Appendix 1). This sample contains clear, colorless, euhedral (2:1) very large zircon prisms. The CL images show zoned zircons with banded zoned cores (Fig. 3o). Two multi-grain fractions provided concordant or slightly discordant data points with a weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 544 ± 2 Ma (MSWD=0.098; 95%CI), which is interpreted to be the time of igneous crystallization (Fig. 5c, Table 1b).

Sample 165 is from a protomylonite trondhjemite (Appendix 1). This sample contains medium to small, euhedral to subhedral, clear, yellow monazite and medium, euhedral to subhedral, simple, clear, colorless to light yellow, (2:1) zircon prisms and large angular fragments. The zircon CL images show regular growth zoning, sector and oscillatory zoning patterns, (Fig. 3p, q), minor recrystallization (Fig. 3q) and cores (Fig. 3r). Three small monazite multi-grain fractions provided points that are 3 to 10% discordant (Fig. 5d, Table 1b). They are co-linear with the concordant zircon fraction Z3 and define a discordia line anchored at 10 ± 10 Ma, with an upper intercept age of 484 ± 10 Ma (probability of fit=71%, 95%CI). The $^{206}\text{Pb}/^{238}\text{U}$ age of Z3 is 483 ± 1.5 Ma and this is the best estimate of the age of igneous crystallization (Fig. 5d, Table 1b). Three other zircon fractions containing single (Z4) or multigrain euhedral (2:1) prisms (Z1, Z2) yield older ages (Table 1b) that are interpreted to be due to an inherited component (Fig. 3r).

Sample 20A is from a garnet amphibolite (Appendix 1). This sample contains large, euhedral, clear, sharp, colorless to light yellow (2:1) zircon prism fragments. The CL images show

banded zoning and recrystallization (Fig. 3s). Seven zircon fractions containing multigrain, large (2:1) prism fragments provided 2 slightly discordant points (Z1 and Z3) and 5 overlapping concordant points (Z2, Z4-Z7) that define a weighted average $^{206}\text{Pb}/^{238}\text{U}$ age of 477 ± 2 Ma (MSWD=0.17, 95%CI), which is interpreted to be the age of igneous crystallization (Fig. 5e, Table 1b).

5. Rb-Sr and Sm-Nd results

Results are listed in Tables 2a and 2b. The Sr and Nd initial ratios and initial ϵNd values (ϵNd_t) were calculated using the corresponding U-Pb igneous ages for samples 321-140, gn, 10, 58A, 321-138, 321-M, 165 and 20A. For other samples, igneous ages were assumed based on identical features of dated samples, such as field relationships, petrography, mineral content and geochemical signatures. The T_{DM} model age is interpreted as the average crustal residence time (Arndt and Goldstein, 1987; Murphy and Nance, 2002).

5.1. Sardoa Complex

The Sr initial ratio and the ϵNd_t values allow us to discriminate various groups of orthogneiss (Fig. 6). The Souto orthogneiss (ca. 692 Ma inferred) has $(^{87}\text{Sr}/^{86}\text{Sr})_i = 0.7057$ and 0.7060 , $\epsilon\text{Nd}_t = -5.2$ to -7.3 and plot within the fields of metasedimentary lower crust and meta-igneous lower crust (Tables 2a, b, Fig. 6). T_{DM} model ages range between 1.60 and 1.65 Ga (Table 2b). The Carvalhal orthogneiss (ca. 570 Ma) has $(^{87}\text{Sr}/^{86}\text{Sr})_i = 0.7077$ - 0.7096 , $\epsilon\text{Nd}_t = -6.0$ to -8.1 (Tables 2a, b) and plot within the fields of metasedimentary lower crust and meta-igneous middle-upper crust (Fig. 6). They yield T_{DM} model ages from 1.53 to 1.69 Ga (Table 2b). The Sardoa orthogneiss (ca. 548 Ma) shows $(^{87}\text{Sr}/^{86}\text{Sr})_i = 0.7092$ to 0.7117 , $\epsilon\text{Nd}_t = -5.9$ to -6.4

and plots within the field of meta-igneous middle-upper crust and show T_{DM} model ages from 1.56 to 1.65 Ga (Tables 2a, b, Fig. 6). The Olalhas orthogneiss shows T_{DM} model ages from 1.48 to 1.56 Ga (Table 2b). These data suggest that the various units of orthogneiss are hybrid rocks and their protoliths were generated from melting of different crustal sources. All the orthogneiss units present old T_{DM} model ages, indicating a strong component of old crustal rocks (e.g. López-Guijarro et al., 2008).

5.2. Mouriscas Complex

The protoliths of the bodies of amphibolite (ca. 544 Ma) are presumed to have been coarse-grained intrusions likely gabbro or diorite, based on the grain size and morphology of zircon. These samples show heterogeneous $(^{87}\text{Sr}/^{86}\text{Sr})_i$ isotopic signatures (0.7053 to 0.7084) (Table 2a). Most samples show ϵNd_t negative values suggesting crustal contamination (-2.9 to -3.4) and plot within the field of mantle array and meta-igneous lower crust (Table 2b, Fig. 6), but sample 311-96A plots within the field of meta-igneous middle-upper crust (Fig. 6). The sample 58A shows a ϵNd_t positive value (3.2) and plots within the field of lithospheric mantle (Table 2b, Fig. 6). All samples exhibit old T_{DM} model ages from 1.22 to 1.81 Ga (Table 2b). Protoliths of protomylonite trondhjemite (ca. 483 Ma) show a narrow range of isotopic compositions with $(^{87}\text{Sr}/^{86}\text{Sr})_i = 0.7039$ to 0.7045 and $\epsilon\text{Nd}_t = 5.0$ to 5.3 , compatible with the field of lithospheric mantle (Tables 2a, b, Fig. 6). T_{DM} model ages are identical in all samples and range from 0.61 to 0.65 Ga (Table 2b), suggesting a rather juvenile source. Protoliths of garnet amphibolite (ca. 477 Ma) show heterogeneous isotopic compositions: one has $(^{87}\text{Sr}/^{86}\text{Sr})_i = 0.7030$, $\epsilon\text{Nd}_t = 8.2$ and plots within the field of MORB; the other has $(^{87}\text{Sr}/^{86}\text{Sr})_i = 0.7042$, $\epsilon\text{Nd}_t = 6.7$ and plots within the field of lithospheric mantle (Tables 2a, b, Fig. 6). Young T_{DM} model ages (0.34 to 0.52 Ga) indicate juvenile sources in both cases (Table 2b).

6. *P-T* calculation

Representative electron microprobe analyses of minerals from sample 311-1, Cabeço da Moura amphibolite (Sardoal Complex), are presented in Appendix 2. The amphibolite is fine-grained, displays granoblastic to nematoblastic textures and contains the following mineral assemblage: $\text{mg-hbl(am)} + (\text{lab+byt})\text{pl} + \text{di(cpx)} + \text{zrn} + \text{qtz} + \text{ilm} + \text{ttn}$. Amphibole shows X_{Mg} values of 0.60-0.62, plagioclase X_{An} contents of 0.65-0.75 and diopside $X_{\text{Wo}}=0.47-0.48$. The *P-T* diagram was computed using the Perple_X program (Connolly, 2009) and the thermodynamic dataset of Holland and Powell (1998, revised 2003). The bulk rock composition used for the calculations is in mol%, as is indicated in the *P-T* diagram. The following solution models were used: amphibole (Dale et al., 2005), clinopyroxene (Green et al., 2007), chlorite, epidote and garnet (Holland and Powell, 1998), ilmenite and magnetite (Anderson and Lindsley, 1988), orthopyroxene (Holland and Powell, 1996), plagioclase (Newton et al., 1980). Quartz, rutile and titanite were considered as pure phases. Calculations were made for NCFMASHTO (Na_2O , CaO , FeO , MgO , Al_2O_3 , SiO_2 , TiO_2 , H_2O , O_2) model chemical system with water and quartz in excess. The *P-T* conditions were estimated based on the compositional isopleths for key mineral phases in the observed stability field (Cpx-Am-Pl-Ilm-Ttn) at 7–8 kbar and 640-660°C, amphibolite facies conditions close to the transition to granulite facies (Fig. 7).

7. Discussion

7.1. Neoproterozoic magmatism

Evidence for island arc magmatism is provided by the Série Negra and Sardoal Complex amphibolite. Both show tholeiitic character (Henriques, 2013), suggesting that they were generated in early stages of the arc (Wilson, 1989). Other protoliths of Série Negra amphibolite have transitional-alkalic character with an intra-plate signature, suggesting a more advanced stage of the arc (Wilson, 1989). The Sardoal Complex amphibolite protoliths, older than ca. 539 Ma, (Fig. 4i), have a MORB signature and were generated from depleted and enriched mantle sources (Henriques, 2013). The existence of an island arc was also recognized in other areas of the Ossa Morena Zone (e.g. Ribeiro et al., 2003).

The Sardoal Complex orthogneiss units (ca. 692-548 Ma), (Figs. 4a-e), have a calc-alkaline and peraluminous character and were generated from protoliths of acid composition with the geochemical signature of an active continental margin (Henriques, 2013). Their Sr and Nd initial isotopic signatures, $(^{87}\text{Sr}/^{86}\text{Sr})_i = 0.7057\text{-}0.7117$ and $\epsilon\text{Nd}_t = -5.2$ to -8.1 , (Tables 2a, b), indicate partial melting of old metasedimentary and meta-igneous crust at different crustal levels (Fig. 6). This information is supported by the ages of inherited zircon (1.7 Ga-2.8 Ga), (Table 1a). The early rift-related granitoids from the Ossa Morena Zone (ca. 524-516 Ma; Sánchez-García et al., 2014), by contrast, show higher ϵNd_t values (-3.6 to -1.8).

The Mouriscas Complex amphibolite bodies, interpreted to have originated as plutonic rocks (ca. 544 Ma), (Figs. 5a-c), have a calc-alkaline character, intermediate and basic compositions with intra-plate and continental arc affinities (Henriques, 2013). Their initial Sr and Nd isotopic signatures of $(^{87}\text{Sr}/^{86}\text{Sr})_i = 0.7053\text{-}0.7084$ and $\epsilon\text{Nd}_t = (-3.6$ to $3.2)$, (Tables 2a, b) suggest an origin from a mantle source and crustal contamination (Fig. 6).

Negative ϵNd_t values and old T_{DM} model ages of Neoproterozoic rocks are characteristic of Cadomian-type terranes (e.g. Murphy et al., 2004, Murphy and Nance, 2002) and are identical to those of other areas of the Cadomian orogen, such as the Bohemian Massif and Armorica (Fig. 8) (e.g. Linnemann et al., 2004; Samson et al., 2003). The major igneous event that

occurred during the Neoproterozoic (ca. 692-544 Ma) is interpreted as the progressive evolution of the Cadomian magmatic arc, on continental margin.

Carvalhal orthogneiss (569 ± 3 Ma), (Fig. 4d), contains Paleoproterozoic and Neoarchean inherited zircons (1.9 Ga-2.8 Ga), (Table 1a), consistent with a West African craton provenance, which is in agreement with Late Neoproterozoic reconstructions that place the Ossa Morena Zone adjacent to the West African craton (e.g. Murphy et al., 2004 and references therein). The absence of Mesoproterozoic inherited zircons ages (1.7-1.0 Ga) also supports proximity to the West African craton (e.g. Fernández-Suárez et al., 2002; Linnemann et al., 2008).

7.2. Early Ordovician magmatism

The Early Ordovician magmatism is represented by the protomylonite trondhjemite and garnet amphibolite both intrusive in the Mouriscas Complex. It occurred in a short period of time between ca. 483 and 477 Ma (Table 1b) and is less important than the Neoproterozoic magmatism that spanned a wider range of time (ca. 692-544 Ma, Tables 1a, b) and space (Fig. 1b). The Early Ordovician rocks have significantly lower T_{DM} values (0.52 to 0.65 Ga) and higher ϵNd_t values (5.0 to 6.7) than the Neoproterozoic rocks (Tables 2a, b), indicating the input of a juvenile source, including a MORB component ($\epsilon Nd_t = 8.2$; $T_{DM} = 0.34$ Ga, Table 2b). Similar igneous ages are found in the Lower Ophiolite of the Ordenes Complex, NW Iberia (497 ± 4 Ma; e.g. Arenas et al., 2007), and the Internal Ossa Morena Zone Ophiolite sequences (IOMZOS) (479 ± 5 Ma; Pedro et al., 2010; Ribeiro et al., 2010a), both considered as remnants of the Rheic Ocean. Lower Ordovician mafic rocks from the Ossa Morena Zone (ca. 471) that are related to intracontinental rifting (Solá 2007; Solá et al., 2008) have lower

ϵNd_t values (1.26 to 3.26). The primitive signature of the Ordovician rocks of this study suggests the existence of mantle melting with possible formation of oceanic crust.

7.3. Metamorphism

The metamorphic Precambrian events are well known in the Ossa Morena Zone and has been mentioned since 1878 (e.g. Eguíluz and Ábalos, 1992; Eguíluz et al., 2000; MacPherson, 1878; Quesada, 1997). Intense deformation and poly-metamorphism (Cadomian, Variscan) affected all the rocks within the studied area, except the Carboniferous rhyodacite dykes. Evidence for a major metamorphic event near the Neoproterozoic-early Cambrian boundary (ca. 540 Ma) is preserved in metamorphic monazite in quartzo-feldspathic schist (540 ± 3 Ma), (Fig. 4b); Carvalhal orthogneiss (540 ± 5 Ma), (Fig. 4d); Souto orthogneiss (539 ± 2 Ma), (Fig. 4g); metamorphic zircon in Cabeço da Moura amphibolite (539 ± 3 Ma), (Fig. 4i) and metamorphic titanite in Vila Nova amphibolite (529 ± 5 Ma), (Fig. 4j). *P-T* thermodynamic modelling for the Sardoal Complex amphibolite ($P=7-8$ kb, $T=640-660^\circ\text{C}$) (Fig. 7) indicates metamorphism in amphibolite facies conditions, near the transition to the granulite facies. Felsic migmatites in the Sardoal Complex indicate crustal anatexis, generated by high-temperatures. Thermal models for active continental margins indicate that fluids ascending from the subducted oceanic crust are released into the mantle wedge where they lower the solidus and promote partial melting (Wilson, 1989). These data suggest subduction of oceanic crust beneath the Northern margin of Gondwana, followed by continental collision of the Ossa Morena Zone with the Iberian Autochthon passive margin (future Central Iberian Zone) and possibly accretion of an island arc, at ca. 540 Ma.

A second metamorphic event is recognized in Ordovician rocks. According to thermodynamic modelling and mineralogy, they were metamorphosed at amphibolite facies conditions:

protomylonite trondhjemite ($P=4.5\text{--}6.2$ kb and $590\text{--}650^\circ$) and garnet amphibolite (6.5 kb and 550° C) (Henriques et al., 2013). In this study it was not possible to determine the age of the metamorphic event, but it is certainly younger than ca. 477 Ma. The presence of metatextitic and diatextitic structures associated with the garnet amphibolite suggests the existence of a high-temperature metamorphic event.

8. Summary and conclusions

The geochronological results are consistent with Neoproterozoic arc magmatism at the Ossa Morena Zone (Figs. 9, 10), generated in different stages of the arc evolution. Island arc magmatism was accompanied by deposition of fine-grained sediments in a Neoproterozoic basin, indicated by the Série Negra succession. The data indicate the existence of an important multistage Cadomian magmatic period at ca. 692 to 544 Ma, in the Ossa Morena Zone (Figs. 9, 10). The age of $692 \pm 77/-60$ Ma is the oldest documented event of arc magmatism in the Ossa Morena Zone. Another age related to the early arc related magmatism (623 ± 3 Ma) has been published by Sánchez-García et al., 2007. In Cadomia this activity began at ca. 755 Ma (e.g. Nance et al., 2008 and references therein). An early phase of Avalonian arc-related magmatism in Newfoundland (ca. 690–670 Ma; e.g. O'Brien, et al., 1996; Valverde-Vaquero et al., 2006) is coeval with the oldest magmatic event of the Ossa Morena Zone. The igneous crystallization age of the Carvalhal orthogneiss (ca. 569 Ma) can be correlated with a second major period of intermediate to granitic magmatism in Cadomia (ca. 580–570 Ma; e.g. Inglis et al., 2004). The last episode of Cadomian magmatic activity (ca. 548 Ma and ca. 544 Ma) involved partial melting of continental crust and mantle and represents the final phase of arc magmatism in the area. The granitoid rocks generated during the Cadomian arc magmatism have lower εNd_t values than the early rift-related granitoids observed in other areas of the

Ossa Morena Zone. The development of the Cadomian arc was accompanied by the formation of a back arc basin, where the deposition of the Série Negra occurred (e.g. Linnemann et al., 2008) (Figs. 9, 10). New *P-T* thermodynamic modelling and U-Pb ages indicate the occurrence of a major medium/high grade metamorphism at ca. 540 Ma, interpreted to represent the continental collision of the Ossa Morena Zone with the Iberian Autochthon passive margin (future Central Iberian Zone) and possibly accretion of an island arc. Although, the continental arc accretion has already previously been considered to have occurred close to the Neoproterozoic-Cambrian boundary (e.g. Sánchez-García et al., 2008 and references therein), the new results constrain significantly the timing of the continental arc collision. In the study area, there is no record of the Cambrian rifting that precedes the opening of Rheic Ocean, when the peri-Gondwanan terranes (e.g. Avalonia) drifted from the northern margin of Gondwana (e.g. Murphy et al., 2009). However, rift related magmatic events (bimodal magmatism) were described at Northeast Alentejo in lower Cambrian (e.g. Mata and Munhá, 1990; Ribeiro et al., 1992) and elsewhere in the Ossa Morena Zone (e.g. Sánchez-García et al., 2008; 2010; 2014). The exhumation of relatively deep crustal segments in the study area might prevent the preservation of the volcanic rift related rocks. The Early Ordovician rocks (ca. 483-477 Ma) display field relationships, textures and isotopic compositions different from those of the host rocks and from the chronologically equivalents described in literature and attributed to intracontinental rifting (e.g. Solá et al., 2008). The primitive signature of the Early Ordovician rocks and their juvenile character suggests that they were generated by processes of mantle melting related to the opening of Rheic Ocean (Fig. 10). The latter was consumed in the Carboniferous during the collision between Laurussia and Gondwana that led to the Variscan orogeny (e.g. Murphy et al., 2009).

Acknowledgments

This study was financially supported by a PhD grant (SFRH/BD/28720/2006) from the Portuguese Foundation for Science given to S.B.A. Henriques. We are grateful to LNEG (Laboratório Nacional de Energia e Geologia, Portugal) where the research was carried out; the Geosciences Centre from Coimbra University, which provided the financial support for the execution of the fieldwork; Ms. Sherri Strong, for technical assistance with U-Pb and tracer Nd and Sr isotopic analyses in the laboratory at Memorial University; Dr. Alain Potrel for assistance with some of the Nd and Sr isotopic analyses; Eng. Fernanda Guimarães (LNEG) and Eng. Miguel Fernández González (Oviedo University) for their technical assistance with the microprobe analyses. SBAH is grateful to Jaime Henriques for sample collecting. We are grateful to Dr. Cecilio Quesada, Prof. Fernando Corfu and Dr. Nelson Eby for their careful reviews and constructive suggestions that greatly improve the quality of our manuscript.

References

- Alía, M., 1963. Rasgos estructurales de la baja Extremadura. Boletín Real Sociedad Española Historia Natural (Geología) 20, 247–262.
- Arenas, R., Martínez Catalán, J.R., Sánchez Martínez, S., Fernández-Suárez, J., Andonaegui, P., Pearce, J.A., Corfu, F., 2007. The Vila de Cruces Ophiolite: a remnant of the early Rheic Ocean in the Variscan suture of Galicia (northwest Iberian Massif). The Journal of Geology 115, 129–148.
- Arndt, N.T., Goldstein, S.L., 1987. Use and abuse of crust-formation ages. Geology 15, 893-895.

651

652 Anderson, D.J., Lindsley, D.H. ,1988. Internally consistent solution models for Fe-Mg-Mn-Ti oxides -
 653 Fe-Ti oxides. *American Mineralogist* 73, 714–726.

654

655 Bea, F., Montero, P., Talavera, C., Abu Anbar, M., Scarrow, J.H., Molina, J.F. and Moreno, J.A.,
 656 2010. The paleogeographic position of Central Iberia in Gondwana during the Ordovician: evidence
 657 from zircon chronology and Nd isotopes. *Terra Nova* 22, 341–346.

658

659 Beccaluva, L., Bianchini, G., Bonadiman, C., Siena, F., Vaccaro, C., 2004. Coexisting anorogenic and
 660 subduction-related metasomatism in mantle xenoliths from the Betic Cordillera (southern Spain).
 661 *Lithos* 75, 67–87.

662

663 Bucher, K., Frey, M., 2002. *Petrogenesis of Metamorphic Rocks*, seventh ed., Springer, Heidelberg,
 664 341 pp.

665

666 Cameron, A.E., Smith, D.H., Walker, R.L., 1969. Mass spectrometry of nanogram-size samples of
 667 lead. *Analytical Chemistry* 41, 525–526.

668

669 Carvalhosa, A., 1965. Contribuição para o conhecimento geológico da região entre Portel e Ficalho
 670 (Alentejo). *Memórias dos Serviços Geológicos de Portugal* 11, 130 pp.

671

672 Conde, L.E.N., 1984. Excursão geológica na região de Ferreira do Zêzêre-Abrantes, in: *Museu e*
 673 *Laboratório Mineralógico e Geológico da Universidade de Coimbra (Eds.), Livro-Guia das Excursões*
 674 *da VI Reunião do Grupo Ossa-Morena*, 8 pp.

675

676 Connolly, J.A.D., 2009. The geodynamic equation of state: what and how. *Geochemistry, Geophysics,*
 677 *Geosystems* 10, Q10014.

678

Dale, J., Powell, R., White, R., Elmer, F.L., Holland, T.J.B., 2005. A thermodynamic model for Ca–Na clinoamphiboles in Na_2O – CaO – FeO – MgO – Al_2O_3 – SiO_2 – H_2O – O for petrological calculations. *Journal of Metamorphic Geology* 23, 771–791.

Davis, D.W., 1982. Optimum linear regression and error estimation applied to U–Pb data. *Canadian Journal of Earth Sciences* 19, 2142–2149.

DePaolo, D.J., 1981a. A neodymium and strontium isotopic study of the Mesozoic calc–alkaline granitic batholiths of the Sierra Nevada and Peninsular Ranges, California. *Journal of Geophysical Research* 86, 10470–10488.

DePaolo, D.J., 1981b. Neodymium isotopes in the Colorado front Range and crust-mantle evolution in the Proterozoic. *Nature* 291, 193–196.

Downes, H., Duthou, J.L., 1988. Isotopic and trace element arguments for the lower-crustal origin of Hercynian granitoids and pre-Hercynian orthogneisses, Massif Central (France). *Chemical Geology* 68, 291–308.

Eguíluz, L., 1987. Petrogénesis de rocas ígneas y metamórficas en el antiformal de Burguillos-Monesterio (Macizo Ibérico Meridional). Ph. D. Thesis, Univ. País Vasco, 456 pp.

Eguíluz, L., Ábalos, B., 1992. Tectonic setting of Cadomian low-pressure metamorphism in the central Ossa-Morena Zone (Iberian Massif, SW Spain). *Precambrian Research* 56, 113–137.

Eguíluz, L., Ibarguchi, J.I.G., Ábalos, B., 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* 112, 1398–1413.

Fernández-Suárez, J., Gutiérrez-Alonso, G., 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* 204, 75–88.

Gorton, M.P., Schandl, E.S., 2000. From continents to island arcs: a geochemical index of tectonic setting for arc-related and within-plate felsic to intermediate volcanic rocks. *The Canadian Mineralogist* 38, 1065–1073.

Green E., Holland T., Powell, R., 2007. An order-disorder model for omphacitic pyroxenes in the system jadeite-diopside-hedenbergite-acmite, with applications to eclogitic rocks. *American Mineralogist* 92, 1181–1189.

Henriques, S.B.A., 2013. Magmatitos e metamorfitos de alto grau no contacto entre as zonas de Ossa Morena e Centro Ibérica: significado geodinâmico. Unpublished PhD thesis, Universidade de Coimbra, Portugal, 249 pp.

Henriques, S.B.A., Neiva, A.M.R., Ribeiro, M.L., Dunning, G.R., 2010a. Geochemistry and geochronology of a Precambrian active continental margin at the boundary between the Ossa Morena Zone and the Central Iberian Zone, Central Portugal. *Goldschmidt Conference Abstracts. Geochimica et Cosmochimica Acta* 74, Supplement 1, A400.

Henriques, S.B.A., Neiva, A.M.R., Ribeiro, M.L., Dunning, G.R., 2010b. Island-Arc signature in amphibolites from the boundary between the Ossa Morena Zone and the Central Iberian Zone in Central Portugal. 20th General Meeting of the International Mineralogical Association. *Acta Mineralogica-Petrographica Abstract Series* 6, 592. World Wide Web Address: http://www.ima2010.hu/img/doc/ima2010_abstracts.pdf.

Henriques S., Ribeiro M. L., Moreira M. E., 2006. Caracterização petrográfica e geoquímica dos magmatitos da região do Sardoal (Abrantes) e seu enquadramento geodinâmico. *Comunicações geológicas INETI* 93, 5–21.

Henriques, S.B.A., Ribeiro, M.L., Neiva, A.M.R., Dunning, G.R., Tajcmanova, L., 2013. P-T Evolution of Neoproterozoic and Ordovician Metamorphic Rocks in the Iberian Massif, Central Portugal. *Goldschmidt Conference Abstracts. Mineralogical Magazine* 77, 1287.

Holland, T.J.B., Powell, R., 1996. Thermodynamics of order-disorder in minerals. 2. Symmetric formalism applied to solid solutions. *American Mineralogist* 81, 1425–1437.

Holland, T.J.B., Powell, R., 1998. An internally consistent thermodynamic data set for phases of petrological interest. *Journal of Metamorphic Geology* 16, 309–343.

Hoskin, P.W.O., 2000. Patterns of chaos: fractal statistics and the oscillatory chemistry of zircon. *Geochimica et Cosmochimica Acta* 64, 1905–1923.

Hoskin, P.W.O., Schaltegger, U., 2003. The composition of zircon and igneous and metamorphic petrogenesis, in: Hanchar, J.M., Hoskin, P.W.O. (Eds.), *Zircon*. Mineralogical Society of America, *Reviews in Mineralogy and Geochemistry* 53, pp. 27–62.

Inglis, J.D., Samson, S.D., D’Lemos, R.S., Hamilton, M., 2004. U–Pb geochronological constraints on the tectonothermal evolution of the Paleoproterozoic basement of Cadomia, La Hague, NW France. *Precambrian Research* 134, 293–315.

Jaffey, A.H., Diamond, H., Bentley, W.C., Flynn, K.F., Rokop, D.J., Essling, A.M., Williams, J., 1977. Half-life of ^{239}Pu by two independent methods. *Physical Review C* 16, 354–369.

762 Julivert, M., Fontboté, J.M., Ribeiro, A., Conde, L., 1972. Mapa tectónico de la Península Ibérica y
 763 Baleares, E: 1:1,000,000. Instituto Geológico y Minero de España, Madrid.
 764
 765 Krogh, T.E., 1973. A low contamination method hydrothermal decomposition of zircon and extraction
 766 of U and Pb for isotopic age determinations. *Geochimica et Cosmochimica Acta* 37, 485–494.
 767
 768 Krogh, T.E., 1982. Improved accuracy of U–Pb zircon ages by the creation of more concordant
 769 systems using an air abrasion technique. *Geochimica et Cosmochimica Acta* 46, 637–649.
 770
 771 Linnemann, U., McNaughton, N.J., Romer, R.L., Gehmlich, M., Drost, K., Tonk, Ch., 2004. West
 772 African provenance for Saxo-Thuringia (Bohemian Massif): Did Armorica ever leave pre-Pangean
 773 Gondwana? U/Pb-SHRIMP zircon evidence and the Nd-isotopic record. *International Journal of Earth*
 774 *Sciences* 93, 683–705.
 775
 776 Linnemann, U., Pereira, M.F., Jeffries, T.E., Drost, K., Gerdes, A., 2008. The Cadomian Orogeny and
 777 the opening of the Rheic Ocean: The diachrony of geotectonic processes constrained by LA-ICP-MS
 778 U–Pb zircon dating (Ossa-Morena and Saxo-Thuringian Zones, Iberian and Bohemian Massifs).
 779 *Tectonophysics* 461, 21–43.
 780
 781 López-Guijarro, R., Armendáriz, M., Quesada, C., Fernández-Suárez, J., Murphy, J.B., Pin, C.,
 782 Bellido, F., 2008. Ediacaran–Palaeozoic tectonic evolution of the Ossa Morena and Central Iberian
 783 zones (SW Iberia) as revealed by Sm–Nd isotope systematics. *Tectonophysics* 461, 202–214.
 784
 785 Lotze, F., 1945. Zur Gliederung der Varisciden der Iberischen Mesetas. *Geotect Forsch* 6, 78–92.
 786 Traducción española por Ríos, J.M. 1950. Observaciones respecto a la división de las Variscides de la
 787 Meseta Ibérica. *Publicaciones extranjeras sobre geología de España* 5, 149–166.
 788

789 Ludwig, K.R. 2003. ISOPLOT 3.00: A geochronological Toolkit for Microsoft Excel. Berkeley
790 Geochronology Center Special Publication 4, 70 pp.
791

792 MacPherson, J., 1878. Sobre la existencia de la fauna primordial en la provincia de Sevilla. Anales de
793 la Sociedad Española de Historia Natural 7, 281–284.
794

795 Manhés, G., Minster, J.F., Allégre, C.J., 1978. Comparative U-Th-Pb and Rb-Sr study of the Saint
796 Séverin amphibolite: consequence for early solar system chronology. Earth and Planetary Science
797 Letters 39, 14–24.
798

799 Mata, J., Munhá, J., 1990. Magmatogénese de metavulcanitos câmbricos do Nordeste Alentejano: os
800 estádios iniciais de *rifting* continental. Comunicações dos Serviços Geológicos de Portugal 76, 61–89.
801

802 Mattinson, J.M., 2005. Zircon U–Pb chemical-abrasion (CA-TIMS) method: combined annealing and
803 multi-step dissolution analysis for improved precision and accuracy of zircon ages. Chemical Geology
804 220, 47–66.
805

806 McCann, T., 2008. Introduction and overview, in: McCann, T. (Ed.), The Geology of central Europe:
807 Precambrian and Paleozoic. Geological Society, London, pp. 1–20.
808

809 Murphy, J.B., Nance, R.D., 2002. Sm–Nd isotopic systematics as tectonic tracers: an example from
810 West Avalonia in the Canadian Appalachians. Earth-Science Reviews 59, 77–100.
811

812 Murphy, J.B., Pisarevsky, S.A., Nance, R.D., Keppie, J.D., 2004. Neoproterozoic–Early Paleozoic
813 evolution of peri-Gondwanan terranes: implications for Laurentia–Gondwana connections.
814 International Journal of Earth Sciences 93, 659–682.
815

816 Murphy, J.B., Gutiérrez-Alonso, G., Nance, R.D., Fernández-Suárez, J., Keppie, J.D., Quesada, C.,
817 Strachan, R.A., Dostal, J., 2006. Origin of the Rheic Ocean: Rifting along a Neoproterozoic suture?
818 *Geology* 34, 325–328.

819

820 Murphy, J.B., Gutiérrez-Alonso, G., Nance, R.D., Fernández-Suárez, J., Keppie, J.D., Quesada C.,
821 Dostal, J.A., Braid, J., 2009. Rheic Ocean mafic complexes: overview and synthesis, in: Murphy J.B.,
822 Keppie, J.D., Hynes, A.J. (Eds.), *Ancient Orogens and Modern Analogues*. Geological Society,
823 London, Special Publications 327, pp. 343–369.

824

825 Nance, R.D., Murphy, J.B., Strachan, R.A., Keppie, J.D., Gutiérrez-Alonso, G., Fernández-Suárez, J.,
826 Quesada, C., Linnemann, U., D’Lemos, R., Pisarevsky, S.A., 2008. Neoproterozoic–early Palaeozoic
827 tectonostratigraphy and palaeogeography of the peri-Gondwanan terranes Amazonian v. West African
828 connections, in: Ennih N., Liégeois J.P. (Eds.), *The Boundaries of the West African Craton*.
829 Geological Society, London, Special Publications 297, pp. 345–383.

830

831 Newton, R.C., Charlú, T.V., Kleppa, O.J., 1980. Thermochemistry of the high structural state
832 plagioclases. *Geochimica Cosmochimica Acta* 44, 933–941.

833

834 O’Brien, S.J., O’Brien, B.H., Dunning, G.R., Tucker, R.D., 1996. Late Neoproterozoic Avalonian and
835 related peri-Gondwanan rocks of the Newfoundland Appalachians, in: Nance, R.D., Thompson, M.A.,
836 (Eds.), *Avalonian and Related Peri-Gondwanan Terranes of the Circum-North Atlantic*. Geological
837 Society of America, Special Papers, 304, pp. 9–28.

838

839 Parrish, R., 1990. U-Pb dating of monazite and its application to geological problems. *Canadian*
840 *Journal of Earth Sciences* 17, 1431–1450.

841

842 Parrish, R.R., Krogh, T.E., 1987. Synthesis and purification of ^{205}Pb for U-Pb for geochronology.
843 *Chemical Geology* 66, 103–110.

844

845 Pearce, J.A., 1983. Role of the sub-continental lithosphere in magma genesis at active continental
846 margins, in: Hawkesworth, C.J., Norry, M.J., (Eds.), *Continental basalts and mantle xenoliths*, Shiva,
847 Nantwich, Cheshire, U.K., pp. 230–249.

848

849 Pedro, J.C., Araújo, A., Fonseca, P.E., Tassinari, C., Ribeiro, A., 2010. Geochemistry and U-Pb zircon
850 age of the Internal Ossa-Morena Zone Ophiolite Sequences: a remnant of Rheic Ocean in SW Iberia.
851 *Ofioliti* 35(2), 117–130.

852

853 Pereira, M.F., Chichorro, M., Linnemann, U., Eguíluz, L., Silva, J.B., 2006. Inherited arc signature in
854 Ediacaran and Early Cambrian basins of the Ossa-Morena Zone (Iberian Massif, Portugal):
855 paleogeographic link with European and North African Cadomian correlatives. *Precambrian Research*
856 144, 297–315.

857

858 Pereira, E., Romão, J., Conde, L., 1998. Geologia da Transversal de Tomar-Mação Sutura entre a
859 Zona Centro Ibérica (ZCI) e a Zona de Ossa-Morena (ZOM), in: Oliveira, J.T., Pereira, R., (Eds.),
860 *Livro guia das excursões do V Congresso Nacional de Geologia*. Instituto Geológico e Mineiro, pp.
861 159–188.

862

863 Quesada, C., Munhá, J., 1990. Metamorphism in the Ossa-Morena Zone, in: Dallmeyer, R.D.,
864 Martínez-García, E. (Eds.), *Pre-Mesozoic Geology of Iberia*. Springer-Verlag, Heidelberg, pp. 314–
865 320.

866

867 Quesada, C., 1990a. Precambrian terranes in the Iberian Variscan foldbelt, in: Strachan, R.A., Taylor,
868 G.K. (Eds.), *Avalonian and Cadomian Geology of the North Atlantic*. Blackie and Sons, Oxford, pp.
869 109–133.

870

871 Quesada, C., 1990b. Precambrian successions in SW Iberia: their relationships to Cadomian orogenic
872 events, in: D'Lemos, R.S., Strachan, R.A., Topley, C.G. (Eds.), The Cadomian Orogeny. Geological
873 Society of London, Special Publication 51, pp. 353–362.

874

875 Quesada, C., 1997. Evolución geodinámica de la Zona Ossa Morena durante el ciclo Cadomiense.,in:
876 Araújo, A.A., Pereira, M.F. (Eds.), Estudo sobre a geologia da zona de Ossa Morena (Maciço Ibérico).
877 Livro homenagem Prof. Francisco Gonçalves, University of Évora, pp. 205–230.

878

879 Quesada, C., 2006. The Ossa Morena Zone of the Iberian Massif: a tectonostratigraphic approach to its
880 evolution. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften* 157(4), 585–595.

881

882 Ribeiro, A., Quesada, C., Dallmeyer, R.D., 1990. Geodynamic evolution of the Iberian Massif, in:
883 Dallmeyer R.D., Martínez-García E. (Eds.), Pre-Mesozoic Geology of Iberia. Springer-Verlag,
884 Heidelberg, pp. 397–410.

885

886 Ribeiro, A., Munhá, J., Mateus, A., Fonseca, P. E., Noronha, F., Romão, J., Rodrigues, J., Castro, P.,
887 Meireles, C., Ferreira, N., 2009. Mechanics of thick-skinned Variscan overprinting of Cadomian
888 basement (Iberian Variscides). *Comptes Rendus Geoscience* 341, 127–139.

889

890 Ribeiro, A., Munhá, J., Fonseca, P.E., Araújo, A., Pedro, J.C., Mateus, A., Tassinari, C., Machado, G.,
891 Jesus, A., 2010a. Variscan ophiolite belts in the Ossa-Morena Zone (Southwest Iberia): geological
892 characterization and geodynamic significance. *Gondwana Research* 17, 408–421.

893

894 Ribeiro A., Romão, J., Henriques, S., Dunning, G., Ribeiro, L., Neiva A., Munhá, J., Pereira, E.,
895 Castro, P., 2010b. Thick-skinned inter-plate and intra-plate tectonics in NW and SW Iberia. VIII
896 Congresso Nacional de Geologia. *e-Terra* 11. World Wide Web Address:
897 <http://metododirecto.pt/CNG2010/index.php/vol/article/view/194/232>.

898

899 Ribeiro, A., 2013. Evolução geodinâmica de Portugal; os ciclos ante-mesozóicos, in: Dias R., Araújo,
900 A., Terrinha, P., Kullberg, J. (Eds.), Geologia de Portugal, Vol. I. Escolar Editora, pp. 15–57.
901

902 Ribeiro, A., Romão, J., Munhá, J., Rodrigues, J. F., Pereira, E., Mateus, A., Araújo, A., Dias, R., 2013.
903 Relações tectono-estratigráficas e fronteiras entre as Zonas Centro-Ibérica e Ossa-Morena do Terreno
904 Ibérico e o Terreno Finisterra, in: Dias R., Araújo A., Terrinha P., Kullberg, J. (Eds.), Geologia de
905 Portugal, Vol. I. Escolar Editora, pp. 439–481.
906

907 Ribeiro, M.L., Mata, J., Piçarra, J.M., 1992. Vulcanismo bimodal da região de Ficalho: características
908 geoquímicas. Comunicações dos Serviços Geológicos de Portugal 78(2), 75–85.
909

910 Ribeiro, M. L., Palácios, T., Munhá, J., 1995. Aspectos petrológicos-geoquímicos do Complexo
911 eruptivo de Mouríscas (Abrantes). Resumo alargado, IV Congressso Nacional de Geologia. Memórias
912 do Museu do Laboratório Mineralógico e Geológico da Faculdade de Ciências da Universidade do
913 Porto 4, 805–807.
914

915 Ribeiro, M. L., Pereira, F., Solá, A. R., 2003. O ciclo cadominano na ZOM: evidências geoquímicas.
916 Resumo: IV Congresso Ibérico de Geoquímica, XIII Semana de Geoquímica, Coimbra, 69–71.
917

918 Rollinson, H.R., 1993. Using geochemical data: evaluation, presentation, interpretation. Longman,
919 Harlow, 352 pp.
920

921 Romão, J., Esperancinha, A., 2000. Carta Geológica de Portugal, escala 1: 50 000, Folha 28–A
922 (Mação). Instituto Geológico e Mineiro, Portugal.
923

924 Romão, J., 2006. Notícia explicativa da Carta Geológica de Portugal à escala 1: 50 000, Folha 28-A
925 (Mação), Instituto Nacional de Engenharia Tecnologia e Inovação, Portugal, 77 pp.
926

927 Sánchez-García, T., Quesada, C., Dunning, G.R., Perejón, A., Bellido, F., Moreno-Eiris, E., 2007.
 928 New geochronological and geochemical data of the Loma del Aire Unit, Ossa- Morena Zone. IGCP
 929 497-Galicia Meeting 2007. Publicaciones del IGME, pp. 164–165.
 930
 931 Sánchez-García, T., Quesada, C., Bellido, F., Dunning, G.R., González del Tánago, J., 2008. Two-step
 932 magma flooding of the upper crust during rifting: the Early Paleozoic of the Ossa Morena Zone (SW
 933 Iberia). *Tectonophysics* 461, 72–90.
 934
 935 Sánchez-García, T., Bellido, F., Pereira, M.F., Chichorro, M., Quesada, C., Pin, Ch. & Silva, J.B.
 936 2010. Rift-related volcanism predating the birth of the Rheic Ocean (Ossa-Morena zone, SW Iberia).
 937 *Gondwana Research* 17, 392–407.
 938
 939 Sánchez-García, T., Pereira, M.F., Bellido, F., Chichorro, M., Silva, J.B., Valverde-Vaquero, P., Pin,
 940 Ch., Solá, A.R., 2014. Early Cambrian granitoids of North Gondwana margin in the transition from a
 941 convergent setting to intra-continental rifting (Ossa-Morena Zone, SW Iberia). *International Journal of*
 942 *Earth Sciences* 103, 1203–1218.
 943
 944 Samson, S.D., D’Lemos, R.S., Blichert-Toft, J., Vervoort, J., 2003. U-Pb geochronology and Hf-Nd
 945 isotope compositions of the oldest Neoproterozoic crust within the Cadomian orogen: New evidence
 946 for a unique juvenile terrane. *Earth and Planetary Science Letters* 208, 165–180.
 947
 948 Schärer, U., 1984. The effect of initial ^{230}Th disequilibrium on young U–Pb ages: the Makalu case,
 949 Himalaya. *Earth and Planetary Science Letters* 67, 191–204.
 950
 951 Siivola, J., Schmid, R., 2007. List of mineral abbreviations, in: Fettes, D., Desmons, J. (Eds.),
 952 *Metamorphic Rocks: A classification and Glossary of Terms, Recommendations of the International*
 953 *Union of Geological Sciences, Subcommittee on the Systematics of Metamorphic Rocks*. Cambridge
 954 University Press, New York, pp. 93–110.

955

956 Solá, A.R., 2007. Relações Petrogeoquímicas dos Maciços Graníticos do NE Alentejano. Unpublished
 957 PhD thesis, University of Coimbra, Portugal, 405 pp.

958

959 Solá, A. R., Pereira, M. F., Ribeiro, M. L., Neiva, A. M. R., Williams, I. S., Montero, P., Bea, F.,
 960 Zinger, T., 2008. New insights from zircon ages on the Lower Ordovician magmatism of the northern
 961 Gondwana margin: the Urro Formation (SW Iberian Massif, Portugal). *Tectonophysics* 461, 114–129.

962

963 Stacey, J.S., Kramers, J.D., 1975. Approximation of terrestrial lead isotope evolution by a two-stage
 964 model. *Earth and Planetary Science Letters* 34, 207-226.

965

966 Steiger, R.H., Jäger, E., 1977. Subcomission on geochronology: convention on the use of decay
 967 constants in geo-and cosmochemistry. *Earth and Planetary Science Letters* 36, 359-362.

968

969 Tanaka, T., Togashi, S., Kamioka, H., Amakawa, H., Kagami, H., Hamamoto, T., Yuhara, M.,
 970 Orihashi, T., Yoneda, S., Shimizu, H., Kunimaru, T., Takahashi, K., Yanagi, T., Nakano, T., Fujimaki,
 971 H., Shinjo, R., Asahara, Y., Tanimizu, M., Dragusanu, C., 2000. JNdi-1: a neodymium isotopic
 972 reference in consistency with LaJolla neodymium. *Chemical Geology* 168, 279-81.

973

974 Teixeira, C., 1981. *Geologia de Portugal: Precâmbrico-Paleozóico*. Fundação Calouste Gulbenkian,
 975 Lisboa, 630 pp.

976

977 Turpin, L., Cuney, M., Friedrich, M., Bouchez, J.L., Aubertin, M., 1990. Meta-igneous origin of
 978 Hercynian peraluminous granites in the NW French Massif Central: implications for crustal history
 979 reconstructions. *Contributions to Mineralogy and Petrology* 118, 13–32.

980

981 Valverde-Vaquero, P., Dunning, G.R., O'Brien, S.J., 2006. Polycyclic evolution of the Late
 982 Neoproterozoic basement in the Hermitage Flexure region (southwest Newfoundland Appalachians):
 983 New evidence from the Cinq-Cerf gneiss. *Precambrian Research* 148, 1–18.
 984

985 Villaseca, C., Barbero, L., Rogers, G., 1998. Crystal origin of Hercynian peraluminous granitic
 986 batholiths of Central Spain: petrological, geochemical and isotopic (Sr, Nd) constraints. *Lithos* 43, 55–
 987 79.
 988

989 Villaseca, C., Orejana, D., Pin, C., López García, J.A., Andonaegui, P., 2004. Le magmatisme basique
 990 hercynien et post-hercynien du Système Central Espagnol: essai de caractérisation des sources
 991 mantelliques. *Comptes Rendus Géosciences* 336, 877–888.
 992

993 Villaseca, C., Belousova, E., Orejana, D., Castiñeiras, P., Pérez-Soba, C., 2011. Presence of
 994 Palaeoproterozoic and Archean components in the granulite-facies rocks of central Iberia: The Hf
 995 isotopic evidence. *Precambrian Research* 187, 143–154.
 996

997 Wilson, M., 1989. *Igneous Petrogenesis*. Unwin Hyman, London, 466 pp.
 998

999 Wood, D.A., 1980. The application of a Th–Hf–Ta diagram to problems of tectonomagmatic
 1000 classification and to establishing the nature of crustal contamination of basaltic lavas of the British
 1001 Tertiary volcanic province. *Earth and Planetary Science Letters* 50, 11–30.
 1002

1003 Zbyszewski, G., Ribeiro, O., Gonçalves, F., Carvalhosa, A., 1983. *Carta Geológica de Portugal, escala*
 1004 *1: 50 000, Folha 28-C (Gavião), Serviços Geológicos de Portugal. Serviços Geológicos de Portugal.*
 1005

1006 Zbyszewski, G., Carvalhosa, A., Gonçalves, F., 1981. *Notícia explicativa da Carta geológica de*
 1007 *Portugal à escala 1: 50 000, Folha 28-C (Gavião). Serviços Geológicos de Portugal, 50 pp.*

Fig. 1. (a) Subdivision of the Iberian Massif after Ribeiro (2013) and location of the studied area. (b) Geological map adapted from Zbyszewski et al. (1983), Conde (1984) and Romão and Esperancinha (2000). Thrust faults after Ribeiro et al. (2013). Projection system: ETRS_1989_Portugal_TM06. (c) SW-NE general cross section of Alvrangel - Olalhas area after Conde (1984).

Fig. 2. Field and petrographic features of the studied rocks. (a) Porphyroclastic texture, mylonitic fabric and ribbon quartz, observed in orthogneiss (Sardoal Complex). (b) Banded structure of Carvalhal orthogneiss (Sardoal Complex). (c) Stromatic migmatite (Sardoal Complex). (d) Muscovite overgrowing sillimanite, observed in Sardoal orthogneiss (Sardoal Complex). (e) Relict staurolite inclusion in muscovite, observed in Olalhas orthogneiss (Sardoal Complex). (f) Granofelsic texture of Mouriscas Complex amphibolite. (g) Porphyroclastic texture and mylonitic fabric observed in amphibolite (Mouriscas Complex). (h) Garnet amphibolite large garnet grains surrounded by light-colored halos (Mouriscas Complex). (Mg-Hbl-Magnesium hornblende; Ms-muscovite; Qtz-quartz; Sil-sillimanite; St-staurolite; Pl-plagioclase).

Fig. 3. Zircon cathodo-luminescence images of the studied samples.

Fig. 4. U-Pb Concordia diagram for samples from Sardoal Complex. Error ellipses are plotted with 2σ uncertainties. M-monazite, T-titanite, Z-zircon.

Fig. 5. U-Pb Concordia diagram for samples from Mouriscas Complex. Error ellipses are plotted with 2σ uncertainties. M-monazite, Z-zircon.

Fig. 6. ϵNd_t vs. $(^{87}\text{Sr}/^{86}\text{Sr})_i$ plot for the studied samples. Fields for MORB from Wilson (1989), lithospheric mantle from Beccaluva et al. (2004) in Villaseca et al. (2004), mantle array from Rollinson (1993), for meta-igneous and metasedimentary middle-upper crust and metasedimentary lower crust from Turpin et al. (1990), Downes and Duthou (1988) in Villaseca et al. (1998). The fields were corrected for the Early Palaeozoic.

Fig. 7. (a, b) P - T diagram for sample 311-1, Cabeço da Moura amphibolite (Sardoal Complex), calculated in NCFMASHTO system. The ellipse represents the estimated P - T conditions in the observed stability field.

Fig. 8. ϵNd_t vs. time (Ga) diagram for the Neoproterozoic rocks in this study (after Murphy et al. 2006; Murphy and Nance 2002). Sm-Nd isotopic data for Armorican rocks are from Samson et al. (2003); Avalonian and Cadomian rocks from Murphy and Nance (2002 and references therein); Saxo-Thuringian rocks (Bohemian Massif) from Linnemann et al. (2004). Depleted mantle curve is from DePaolo (1981b). CHUR: chondrite uniform reservoir.

Fig. 9. Global paleocontinental reconstruction from the Late Neoproterozoic and schematic representation of the island-arc, Ossa Morena Zone (OMZ) and other Cadomian-type terranes: Armorican Massif (AM) and Saxo-Thuringian Zone (SXZ). Modified from Linnemann et al. (2008), McCann 2008 and Nance et al. 2008.

Fig. 10. Schematic representation of the main magmatic and tectonometamorphic events. Cross-sections of island-arc (I) and active continental margin (II) are based on cross-sections from Wilson (1989). OMZ-Ossa Morena Zone; CIZ-central Iberian Zone.

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Fig. 9

I) Deposition of fine-grained sediments on a Neoproterozoic basin with evidence of an island arc, Cryogenian? - Ediacaran.

II) Development of the Cadomian arc with formation of a back-arc basin (ca. 692 - 544 Ma; Cryogenian - Ediacaran).

III) Continental collision of the Ossa Morena Zone (OMZ) with the Iberian autochthon (ca. 540 Ma).

IV) Intrusion of depleted mantle magmas at the Tomar-Badajoz-Córdoba shear zone (TBCSZ) in the Early Ordovician (ca. 483-477 Ma).

Fig. 10

Table 1a U - Pb isotopic data for zircon, monazite and titanite of the rocks from Sardoal Complex, Central Portugal.

Fraction	Concentration			Measured		Corrected Atomic Ratios*						Age Ma			
	Weight (mg)	U	Pb	Total	²⁰⁶ Pb	²⁰⁸ Pb	²⁰⁶ Pb	²⁰⁷ Pb	²⁰⁷ Pb	²⁰⁶ Pb	²⁰⁷ Pb	²⁰⁷ Pb			
		(ppm)	rad (ppm)	common Pb(pg)	²⁰⁴ Pb	²⁰⁶ Pb	²³⁸ U	2σ	²³⁵ U	2σ	²⁰⁶ Pb	2σ	²³⁸ U	²³⁵ U	²⁰⁶ Pb
Quartzo-feldspathic schist (321-140) (39°34'28.66"N, 8°16'2.44"W)															
Z1 2 lrg clr euh prm	0.002	756	75.0	5.5	1748	0.0860	0.10058	66	0.8457	50	0.06098	32	618	622	638
Z2 1 lrg clr euh prm	0.001	936	87.0	5.8	972	0.0778	0.09509	56	0.7839	52	0.05979	26	586	588	596
Z3 1 lrg clr euh prm	0.001	1061	92.5	4.7	1285	0.0666	0.09008	42	0.7316	32	0.05890	18	556	557	563
Z4 2 lrg clr euh prm	0.002	615	98.6	4.7	2530	0.0953	0.15452	72	2.3724	114	0.11135	16	926	1234	1822
Z5 1 euh prm	0.002	172	38.5	1.3	3607	0.0803	0.21161	82	4.4025	170	0.15089	34	1237	1713	2356
Z6 1 euh prm	0.002	422	38.2	4.2	1179	0.0739	0.09293	96	0.7561	84	0.05901	50	573	572	568
Z7 2 euh prm	0.004	63	6.0	1.8	855	0.0947	0.09591	80	0.7849	82	0.05935	60	590	588	580
Z8 1 clr euh prm	0.001	781	75.7	7.4	667	0.0832	0.09868	70	0.8157	86	0.05995	54	607	606	602
M1 1 flat euh med yel A	0.001	30735	6632.2	677	269	1.7763	0.08808	88	0.7020	88	0.05780	42	544	540	522
M2 1 flat euh med yel A	0.001	20781	3859.2	247	478	1.4103	0.08708	52	0.6973	44	0.05808	12	538	537	533
M3 1 lrg flat euh yel A	0.002	25074	3838.0	523	398	1.0418	0.08444	68	0.6735	58	0.05785	20	523	523	524
Carvalhal orthogneiss (qn) (39°28'17.32"N, 8° 3'19.34"W)															
Z1 2 lrg clr euh A	0.004	244	37.5	1	9059	0.1366	0.14588	78	1.7251	96	0.08577	30	878	1018	1333
Z2 3 lrg clr euh A	0.006	255	34.7	1	8544	0.1358	0.12954	64	1.4810	70	0.08292	20	785	923	1267
Z3 4 lrg clr euh A	0.008	250	30.3	75	209	0.1545	0.11486	62	1.1424	102	0.07214	48	701	774	990
Z4 2 lrg clr euh A	0.004	220	42.8	3	3767	0.1392	0.18302	96	2.4612	132	0.09753	22	1083	1261	1577
Z5 3 lrg cl euh A	0.006	364	102.2	7	5123	0.0961	0.25364	262	6.6954	682	0.19145	40	1457	2072	2755
Z6 1 lrg clr euh A	0.002	338	33.4	1	3072	0.1859	0.09204	78	0.7545	90	0.05945	68	568	571	584
Z7 1 lrg clr euh A	0.002	360	36.6	7	695	0.1415	0.09825	76	0.8222	70	0.06069	46	604	609	628
Z8 1 lrg clr euh A	0.002	244	28.2	1	3545	0.2626	0.10172	64	0.8570	46	0.06110	32	625	628	643
Z10 1 clr prm A	0.002	98	9.2	4	288	0.1201	0.09247	108	0.7585	242	0.05949	176	570	573	585
Z11 1 clr euh A	0.002	100	56.3	3	2214	0.1109	0.49941	866	13.5602	1728	0.19693	244	2611	2719	2801
Z12 1 med clr prm A	0.002	114	12.5	3	486	0.3097	0.09253	124	0.7536	186	0.05907	130	570	570	570
Z13 1 med clr prm A	0.002	184	18.2	4	523	0.1536	0.09502	110	0.7848	172	0.05990	122	585	588	600
Z14 1 med clr prm A	0.002	132	14.6	3	521	0.2894	0.09496	48	0.7817	110	0.05970	76	585	586	593
M1 2 med subh A	0.004	2298	460.9	7	7329	1.6795	0.08475	134	0.6784	110	0.05805	50	524	526	532
M2 1 subhed med A	0.002	6156	942.8	20	3346	0.9690	0.08751	76	0.7028	64	0.05825	34	541	540	539
M3 2 med subhed A	0.004	4972	864.1	6	17722	1.2802	0.08604	60	0.6882	44	0.05801	26	532	532	530
M4 1 subhed A	0.002	1749	696.9	88	200	5.2657	0.07279	62	0.5627	112	0.05606	100	453	453	455
Sardoal orthogneiss (10) (39°28'18.66"N, 8° 3'56.42"W)															
Z1 5 clr prms A	0.007	260	23.0	16	678	0.0973	0.08876	100	0.7409	130	0.06055	88	548	563	623
Z2 5 clr sharp prm A	0.007	339	28.5	2	6680	0.0859	0.08545	118	0.6878	92	0.05838	44	529	531	544
Z3 2 3:1 clr prm A	0.004	157	14.2	2	1654	0.0914	0.09170	66	0.7535	100	0.05960	76	566	570	589
Z4 1 clr sharp prm A	0.002	440	35.7	1	5666	0.0568	0.08462	40	0.6824	34	0.05849	14	524	528	548
Z5 3 clr sharp prm A	0.006	128	12.8	2	2327	0.0950	0.09994	76	0.8653	70	0.06280	32	614	633	701
Z6 1 clr sharp prm A	0.002	272	21.7	1	2103	0.0552	0.08337	58	0.6722	58	0.05848	32	516	522	548
Z7 2 clr sharp prm A	0.004	314	24.8	2	3298	0.0336	0.08407	80	0.6780	70	0.05850	46	520	526	548
Souto orthogneiss (311-56) (39°36'31.87"N, 8°17'28.01"W)-															
Z1 1 med clr prm E	0.001	1430	265.3	4	3913	0.0782	0.18327	82	2.5036	112	0.09907	22	1085	1273	1607
Z2 2 med-lrg prm E	0.002	1461	162.3	4	5204	0.0589	0.11347	136	1.2537	138	0.08013	42	693	825	1200
Z3 1 med-lrg prm E	0.001	1319	123.7	5	1494	0.0741	0.09612	40	0.7949	34	0.05998	14	592	594	603
M1 1 lrg yel clr sub A	0.002	66231	12831.3	22	24826	1.5303	0.08662	42	0.6932	34	0.05804	4	536	535	531
M2 1 lrg yel clr sub A	0.002	44622	10970.3	33	11227	2.1972	0.08733	42	0.6998	34	0.05812	6	540	539	534
Olalhas orthogneiss (311-30) (39°38'19.76"N, 8°16'32.65"W)															
Z1 4 med 3:1 prm E	0.006	443	58.0	7	2797	0.1575	0.12048	54	1.7270	72	0.10396	26	733	1019	1696
Z2 3 med 3:1 prm E	0.004	257	27.9	7	1081	0.0859	0.10999	38	0.9757	60	0.06434	30	673	691	753
Z3 5 med 3:1 prm E	0.007	243	23.7	10	1158	0.1223	0.09602	38	0.8003	54	0.06045	32	591	597	620
Z4 3 med prm E	0.004	365	41.1	11	1011	0.1359	0.10920	60	0.9555	72	0.06347	34	668	681	724
Cabeço da Moura amphibolite (311-1) (39°37'57.06"N, 8°15'29.24"W)															
Z1 15 sml mfacet A	0.023	162	13.8	2	8319	0.0763	0.08738	84	0.7038	68	0.05842	36	540	541	546
Z2 5 sml mfacet A	0.007	214	18.3	1	5938	0.0829	0.08681	124	0.6990	100	0.05840	64	537	538	545
Z3 1 long prm A	0.002	39	3.4	1	322	0.0768	0.08714	104	0.7135	100	0.05938	54	539	547	581
Z4 5 sml rnd A	0.010	59	5.0	25	145	0.0693	0.08721	150	0.7088	302	0.05895	240	539	544	565
Vila Nova amphibolite (311-62) (39°36'10.32"N, 8°16'44.24"W)															
T1 1 med lp cast A	0.002	1833	209.7	18	1105	0.4918	0.08563	122	0.6870	90	0.05819	44	530	531	537
T2 2 med lp cast A	0.004	898	101.8	21	948	0.4800	0.08550	148	0.6871	112	0.05829	50	529	531	541

Notes: Z=zircon, M=monazite, T=titanite, 1,2=number of grains, lrg=large, clr=clear, yel=yellow, med=medium, sml=small, prm=prism, A=abraded, E=etched; euh=euhedral; subhed=subhedral; mfacet=multi-faceted. Weights were estimated. Zircon grains were physically abraded (cf. Krogh, 1982), or annealed and etched in HF acid (cf. Mattinson, 2005). * Atomic ratios corrected for fractionation, spike, laboratory blank of 1-4 picograms of common lead, and initial common lead at the age of the sample calculated from the model of Stacey and Kramers (1975), and 0.5-1 picogram U blank. Datum: D_ETRS_1989.

Table 1b U- Pb isotopic data for zircon and monazite of the rocks from the Mouriscas Complex, Central Portugal.

Fraction	Concentration			Measured Total common Pb(pg)	Corrected Atomic Ratios*								Age Ma		
	Weight (mg)	U (ppm)	Pb rad (ppm)		²⁰⁶ Pb	²⁰⁸ Pb	²⁰⁶ Pb	²⁰⁷ Pb	²⁰⁷ Pb	²⁰⁶ Pb	²⁰⁷ Pb	²⁰⁷ Pb			
					----- ²⁰⁴ Pb	----- ²⁰⁶ Pb	----- ²³⁸ U	----- ²³⁵ U	----- ²⁰⁶ Pb	----- ²³⁸ U	----- ²³⁵ U	----- ²⁰⁶ Pb			
					2σ	2σ	2σ	2σ	2σ	2σ	2σ				
Amphibolite (321-138) (39°34'35.15"N, 8°15'46.02"W)															
Z1 3 med prm E	0.006	772	69.3	10	2494	0.1284	0.08791	56	0.7088	44	0.05848	14	543	544	548
Z2 6 med prm E	0.012	1543	140.4	12	8651	0.1392	0.08834	56	0.7106	46	0.05834	8	546	545	543
Z3 3 med prm E	0.006	814	73.8	12	2223	0.1400	0.08802	46	0.7090	36	0.05842	14	544	544	546
Amphibolite (58A) (39°28'6.42"N, 8° 4'26.41"W)															
Z1 2 lrg euh prm E	0.003	2141	187.7	7	5166	0.1086	0.08736	62	0.7033	50	0.05840	16	540	541	545
Z2 3 prm E	0.004	1723	146.7	7	4662	0.0714	0.08763	40	0.7053	30	0.05837	12	542	542	544
Z3 3 sml euh prm E	0.003	1563	137.6	5	4939	0.1090	0.08770	32	0.7061	26	0.05839	10	542	542	545
Amphibolite (321-M) (39°29'46.96"N, 8° 9'8.59"W)															
Z1 2 lrg clr euh prm E	0.005	2142	186.7	4	13257	0.0965	0.08778	58	0.7066	48	0.05838	8	542	543	544
Z2 2 lrg clr euh prm E	0.004	2923	246.4	17	3713	0.0823	0.08595	74	0.6916	58	0.05836	10	532	534	543
Protomylonite thondhemite (165) (39°28'17.17"N, 8° 5'31.09"W)															
Z1 2 clr 2:1 prm A	0.003	75	6.0	1	804	0.0918	0.08100	176	0.6722	142	0.06019	114	502	522	610
Z2 2 clr 2:1 prm E	0.002	272	22.1	4	732	0.0755	0.08331	42	0.6669	58	0.05806	42	516	519	532
Z3 2 clr prm E	0.002	364	27.4	4	894	0.0706	0.07775	20	0.6088	42	0.05679	34	483	483	483
Z4 1 clr euh prm E	0.001	253	22.1	4	358	0.0697	0.08983	66	0.7224	164	0.05832	120	555	552	542
M1 15 v sml euh	0.010	36	6.9	5	337	2.0608	0.07199	72	0.5691	104	0.05733	98	448	457	504
M2 6 v sml euh	0.004	94	17.3	3	650	1.9503	0.07047	100	0.5511	130	0.05672	124	439	446	481
M3 4 v sml euh-sbhed	0.002	185	46.5	2	1212	2.7845	0.07556	48	0.5903	84	0.05666	74	470	471	478
Garnet amphibolite (20A) (39°27'56.80"N, 8° 4'48.24"W)															
Z1 4 lrg clr prm A	0.008	54	5.1	2	1273	0.3811	0.07673	54	0.6047	46	0.05716	24	477	480	498
Z2 2 lrg clr prm A	0.004	104	9.6	3	719	0.3412	0.07635	58	0.5980	72	0.05680	54	474	476	484
Z3 2 lrg clr prm/frg A	0.004	99	7.7	3	727	0.1562	0.07455	52	0.5836	56	0.05678	46	464	467	483
Z4 2 clr prm E	0.002	63	5.6	4	174	0.2865	0.07683	72	0.6012	234	0.05675	208	477	478	482
Z5 4 clr prm E	0.004	154	13.8	4	689	0.3028	0.07663	38	0.5995	48	0.05674	38	476	477	482
Z6 2 clr prm E	0.002	329	30.1	5	653	0.3220	0.07691	62	0.6022	80	0.05679	72	478	479	483
Z7 2 clr prm E	0.002	99	8.6	5	215	0.2625	0.07674	132	0.6016	168	0.05686	148	477	478	486

Notes: Z=zircon, M=monazite, T=titanite, 1,2=number of grains, lrg=large, clr=clear, yel=yellow, med=medium, sml=small, prm=prism, A=abraded, E=etched; euh=euhedral; sbhed=subhedral; mfacet=multi-faceted. Weights were estimated. Zircon grains were physically abraded (cf. Krogh, 1982), or annealed and etched in HF acid (cf. Mattinson, 2005). * Atomic ratios corrected for fractionation, spike, laboratory blank of 1-4 picograms of common lead, and initial common lead at the age of the sample calculated from the model of Stacey and Kramers (1975), and 0.5-1 picogram U blank. Datum: D_ETRS_1989.

Table 2a Rb-Sr isotopic data of the rocks from Sardoal Complex and Mouriscas Complex, Central Portugal.

			Igneous age (Ma)	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	2σ (%)	$(^{87}\text{Sr}/^{86}\text{Sr})_i$
Sardoal Complex	Souto orthogneiss	311-66	692+77/-60	122	202	1.7498	0.722968	0.0009	0.7057
		321-140b	692+77/-60	68	184	1.0700	0.716589	0.0009	0.7060
	Carvalhal orthogneiss	321-26	569 ± 3	120	200	1.7381	0.721759	0.0010	0.7077
		84B	569 ± 3	111	207	1.5534	0.721980	0.0011	0.7094
		gn	569 ± 3	99	239	1.1997	0.719335	0.0008	0.7096
	Sardoal orthogneiss	321-27	548 ± 4	111	174	1.8485	0.724678	0.0010	0.7102
		322-AF6	548 ± 4	117	153	2.2168	0.729038	0.0008	0.7117
		10	548 ± 4	108	194	1.6127	0.721771	0.0016	0.7092
	Olalhas orthogneiss	311-30	*	107	125	2.4811	0.727605	0.0010	–
		311-37	*	98	222	1.2785	0.719562	0.0010	–
Mouriscas Complex	Amphibolites	38A	544 ± 2	22	144	0.4421	0.709878	0.0010	0.7065
		321-M	544 ± 2	79	170	1.3456	0.717179	0.0009	0.7067
		311-96A	544.2 ± 1.7	101	165	1.7733	0.722111	0.0008	0.7084
		321-138	544.2 ± 1.7	51	197	0.7492	0.712258	0.0009	0.7064
		321-31	544.3 ± 2.5	32	238	0.3890	0.709103	0.0009	0.7061
		58A	544.3 ± 2.5	57	174	0.9481	0.712619	0.0013	0.7053
	Protomylonite thronthjemite	18A	483 ± 1.5	5	260	0.0556	0.704862	0.0010	0.7045
		19C1	483 ± 1.5	16	245	0.1889	0.705243	0.0010	0.7039
		165	483 ± 1.5	17	181	0.2717	0.705923	0.0010	0.7041
	Garnet amphibolite	20A	477 ± 2	2	286	0.0202	0.703126	0.0009	0.7030
		69A	477 ± 2	5	240	0.0602	0.704566	0.0010	0.7042

* Unknown igneous age; – not determined.

Table 2b Sm-Nd isotopic data of rocks from Sardaoal Complex and Mouriscas Complex, Central Portugal.

			Igneous age (Ma)	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	2 σ (%)	$(^{143}\text{Nd}/^{144}\text{Nd})_i$	ϵNd_t	T_{DM} (Ga)
Sardaoal Complex	Souto orthogneiss	311-66	692+77/-60	7.41	36.6	0.1153	0.511979	0.0007	0.511573	-7.3	1.65
		321-140b	692+77/-60	5.07	23.9	0.1265	0.512123	0.0007	0.511677	-5.2	1.60
	Carvalho orthogneiss	321-26	569 $\pm$ 3	5.34	28.8	0.1124	0.512027	0.0007	0.511623	-6.0	1.53
		84B	569 $\pm$ 3	6.15	32.4	0.1126	0.511947	0.0007	0.511543	-7.6	1.65
		gn	569 $\pm$ 3	4.35	24.1	0.1114	0.511907	0.0007	0.511492	-8.1	1.69
	Sardaoal orthogneiss	321-27	548 $\pm$ 4	5.16	26.6	0.1146	0.512029	0.0007	0.511602	-5.9	1.56
		322-AF6	548 $\pm$ 4	4.33	24.7	0.1184	0.512017	0.0007	0.511576	-6.4	1.64
		10	548 $\pm$ 4	6.39	28.1	0.1248	0.512078	0.0007	0.511630	-5.9	1.65
	Olalhas orthogneiss	311-30	*	5.76	27.6	0.1205	0.512138	0.0007	–	–	1.48
		311-37	*	7.54	40	0.1136	0.512016	0.0007	–	–	1.56
Mouriscas Complex	Amphibolites	38A	544 $\pm$ 2	1.83	7.73	0.1486	0.512317	0.0007	0.511787	-2.9	1.69
		321-M	544 $\pm$ 2	2.4	9.49	0.1516	0.512302	0.0006	0.511762	-3.4	1.81
		311-96A	544.2 $\pm$ 1.7	6.27	25.9	0.1457	0.512270	0.0006	0.511751	-3.6	1.73
		321-138	544.2 $\pm$ 1.7	4.44	18.6	0.1429	0.512294	0.0008	0.511785	-3.0	1.61
		321-31	544.3 $\pm$ 2.5	5	21.7	0.1318	0.512231	0.0007	0.511761	-3.4	1.51
		58A	544.3 $\pm$ 2.5	2.71	9.33	0.1735	0.512720	0.0007	0.512102	3.2	1.22
	Protomylonite thronthjemite	18A	483 $\pm$ 1.5	3.45	16.3	0.1169	0.512646	0.0007	0.512276	5.1	0.64
		19C1	483 $\pm$ 1.5	2.99	15.8	0.1017	0.512609	0.0007	0.512287	5.3	0.61
		165	483 $\pm$ 1.5	3.83	17.8	0.1174	0.512644	0.0007	0.512273	5.0	0.65
	Garnet amphibolite	20A	477 $\pm$ 2	4.49	17.1	0.1572	0.512934	0.0006	0.512443	8.2	0.34
		69A	477 $\pm$ 2	3.82	14.2	0.1387	0.512798	0.0007	0.512365	6.7	0.52

* Unknown igneous age; – not determined; The ϵ_{Nd} values are calculated using $^{147}\text{Sm}/^{144}\text{Nd}=0.1967$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$ values for the present day chondrite uniform reservoir (CHUR); T_{DM} is calculated with respect to the DePaolo (1981a).

Appendix 1. Petrographic features of the rocks from Sardaoal Complex and Mouriscas Complex, Central Portugal.

Unit	Rock-type		Texture	Mineral assemblage	Igneous age (Ma)	Metamorphic age (Ma)
Sardaoal Complex	Quartzo-feldspathic schist		Fine- to medium- grained; porphyroclastic, mylonitic foliation	Qtz + Olg + Bt + Ms ± Kfs ± Sil ± Alm ± Zrn ± Tur + Ilm ± Rt ± Mnz ± Ap ± Ab ± Ep	692 ± 77/-60	538 ± 2
	Orthogneiss	Souto	Medium- to coarse-grained; porphyroclastic, mylonitic foliation	Qtz + Olg + Bt + Ms ± Kfs ± Alm ± Sil + Zrn ± Tur ± Mnz + Ap + Ilm + Rt	—	539 ± 2
		Carvalhal	Fine- to medium-grained; porphyroclastic, mylonitic foliation	Qtz + Olg ± Ads + Or + Mc + Bt + Ms ± Tur ± Alm + Zrn + Ap + Mnz ± Ilm ± Rt ± Mag	569 ± 3	540 ± 5
		Sardaoal	Coarse-grained; augen texture	Qtz + Olg + Or + Bt + Ms ± Sil ± Tur + Zrn + Ap ± Ilm ± Mag ± Rt ± Py	548 ± 4	—
		Olalhas	Fine- to medium-grained; porphyroclastic, mylonitic foliation	Qtz + Olg + Bt + Ms ± Kfs ± Sil ± St ± Alm ± Tur + Zrn + Ap ± Ilm ± Py	—	—
	Amphibolite	Cabeço da Moura	fine-grained; granoblastic to nematoblastic; foliated	Mg-Hbl ± Fe2-Hbl ± Fe2-Ed + Lab ± Ads ± Byt + Di ± Aug + Ilm + Zrn + Ttn + Ap + Qtz ± Mag ± Py ± Act ± Ep	—	539 ± 3
		Vila Nova	fine-grained; granoblastic to nematoblastic; foliated	Mg-Hbl ± Prg + Ads + Lab + Di + Ilm + Ttn + Ap + Qtz ± Py ± Act ± Ep	—	529 ± 5
Mouriscas Complex	Amphibolite		medium-grained; relic igneous texture	Ads + Lab + Mg-Hbl + Fe2-Ts + Qtz + Bt + Tur + Zrn + Ilm + Ttn	544.2 ± 1.7	—
			fine-grained; granofelsic texture	Ads + Lab + Mg-Hbl + Act + Qtz + Chl + Ep + Zrn + Ap + Ilm	544.3 ± 2.5	—
			medium-grained; porphyroclastic, mylonitic fabric	Ads + Mg-Hbl + Fe2-Ts + Cum + Qtz + Bt + Zrn + Ap + Ilm + Py	544 ± 2	—
	Protomylonite trondhjemite		medium- to coarse-grained; porphyroclastic, mylonitic fabric	Qtz + Olg + Ms + Bt + Sil + Alm + St ± Or + Zrn + Mnz + Ap ± Ilm ± Rt	483 ± 1.5	—
	Garnet amphibolite		medium- to coarse-grained; porphyroblastic, foliated	Ads ± Olg + Gru + Fe2-Ts + Bt + Qtz + Alm + Chl + Ep + Zrn + Ilm ± Mag	477 ± 2 Ma	—

Mineral abbreviations from Siivola and Schmid (2007): Ab, Albite; Act, Actinolite; Alm, Almandine; Ap, Apatite; Aug, Augite; Bt, Biotite; Chl, Chlorite; Cum, Cummingtonite; Di, Diopside; Ep, Epidote; Fe2-Ed, Ferro-Edenite; Fe2-Hbl, Ferrohornblende; Fe2-Ts, Ferrotschermakite; Gru, Grunerite; Ilm, Ilmenite; Kfs, K-feldspar; Mag, Magnetite; Mc, Microcline; Mg-Hbl, Magnesiohornblende; Mnz, Monazite; Ms, Muscovite; Or, Orthoclase; Prg, Pargasite; Py, Pyrite; Qtz, Quartz; Rt, Rutile; Sil, Sillimanite; St, Staurolite; Ttn, Titanite; Tur, Tourmaline; Zrn, Zircon. Other mineral abbreviations: Ads, Andesine; Byt, Bytownite; Lab, Labradorite; Olg, Oligoclase.

Appendix 2. Representative analyses of minerals of Cabeço da Moura amphibolite (sample 311-1), Central Portugal.

	Mg-hbl 1	Mg-hbl 2	Mg-hbl 3		Di (Cpx 1)	Di (Cpx 2)		Lab (Pl)	Byt (Pl)
SiO ₂	45.10	46.24	46.42	SiO ₂	51.79	51.43	SiO ₂	52.45	49.65
TiO ₂	1.55	1.44	1.33	TiO ₂	0.22	0.32	TiO ₂	0.00	0.06
Al ₂ O ₃	9.58	9.32	8.94	Al ₂ O ₃	1.46	1.75	Al ₂ O ₃	30.18	31.43
Cr ₂ O ₃	0.18	0.09	0.04	FeO	9.66	10.16	FeO	0.03	0.11
FeO	15.01	14.54	14.55	Cr ₂ O ₃	0.03	0.00	MnO	0.01	0.08
MnO	0.27	0.27	0.21	MnO	0.38	0.30	MgO	0.00	0.01
MgO	11.39	11.67	12.04	MgO	12.67	12.47	BaO	0.00	0.08
CaO	11.53	11.74	11.81	CaO	23.22	22.97	CaO	13.01	15.00
Na ₂ O	1.46	1.29	1.29	Na ₂ O	0.23	0.21	Na ₂ O	3.77	2.87
K ₂ O	0.16	0.12	0.11	K ₂ O	0.00	0.02	K ₂ O	0.01	0.02
Total	96.23	96.73	96.75	Total	99.66	99.63	P ₂ O ₅	0.13	0.11
							Total	99.59	99.40