Provenance of the Variscan Upper Allochthon (Cabo Ortegal Complex, NW Iberian Massif)

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Abstract. This study focuses on the provenance of the uppermost unit of the Upper Allochthon of the Variscan belt with combined U-Pb and Lu-Hf zircon (LA-ICPMS) and Sm-Nd whole-rock analyses. This unit is represented in the Cabo Ortegal Complex (NW Iberia) by the metasiliciclastic Cariño Gneisses which overlaps ophiolitic units that represent the Rheic Ocean. The data set indicates a maximum depositional age of c. 510 Ma and a c. 1.73 Ga Sm-Nd model age, typifying a late or post Pan-African (or Cadomian) and Eburnean events, which entailed abundant input of juvenile material involving broad mixing with older crustal sources. The Mesoproterozoic activity is scarce and scattered and therefore unlikely to represent a major crust generation pulse in the source area of the siliciclastic unit. The data set also records an Archean orogenic pulse in its source area followed by a long lasting crust reworking process, where the Eburnean juvenile materials intruded. These data are interpreted as indicative of a West Africa Craton provenance, where the siliciclastic series from which the Cariño Gneisses are derived were probably deposited in a back-arc type basin where detritus was mostly sourced by the continent rather than the magmatic arc.

Key words: Detrital zircons, Provenance, Isotope geochemistry, Variscan Upper Allochthon, Cabo Ortegal Complex

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1. Introduction

The Variscan–Appalachian–Alleghenian orogeny was formed when the Pangea supercontinent assembled during Carboniferous and Early Permian. Part of the European branch of this orogen, the Variscan belt, is well preserved in the Iberian Massif. This Massif exhibits an almost complete section of the southern part (present day coordinates) of the orogen from the most external zones (Autochthon) to the internal sections which are represented by the Parautochthon and the allochthonous complexes.

Our understanding of the sources and provenance of the rock series involved in the Variscan Orogeny has significantly increased in the last few years mostly driven by U-Pb and Lu-Hf zircon (LA-ICPMS) and Sm-Nd whole rock studies. In the NW Iberian Massif most of the provenance studies have been focussed on sedimentary series located below the ophiolitic units, either in the autochthonous domain (Cantabrian zone, CZ, West-Asturian-Leonese zone, WALZ, and Central Iberian zone, CIZ, Fig. 1a, [Fernández-Suárez et al., 1999](#); [Gutiérrez-Alonso et al., 2003](#); [Martínez Catalán et al., 2004](#); [Fernández-Suárez et al., 2013](#); [Shaw et al., 2014](#)), the Parautochthon ([Díez Fernández et al., 2012b](#)) or the basal units ([Díez Fernández et al., 2010](#)). These studies suggest as a main conclusion that the rock series were formed at the periphery of the Gondwanan margin, between the Nubian platform and the periphery of West African Craton (WAC), although their exact location is still a matter of debate. The key for paleogeographic reconstructions is usually focussed on the presence or absence of a Stenian - Tonian zircon population in Ediacaran and post-Ediacaran rock series. Rocks containing this population are usually placed in front of the Sahara Craton or the Nubian Shield ([Díez Fernández et al., 2010](#); [Fernández-Suárez et al., 2013](#); [Shaw et al., 2014](#)), whereas those lacking or having an extremely low quantity of it are considered to have a proximal WAC provenance ([Abati et al., 2010a, 2012](#)). Nevertheless, the real importance of the isotopic sources has not been completely evaluated in NW Iberia as there are almost no previous studies integrating U-Pb/Lu-Hf (zircon) and Sm-Nd (whole rock) data systematics. This kind of studies is absent in metasedimentary rock series and only very few works have presented some of these combined results for metaigneous rocks (i.e. [Sánchez Martínez et al., 2011](#)).

The Upper Allochthon or upper units is located above the ophiolitic units, which are considered to represent the Variscan suture in the NW Iberian Massif. This issue poses first order questions, not only about tectonic settings but also about provenance and sources of the involved rock series. In the Upper Allochthon, two works were carried out separately publishing U-Pb detrital zircon and Sm-Nd whole rock data on metagreywackes ([Fernández-Suárez et al., 2003](#); [Fuenlabrada et al., 2010](#)). Both studies focussed on the siliciclastic series located at the

uppermost structural position of the Órdenes Complex which is situated to the West of the Cabo Ortegal Complex (Fig. 1b-1c), where the mentioned series are not represented. According to the data in the works mentioned above, this terrane has been considered as WAC derived, but the young Nd model ages obtained from the metagreywackes (c. 1 Ga) are inconsistent with the old isotopic sources expected from the WAC. This observation requires additional explanations. Also, new and integrated U-Pb/Lu-Hf (zircon) and Sm-Nd (whole rock) data are needed to present a complete picture for the provenance of the upper units, as the previously studied greywacke series are only representative for the uppermost stratigraphic levels of this thick terrane (c. 10000 - 12000 m).

This contribution presents a provenance study of the upper units combining U-Pb and Lu-Hf in zircon (LA-SF-ICPMS) and Sm-Nd whole rock analyses. The rocks studied belong to the Cariño Gneiss formation, which is the top member of the Upper Allochthon of the Cabo Ortegal Complex, different to and occupying a lower position than the metagreywackes previously studied in the Órdenes Complex. This will allow a straightforward comparison and a better understanding of the origin of this terrane.

2. Geological framework of the Upper Allochthon in NW Iberia

The NW sector of the Iberian Massif includes an autochthonous domain, represented by the Cantabrian (CZ), West-Asturian-Leonese (WALZ) and Central Iberian (CIZ, Fig. 1a) zones. This domain is overlain by an allochthonous domain which is represented by the Galicia-Trás-os-Montes Zone (GTOMZ). In the GTOMZ a lower assemblage is considered as the Lower Allochthon or Parautochthon. Above it, a group of five allochthonous complexes include the remnants of the Variscan suture which can be followed throughout Europe, from the Iberian to the Bohemian Massif (Fig. 1a; [Martínez Catalán et al., 2009](#)). These allochthonous complexes have an intricate internal structure, but they appear clearly constituted by three terranes with contrasting origin, structure and tectonothermal evolution. The complexes are nappe piles structured as late Variscan synforms, and they are divided upwards as basal, ophiolitic and upper units.

The basal units represent a crustal terrane formed by the subduction of the Gondwanan continental margin below Laurussia at c. 370 Ma ([Gil Ibarguchi and Ortega Gironés, 1985](#); [Arenas et al., 1995](#); [Rodríguez et al., 2003](#); [Abati et al., 2010b](#); [Díez Fernández et al., 2011](#); [López-Carmona et al., 2014](#)). This terrane contains metasedimentary rock series with Ediacaran to Early Ordovician maximum depositional ages ([Díez Fernández et al., 2010](#); [2012b](#)), intruded

by abundant calc-alkaline (c. 493 Ma; [Abati et al., 2010b](#)) to alkaline - peralkaline (c. 475 - 470 Ma; [Díez Fernández et al., 2012a](#)) granitic bodies.

The ophiolitic units are formed by mafic - ultramafic rock series that have been the object of recent works. They represent a varied assemblage with units formed in different stages in the evolution of the Paleozoic oceans. Part of these ophiolites have been interpreted as Cambrian remnants of the peri - Gondwanan oceans, including sequences accreted at the base of a fore - arc ([Sánchez Martínez et al., 2012](#)) and back - arc sequences ([Arenas et al., 2007](#)). However the most extended ophiolitic units in NW Iberia, and also along the Variscan suture in the rest of Europe, are c. 395 Ma mafic - ultramafic rock series. The interpretation of these units has changed over time. They were first considered supra - subduction zone ophiolites formed during the last stages of the closure of the Rheic Ocean ([Díaz García et al., 1999](#); [Sánchez Martínez et al., 2007](#)). However these ophiolites, according to new U-Pb/Lu-Hf zircon data, have been recently considered to be related to the opening of a long pull-apart basin, which show an interaction of the mafic rocks with an old continental basement ([Sánchez Martínez et al., 2011](#); [Arenas et al., 2013](#); [Arenas et al., 2014](#)).

The upper units or Upper Allochthon constitutes a terrane with continental-crust affinity which can be divided into high pressure - high temperature (HP-HT) units below and intermediate pressure (IP) units above. The HP-HT base of this terrane is mainly composed of ultramafic rocks, basic, intermediate and acid granulites, eclogites, orthogneisses and paragneisses ([Vogel, 1967](#); [Gil Ibarguchi et al., 1990](#); [Peucat et al., 1990](#); [Ábalos et al., 2003](#)). The protolith ages for the igneous rocks are clustered around c. 490 Ma and the age of the HP-HT metamorphism is c. 400-390 Ma ([Ordóñez Casado et al., 2001](#); [Fernández-Suárez et al., 2007](#)). The uppermost section of the Upper Allochthon, the IP upper units, is composed of a thick siliciclastic series with greywacke and pelitic members and minor conglomerates ([Díaz García, 1990](#); [Díaz García et al., 2010](#)). In the Órdenes Complex the greywackes have chemical compositions characteristic of volcanic-arc settings ([Fuenlabrada et al., 2010](#)) and maximum depositional ages in the range of 530 - 500 Ma ([Fernández-Suárez et al., 2003](#); [Fuenlabrada et al., 2010](#)). This series is intruded by large massifs of gabbros with tholeiitic arc affinity ([Andonaegui et al., 2002](#)) and granitoids with calc-alkaline compositions ([Andonaegui et al., 2012](#)). U-Pb dating of these mafic and felsic metaigneous rocks yielded protolith ages at c. 500 Ma ([Abati et al., 1999](#); [Andonaegui et al., 2012](#)). A doleritic dyke swarm dated at c. 510 Ma also intrudes into the top greywacke series ([Díaz García et al., 2010](#)). The IP upper units metamorphic grade decreases upwards from granulite to greenschist facies, with characteristic counter-clockwise P-T paths interpreted as associated to magmatic underplating in a volcanic arc setting ([Abati et al., 2003](#)). This arc-related metamorphic event is dated at c. 496 - 482 Ma ([Abati](#)

et al., 1999; 2007). Therefore multiple evidence support the original volcanic-arc setting for the upper units of the allochthonous complexes. This volcanic arc was part of the Early Paleozoic peri-Gondwanan arc system. The uppermost part of the preserved section of this arc seems to be only slightly affected by the Variscan and eo-Variscan activity, whereas the lower part was strongly reworked during the Variscan collision developing a high-P and high-T recrystallization in the Devonian.

Most of the terranes and minor members described in the allochthonous complexes of NW Iberia are present in the Cabo Ortegal Complex, a small but well exposed complex on the Northern Galician coast (Fig. 1a). The upper units are mostly represented by the HP-HT units (Figs. 1b and 1c). The IP upper units are only represented by the Cariño Gneiss formation, which is the uppermost structural unit of the Cabo Ortegal Complex. It is formed by metasedimentary rocks in amphibolite facies with peak metamorphic conditions at 700 °C and 12 kbar (Castiñeiras, 2005). It is a homogeneous metaturbiditic sequence of centimetre-scale alternations of fine-grained pelitic bands with lepidoblastic texture and medium-grained psamitic bands with granoblastic texture, where the amount of medium-grained bands seems to decrease upwards (Castiñeiras, 2005). On the base of their mineralogical composition the psamitic types are described as quartz- and normal greywackes and the pelitic bands as normal and quartz-poor greywackes (Vogel, 1967). This compositional banding is an inherited sedimentary feature representing the deposition of greywackes by turbidity currents. The limits between sedimentary bands also coincide with the foliation, which is defined by preferential orientation of the rock forming minerals. This foliation strikes N-S to c. N45° and dips up to 75° westwards at the western part of the formation and eastwards at the eastern part defining a wide and open antiform (Fig. 2). The dominant regional lineation plunges c. 5° to 30° with a N20° - N55° trend. The formation is folded in a large recumbent synform with subordinated folds with an East vergence. Its axial plane strikes c. N-S and dips to the West in the western part of the formation. Associated with this synform an axial plane foliation developed locally in the fine-grained bands. This large synform does not only affect the Cariño Gneiss formation but also all of the upper units of the Cabo Ortegal Complex. The synform was early mapped by Vogel (1967) and Marcos et al. (1984), and a recent interpretative section has been presented by Arenas et al. (2013).

3. Sample description

Six samples were chosen from the Cariño Gneiss formation. The location of these samples is shown in Fig. 2. Samples GCH- 07, 08 and 09 were collected at Peiral beach (N43° 44' 40", W7° 52' 2"), samples GCH- 11 and 12 from the old shellfish breeding centre (N43° 44'

23", W7° 51' 53") and sample GCH- 10 from Fornos beach (N43° 42' 41", W7° 51' 5"; Simple Cylindrical projection, WGS84 datum). All samples are texturally and compositionally very similar, and were selected from the medium-grained psamitic bands instead of the fine-grained pelitic bands. Microscopically the samples are inequigranular and medium to fine -grained, and show a granoblastic-lepidoblastic texture. Qtz and Pl are the mayor components. Qtz is slightly undulose and Pl is usually altered. Micas are smaller than Qtz and Pl, Bt is usually retrogressed to Chl, and the preferred orientation that both Bt and Ms define is poorly developed. Grt are strongly corroded and have a dusty appearance due to high abundance of inclusions. Ky and St are very rare in the selected samples but are more abundant in the pelitic bands of these rocks. Other constituents are Spn, Rt, Ilm, Ap, Zrn and opaque matter (mineral abbreviations after [Kretz, 1983](#)).

4. Sample preparation and analytical procedures

4.1. Zircon sample preparation

Zircon crystals were separated from bulk samples using conventional mineral separation techniques at the Facultad de Ciencias Geológicas, Universidad Complutense de Madrid (UCM). Samples were cleaned and dried before crushing them in a jaw crusher and in a tungsten disc mill. The light fraction was removed by floatability using a Wilfley table. The magnetic fraction was separated with a hand magnet for the most magnetic minerals and with a Franz model magnetic separator to remove those minerals susceptible to a magnetic field induced by an electric current up to 1.7 A. Minerals with a density below 3,325 kg·m⁻³ were removed using CH₂I₂ (diiodomethane) heavy liquid. Zircon hand picking, mounting, imaging and analysis were performed at the J. W. Goethe Universität of Frankfurt am Main (GUF). Hand-picked zircons of all sizes and morphologies were mounted in epoxy filled mounts depending on their size and polished to approximately 50% of their thickness. All zircons studied were documented by back-scattered electron (BSE) and cathodoluminescence (CL) images using a JSM 6490 scanning electron microscope to study their internal structure in order to choose the best areas for laser ablation.

4.2. U-Pb zircon analyses

Zircons were analysed for U, Th and Pb isotopes at the GUF using a ThermoScientific Element 2 sector field ICP-MS coupled to a Resolution M-50 (Resonetics) 193 nm ArF excimer

laser (CompexPro 102, Coherent) system using a slightly modified method as described in Gerdes and Zeh (2006, 2009); Zeh and Gerdes (2012). Laser spot-size was 23 to 33 μm for unknowns, 15 μm for Plešovice, 33 μm for GJ1 and 91500, and 50 μm for Felix standard zircons. Sample surface was cleaned directly before each analysis by four pre-ablation pulses. Ablation was performed in a 0.6 $\text{L}\cdot\text{min}^{-1}$ He stream, which was mixed directly after the ablation cell with 0.07 $\text{L}\cdot\text{min}^{-1}$ N_2 and 0.68 $\text{L}\cdot\text{min}^{-1}$ Ar prior introduction into the Ar plasma of the SF-ICP-MS. The sensitivity achieved was in the range of 8000-12000 cps/ $\mu\text{g}\cdot\text{g}^{-1}$ for ^{238}U with a 23 μm spot size, at 5.5 Hz and 4-5 $\text{J}\cdot\text{cm}^{-2}$ using GJ1 zircon. The two-volume ablation cell (Laurin Technic, Australia) of the M50 laser enables detection and sequential sampling of heterogeneous grains (e.g., growth zones) during time resolved data acquisition, due to its quick response time of <1 s (time until maximum signal strength was achieved) and wash-out (<99 % of previous signal) time of <3 s. All analyses were common-Pb corrected following the method described in Millonig et al. (2012). ^{204}Hg during the analytical session was about 200 cps. For the analysed sample the common ^{204}Pb contents were mostly near or below the detection limit, and thus a ^{208}Pb -based common Pb correction has been usually applied. The analytical results are presented as supplementary electronic material (Suppl. Electr. Mat., Tables 1 to 6). The accuracy of the method was verified by repeated analyses of reference zircon 91500 (Wiedenbeck et al., 1995), Plešovice (Slama et al., 2008) and in-house standard Felix (Millonig et al., 2012). Data were plotted using Isoplot 3.75 software (Ludwig, 2012).

From the six samples studied a total of 889 zircon cores were dated (Suppl. Electr. Mat., Tables 1 to 6), from which 839 are considered valid analysis (5.6% rejected) in terms of concordance (up to 10% discordance accepted). Following recommendations made by Vermeesch (2004) more than 117 zircons were analysed in each sample to achieve statistical adequacy. Data have been represented for visualization in complete and partial conventional concordia diagrams (from 450 Ma to 750 Ma) for each sample (Fig. 3). Data have also been plotted as adaptive Kernel Density Estimates (KDEs) and Probability Density Plots (PDPs) on Fig. 4, using DesityPlotter5.0 software (Vermeesch, 2012). KDEs were built with bandwidth = 15 Ma and histograms with binwidth = 25 Ma. The age assigned to each zircon core was chosen depending on $^{207}\text{Pb}/^{206}\text{Pb}$ age. If $^{207}\text{Pb}/^{206}\text{Pb}$ age < 1 Ga, $^{206}\text{Pb}/^{238}\text{U}$ age was chosen, if not $^{207}\text{Pb}/^{206}\text{Pb}$ age was preferred.

Maximum depositional ages (MDAs) for each sample were calculated following the most conservative method (YC2 σ (3+)) reported by Dickinson and Gehrels (2009) with some modifications. MDAs were calculated as the weighted mean of the youngest cluster of zircon ages that can be used to calculate a concordia age with Isoplots normal “ConcAge” tool (i.e.

probability of data-point equivalence higher than 0.001), choosing the first (younger) zircon age of the cluster as to have less than 1 % age difference with the next zircon age.

No mayor differences have been found between the studied samples. As all six samples were collected from the same formation it is assumed that the original detritus were derived from the same source area. To support this assumption a comparison between distributions of detrital zircon ages has been performed using a Kolmogorov-Smirnov nonparametric test (Fig. 5a), in a similar way as had been used previously to establish common provenance (Fernández-Suárez et al., 2013 and references therein), and a Cumulative Distribution Plot (CDP) with errors has also been reported (Fig. 5b). This test and plot were performed with a MS Excel[®] spreadsheet downloaded from the Arizona Laserchron Center webpage (<https://sites.google.com/a/laserchron.org/laserchron/>).

4.3. Lu-Hf zircon analyses

Hafnium isotope measurements (Suppl. Electr. Mat., Tables 7 to 11) were performed with a Thermo-Finnigan Neptune multicollector ICP-MS at GUF coupled to the same laser as described in the U-Pb method. Laser spots with diameter mostly of 40 μm were drilled with a repetition rate of 5.5 Hz and an energy density of 6 J/cm² during 55 s of data acquisition. All data were adjusted relative to the JMC475 of $^{176}\text{Hf}/^{177}\text{Hf}$ ratio = 0.282160 and quoted uncertainties are quadratic additions of the within run precision of each analysis and the reproducibility of the JMC475 (2 SD = 0.0033%, n = 16). Accuracy and external reproducibility of the method was verified by repeated analysis of reference zircon GJ-1 and Plešovice, (see Suppl. Electr. Mat., Table 12) which are well within the range of solution mode data (Woodhead and Hergt, 2005; Gerdes and Zeh, 2006).

For calculation of epsilon Hf (ϵHf_i) chosen values for chondritic uniform reservoir (CHUR) are $^{176}\text{Lu}/^{177}\text{Hf}$ = 0.0336 and $^{176}\text{Hf}/^{177}\text{Hf}$ = 0.282785 (Bouvier et al., 2008), and a ^{176}Lu decay constant of $1.867 \times 10^{-11} \text{ a}^{-1}$ (average of Scherer et al., 2001 and Soderlund et al., 2004 calculated from terrestrial mineral isochrones). Initial $^{176}\text{Hf}/^{177}\text{Hf}_i$ and ϵHf_i for all analysed zircon domains were calculated using the preferred U-Pb ages.

Depleted mantle hafnium model ages (TDM) were calculated using present day $^{176}\text{Hf}/^{177}\text{Hf}$ = 0.283164 value for average MORB (Chauvel et al., 2008) which is assumed to be present day depleted mantle composition. This value corresponds to an initial $\epsilon\text{Hf}_{(t=0\text{Ga})}$ = 13.4. DM evolution trend was propagated to $\epsilon\text{Hf}_{(t=4\text{Ga})}$ = 0, because the existence of a voluminous depleted mantle reservoir during Hadean-Early Archean is highly speculative (see Hawkesworth et al., 2010; Kemp et al., 2010 and discussions of Zeh et al., 2011). TDM values for all data were

calculated using a mean $^{176}\text{Lu}/^{177}\text{Hf}$ of 0.0113 (average continental crust; [Rudnick and Gao, 2003](#)) for the zircon crystallization age.

MORB $^{176}\text{Hf}/^{177}\text{Hf}$ interval were taken from the Atlantic, Pacific and Indian MORB values (excepting three unusual low values from the Indian Ocean) reported by [Chauvel and Blichert-Toft \(2001\)](#) considering a minimum $^{176}\text{Hf}/^{177}\text{Hf} = 0.28302$ ($\varepsilon\text{Hf}_{(t=0\text{Ma})} = 8.3$) and a maximum $^{176}\text{Hf}/^{177}\text{Hf} = 0.28337$ ($\varepsilon\text{Hf}_{(t=0\text{Ma})} = 20.7$). These values are propagated to $\varepsilon\text{Hf}_{(t=4\text{Ga})} = 0$ defining a field (blue discontinuous lines) around the DM-evolution trend where the real DM composition should lie (i.e. error field for DM-evolution line).

4.4. Sm-Nd whole rock analyses

Sample preparation and analyses were performed at the laboratory of Geocronología y Geoquímica Isotópica at the Universidad Complutense de Madrid.

Whole rock samples were dissolved by oven digestion in ultra-pure HF and HNO₃ acids together with the $^{149}\text{Sm}/^{150}\text{Nd}$ spike in sealed teflon microreactors. Once the samples were dissolved and dried HNO₃ was added to eliminate silica fluorides and after that HCl was added to form chlorine molecules. Then the sample was subjected to a centrifugal process and to a two stage conventional ion-exchange chromatography to concentrate and separate REEs with DOVEX AG-50x12 (200-400 mesh) resin, and to separate Sm from Nd with HEDHP resin. The fractions where Sm and Nd are present in high concentrations are dried and loaded with H₃PO₄ on rhenium filaments in triple disposition, and analysed in a thermal ionization mass spectrometer TIMS-Phoenix HCT040[®] following a dynamic multicollector method. The measured $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic ratios were corrected for possible isobaric interferences from ^{142}Ce and ^{144}Sm (only for samples with $^{147}\text{Sm}/^{144}\text{Sm} < 0.0001$) and normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ ([O'Nions et al., 1977](#)) to correct for mass fractionation. The LaJolla Nd international isotopic standard was analysed during sample measurement, and gave an average value of $^{143}\text{Nd}/^{144}\text{Nd} = 0.511850$ for 7 replicas, with an internal precision of ± 0.00001 (2 σ). These values were used to correct the measured ratios for possible sample drift following reference values from [Lugmair et al. \(1983\)](#). The analytic errors for $^{147}\text{Sm}/^{144}\text{Nd}$ ratio is 0.1 % and for $^{143}\text{Nd}/^{144}\text{Nd} = 0.006$ %.

Chondritic uniform reservoir (CHUR) present day values considered for this study are $^{147}\text{Sm}/^{144}\text{Nd} = 0.1967$ ([Jacobsen and Wasserburg, 1980](#)) and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$ ([Hamilton et al., 1983](#)). The DM evolution trend and DM model ages (TDMs) have been calculated as described by [DePaolo \(1981\)](#) using $^{147}\text{Sm}/^{144}\text{Nd}$ ratios and MDAs for each sample. A ^{147}Sm decay constant of $6.539 \times 10^{-11} \text{ a}^{-1}$ has been used, calculated from ^{147}Sm half-life reported by

[Lugmair and Marti \(1978\)](#) and [Begemann et al. \(2001\)](#). MORB epsilon values of +7 to +12 used are those reported by [DePaolo and Wasserburg \(1976\)](#).

5. Results

5.1. U-Pb results

The results of U-Pb dating are given as supplementary electronic material (Suppl. Electr. Mat., Tables 1 to 6) and represented on Fig. 3. In order to allow forward comparisons, the age spectrum has been divided in four mayor groups: Paleozoic-Neoproterozoic (< 1 Ga), Mesoproterozoic (1 - 1.6 Ga), Paleoproterozoic (1.6 - 2.5 Ga) and Archean (> 2.5 Ga; see Fig. 6). Descriptions of U-Pb results of each sample are as follows.

From sample GCH-07, 166 analyses were performed of which 149 were concordant (< 10 % discordance, $d = 10.2\%$, d : percentage of discordant analyses). 63 of them are Paleozoic-Neoproterozoic (42.3 %), 3 are Mesoproterozoic (2 %), 54 are Paleoproterozoic (36.2 %) and 29 are Archean (19.5 %). MDA_{07} (GCH-07 maximum depositional age) calculated for this sample (see above) is 510.4 ± 2.4 Ma, using 12 ages.

From sample GCH-08, 122 analyses were performed of which 117 were concordant ($d = 4.1\%$). 46 of them are Paleozoic-Neoproterozoic (39.3 %), 3 are Mesoproterozoic (2.6 %), 53 are Paleoproterozoic (45.3 %) and 15 are Archean (12.8 %), with a MDA_{08} of 515.6 ± 3.8 Ma, using 15 ages.

From sample GCH-09, 131 analyses were performed of which 128 were concordant ($d = 2.3\%$). 45 of them are Paleozoic-Neoproterozoic (35.2 %), 4 are Mesoproterozoic (3.1 %), 54 are Paleoproterozoic (42.2 %) and 25 are Archean (19.5 %), with a MDA_{09} of 507.1 ± 4.2 Ma, using 10 ages.

From sample GCH-10, 154 analyses were performed of which 144 were concordant ($d = 6.5\%$). 52 of them are Paleozoic-Neoproterozoic (36.1 %), 7 are Mesoproterozoic (4.9 %), 72 are Paleoproterozoic (50 %) and 13 are Archean (9 %), with a MDA_{10} of 506 ± 10 Ma, using 4 ages.

From sample GCH-11, 168 analyses were performed of which 159 were concordant ($d = 5.4\%$). 51 of them are Paleozoic-Neoproterozoic (32.1 %), 6 are Mesoproterozoic (3.8 %), 79 are Paleoproterozoic (49.7 %) and 23 are Archean (14.5 %), with a MDA_{11} of 506.3 ± 2.8 Ma, using 9 ages.

From sample GCH-12, 148 analyses were performed of which 142 were concordant ($d = 4.1\%$). 45 of them are Paleozoic-Neoproterozoic (31.7 %), 7 are Mesoproterozoic (4.9 %), 81

are Paleoproterozoic (57 %) and 9 are Archean (6.3 %), with a MDA_{12} of 509.4 ± 7.1 Ma, using 5 ages.

To merge all samples and treat them as a single sample a Kolmogorov-Smirnov test has been performed. Fig. 5a shows its P-values and Fig. 5b the cumulative density function plot (CDF) which includes age errors. P-values indicate that all six samples pass the test with the exception of GCH-07 with GCH-11 ($P = 0.044$) and GCH-07 with GCH-12 ($P = 0.027$) comparison. Both P-values are near to 0.05 (value required to pass the test) and taking into account that the other 13 comparisons are satisfactory and the similarity between age distributions observed on KDE, PDP (Fig. 4) and CDF plots (Fig. 5b), it is concluded that all samples are shed from the same source area and that the differences between zircon age populations are explained by sampling bias or/and because each sample is a small fraction of the same thick pile of sediments (i.e. the same formation) located in different parts of the stratigraphic column, and so in different positions in relation to the source area.

Analyses from all samples are summarized on Fig. 6 and add a total of 889 age determinations, from which 839 have less than 10 % discordance ($d = 5.6$ %). 36 % of the analyses ($n = 302$) have a Paleozoic-Neoproterozoic age with peaks at 505, 525, 540, 557, 590, maximum abundance at 525 Ma, and a tail with minor peaks between 600 and 800. Mesoproterozoic ages are scattered in the interval age of c. 1.0 to 1.5 Ga and do not define any maxima, comprising 3.6 % ($n = 30$) of the total ages. The main age group is Paleoproterozoic (46.8 %, $n = 393$) and it is constrained between c. 1.98 and 2.17 Ga with a well-defined maximum at 2.09 Ga. The Archean population represents 13.6 % ($n = 114$) of the analyses with maxima at c. 2.6, 2.64 and 2.7 Ga. MDAs calculated for each sample vary from 506 to 516 Ma, with an average of 509.5 ± 3.6 Ma (Fig. 7; calculated as weighted average of all six MDAs with Isoplot software). The conservative way in which these MDAs have been calculated guarantees with a high level of confidence that the age of deposition is c. 510 Ma or younger.

5.2. Lu-Hf results

From the 839 concordant zircon cores analysed with U-Pb method 420 were analysed for Lu-Hf isotopes (Suppl. Electr. Mat., Tables 7 to 11). Around 58 % of all analyses have positive ϵ_{Hf} (Fig. 8a). When these superchondritic zircon data plot near the DM evolution trend it can be surmised that they were crystallised from magmas more or less directly derived from a depleted mantle source.

Paleozoic-Neoproterozoic zircons (in particular Cambrian-Ediacaran) are arranged in the Hf-U-Pb age diagram in two ways (Figs. 8a and 8b). First as positive ϵ_{Hf} zircons (from 0 to +10

epsilon units) with TDMs from c. 0.65 to 1.2 Ga (average at 0.9 Ga), pointing to a high production of juvenile (depleted mantle derived) magmas between c. 500 to 560 Ma, most of them crystallizing at c. 525 Ma. This observation is consistent with a developed magmatic arc setting. The second way in which these zircons are arranged is with a wide range in their ϵHf units, from 0 to -16. There is also a small cluster of 7 zircons with ϵHf of -23 to -26, and a single analyses with $\epsilon\text{Hf} = -49$. There are two explanations for the generation of these negative ϵHf zircons: i) by a mixing process between juvenile magmas and materials with strong negative ϵHf values and ii) by an intense c. 500 to 560 Ma crustal reworking process of c. 0.8 - 2.1 Ga DM derived materials. This second explanation is not favoured owing to the very low proportion of Mesoproterozoic zircons in the samples. The first explanation requires the juvenile magmas to mix with a source with an $\epsilon\text{Hf}_{(\text{c. } 525\text{Ma})} < -16$ to give this wide negative range of ϵHf to the zircons. If we follow the evolutionary field array on Fig. 8a, this source is represented by the c. 2.09 Ga zircons that lie on the Eburnean crust evolution trend. The other 8 Paleozoic-Neoproterozoic zircons with ϵHf values below -23 lie on the Archean crust evolution field and therefore were probably formed by recycling Archean crust. Zircons with ages between c. 560 - 750 Ma plot around or slightly above the CHUR evolution trend, which is in line with an early magmatic arc setting. All these observations are in agreement with the development of a c. 500 - 750 Ma magmatic arc setting.

Paleoproterozoic 1.9 - 2.2 Ga zircons are arranged in a similar way as the Paleozoic-Neoproterozoic zircons. Superchondritic clustered zircon data have TDM values from c. 2.0 to 2.6 Ga (average at 2.3 Ga) and resemble a crust formation event where DM derived magma intrusion started at c. 2.17 Ga, with crystallization ages concentrated at 2.09 Ga and finished around 1.98 Ga. This timing falls within the timespan considered for the Eburnean Orogeny (c. 1.8 - 2.2 Ma; [Ennih and Liégeois, 2008](#)). Subchondritic zircon data have ϵHf values from 0 to -15, and point to a mixing process between the DM derived magmas and older rocks, probably the Archean crust.

Paleoproterozoic and Archean zircon ages range between c. 2.24 and 3.03 Ga and have slightly positive ϵHf up to +4 and negative ϵHf down to -15, with TDMs from c. 2.8 to 3.6 Ga (maximum at 3.1 Ga). These analyses are not clustered but they are arranged in a linear trend, which is slightly lower than the average continental crustal evolution trend of $^{176}\text{Lu}/^{177}\text{Hf} = 0.0113$ used to calculate TDMs in this study. These linear arranged analyses (vs. cluster superchondritic arrange) points to an Archean crust formation event at c. 3.1 Ga, where its materials underwent subsequent crustal reworking during the Late Archean.

5.3. Sm-Nd results

In crustal evolution models based on Nd isotopic compositions, the main fractionation event during the formation and evolution of continental crust takes place during partial melting of lithospheric mantle to generate the source of crustal rocks ([McLennan and Hemming, 1992](#)). The ϵNd model age of a sedimentary rock represents the average age of the extraction of its components from the mantle. In the case of detrital rocks, model ages usually reflect complex mixtures based on the different age and provenance of their components. The combined interpretation of Nd model ages and detrital zircon ages has proven to be a powerful tool for investigating the evolution of continental crust, especially in orogenic belts (e.g., [Linnemann et al., 2004](#)).

Whole rock Sm-Nd analyses were performed on 10 Cariño Gneiss samples. Results (Table 1) have been plotted on Fig. 9. Present day Nd epsilon values ($\epsilon\text{Nd}_{t=0\text{Ma}}$) vary from -16.0 to -11.4 and ϵNd for the time of sedimentation ($\epsilon\text{Nd}_{t=510\text{Ma}}$) varies from -10.2 to -6.3. Depleted mantle model ages (TDM) range between 1.82 and 1.58 Ga, with an average of 1.73 Ga.

Results were plotted together with Sm-Nd data for the uppermost siliciclastic series of the Upper Allochthon of the Órdenes Complex ([Fuenlabrada et al., 2010](#)) to establish similarities between detrital units belonging to this terrane (Fig. 9). These low-grade metagreywackes have a Nd TDM average of c. 1 Ga ($n = 20$) and the Cariño Gneisses an older mean of c. 1.73 Ga ($n = 10$). This isotopic difference between sedimentary rock series included in the Upper Allochthon and with similar maximum depositional ages is interpreted to reflect changes in the setting of individual series in relation to the peri-Gondwanan arc system. The Cariño Gneisses have a higher input of detritus with older isotopic signatures and therefore it is assumed that this series was deposited closer to the mainland than the top greywacke series of the Órdenes Complex. This last series would have been deposited closer to the most active part of the magmatic arc that shed juvenile detritus into the basin.

6. Provenance of the Upper Allochthon involved in the Variscan suture

According to the data presented in this contribution the maximum depositional age is c. 510 Ma, so its protolith was a Middle Cambrian or younger sedimentary series. Concordia (Fig. 3) and PDP-KDE (Fig. 4) plots reveal two main age populations, with pronounced age peaks at c. 525 Ma (Paleozoic-Neoproterozoic population: 36 %) and c. 2.09 Ga (Paleoproterozoic population: 46.8 %; Fig. 6). Archean populations compromise around 13.6 % of the total Cariño Gneiss zircons and Mesoproterozoic zircons are scarce with only a 3.6 %.

The main Archean U-Pb zircon population in the Cariño Gneisses is bracketed at 2.7-2.5 Ga (Fig. 4). The ϵ_{Hf} vs. age pattern for these zircons (Fig. 8a) is a linear trend that points to a long lasting continental crust reworking process of juvenile rocks formed at c. 3.3 - 2.9 Ga (maximum at 3.1 Ga), with no mixing processes, supporting an intracratonic or a passive margin setting. In the Northern WAC, Archean igneous rocks have mainly been reported in the Western Reguibat Shield. [Potrel et al. \(1998\)](#) published ages of around 3 Ga for juvenile magmatic rocks and [Schofield et al. \(2012\)](#) reported main intrusion events at c. 2.9, 2.7 and 2.5 Ga in this area. Based on the above studies, the Western part of the Reguibat Shield is a viable candidate for the provenance of the Cariño Gneiss Archean zircons.

The Cariño Gneiss Paleoproterozoic fraction makes up 46.8 % of the total population (Fig. 6). Maximum abundance clusters at c. 2.17 - 1.98 Ga with a maximum peak at 2.09 Ga (Fig. 4). This Paleoproterozoic population falls within the time span of the Eburnean orogeny (2.2 - 2.0 Ga according to [Egal et al., 2002](#), or 1.8 - 2.2 according to [Ennih and Liégeois, 2008](#)). This orogenic cycle was defined at the Southern WAC and has been extended to all rocks of the WAC affected by c. 2.0 Ga geological events, so the Paleoproterozoic materials of the Cariño Gneisses are possibly derived from rocks generated or reworked during the Eburnean orogeny. Close similarities are observed when comparisons are made with WAC Eburnean rocks. Eburnean ages between c. 2.1 and 2.04 Ga in igneous and sedimentary rocks have been reported in the Eastern Reguibat Shield ([Peucat et al., 2005](#)) and in the Anti-Atlas belt ([Thomas et al., 2002](#); [Abati et al., 2012](#); [Avigad et al., 2012](#)), supporting a WAC provenance for the Paleoproterozoic zircons in the Cariño Gneisses. The Cariño Gneiss Lu-Hf data (Fig. 8a) for zircons of Eburnean age (c. 2.13 - 1.97 Ga) are arranged as a cluster with positive ϵ_{Hf} values representing juvenile rocks and few values with negative ϵ_{Hf} units suggesting a mixing process of juvenile and reworked rocks, i.e. Eburnean DM derived magmas intruded in an older basement triggering mixing processes. As the most negative ϵ_{Hf} value for Eburnean zircons is -15 and the Archean linear arrangement intersects at c. 2 Ga at c. $\epsilon_{\text{Hf}} = -15$, this old basement could well be that represented by the Cariño Gneiss Archean zircons. All these observations are in agreement with the geodynamic setting proposed by [Egal et al. \(2002\)](#), where the Eburnean is an active margin orogen formed by oceanic subduction along the edge of the pre-existing Archean craton. The input of this population in the Cariño Gneisses is much higher than in the other samples (i.e. [Abati et al., 2012](#); [Avigad et al., 2012](#)). This is probably due to the deposition of the Cariño Gneisses closer to the Paleoproterozoic source area, i.e. the Northern WAC.

In the Mesoproterozoic Era the WAC became a stable craton ([Ennih and Liégeois, 2008](#)) which gave as a result a characteristic c. 1.7 - 1.0 Ga “magmatic gap” ([Linnemann et al., 2008](#) and references therein). Nevertheless, in some peripheral WAC derived samples,

Mesoproterozoic zircons are relatively common in Ediacaran – Ordovician and younger siliciclastic samples. This is the case in NW Iberia, where the provenance of these series is frequently assigned to a provenance from the Saharan metacraton (i.e. [Díez Fernández et al., 2010](#)). However, recently a Middle Cambrian sandstone from the Anti-Atlas belt has been reported to contain zircons with Stenian Mesoproterozoic ages from c. 1.1 to 1 Ga ([Avigad et al., 2012](#)). Therefore siliciclastic series formed in the Cambrian close to the WAC can also contain this zircon population. In the Cariño Gneisses, the Mesoproterozoic zircons are scarce and scattered, constituting 3.6 % of the total population and not defining a clear maximum (Fig. 4). This population is also present in the Parautochthon ([Díez Fernández et al., 2012b](#)) and in the Basal Allochthon (basal units) of NW Iberia ([Díez Fernández et al., 2010](#)). These populations could derive from cratons adjacent to the WAC, i.e. Amazonian, Saharan or the Arabian-Nubian cratons (Fig. 10), transported by rivers, wind or by a tectonic along-strike transport of terranes during Cadomian orogenic processes ([Fernández-Suárez et al., 2002](#); [Gutiérrez-Alonso et al., 2003](#)), or even from unknown Mesoproterozoic igneous rocks in the WAC. In any case the Mesoproterozoic population is still enigmatic but it is present in the siliciclastic derived formations of the allochthonous complexes of NW Iberia, albeit in much lower proportions than in putative coeval rocks of the Autochthon ([Fernández-Suárez et al., 2013](#) and references therein) and it could be a distinctive feature for these rocks.

The Paleozoic-Neoproterozoic fraction constitutes 36 % of the Cariño Gneiss zircons, most of them with ages of c. 750 - 490 Ma and with a maximum abundance at c. 525 Ma. These ages coincide with the reported ages for the Cadomian and Pan-African orogenies (c. 750 - 540 Ma; e.g. [Ennih and Liégeois, 2008](#); [Linnemann et al., 2014](#)) but the c. 525 Ma Cariño Gneiss maximum is younger, suggesting a different metacratonic WAC activity or a late development of the Cadomian - Pan-African orogenies. Paleozoic-Neoproterozoic populations in the WAC are very common. For example, merged samples published by [Abati et al. \(2012\)](#) from the Sirwa Window (Anti-Atlas belt) have an age range of c. 540 - 770 Ma with peaks at c. 560 and 610 Ma. [Thomas et al. \(2002\)](#) reported igneous rock zircon U-Pb ages from the same area with ages of c. 560-580, 610 and 740 Ma, and from the NE flank of the Zenaga inlier (Anti-Atlas belt) two groups of detrital U-Pb ages where published by [Avigad et al. \(2012\)](#). Ages in these samples were c. 532 - 668 Ma with a peak at 570 Ma and c. 545 - 750 Ma with a peak at 655 Ma (in addition to Cryogenian and Tonian peaks). Cariño Gneiss zircons with ages between c. 760 and 560 Ma are not abundant and plot in the Lu-Hf diagram (Figs. 8a and 8b) around the CHUR evolution trend, pointing to a crustal recycling of early Cadomian - Pan-African material. C. 560 - 500 Ma Cariño Gneiss zircons are very abundant with a maximum peak at c. 525 Ma. The Lu-Hf isotopic pattern (Figs. 8a and 8b) shows that these Cariño Gneiss zircons are arranged as a

cluster with positive ϵ_{Hf} values plotting near the DM evolution trend and as a variably negative ϵ_{Hf} arrangement. These patterns can be explained by the intrusion of juvenile magmas that triggered mixing process with an Eburnean and Archean crust and with a small proportion of reworked early Cadomian - Pan-African crustal material, consistent with a peripheral arc activity at the Northern WAC.

As discussed by [Cawood et al. \(2012\)](#) convergent margin basins have a high proportion of detrital zircons with ages close to the age of the sediment, where back arc basins have an increasing input of older detritus from the adjoining mainland. The Cariño Gneiss U-Pb age distribution pattern is a strongly bimodal one where the majority of the Paleozoic-Neoproterozoic fraction is concentrated near its MDA, as appreciated by the steep slope of the CDF diagram (Fig. 5b), or the narrow bell shaped curve of the KDE plot (Fig. 4). These observations suggest that the Cariño Gneisses turbiditic greywacke sediments were deposited in a relatively narrow back-arc type basin, where the late/post Cadomian - Pan-African volcanic arc system was very active, shedding its juvenile materials into the basin at the same time as the adjacent WAC furnished the Eburnean and Archean detritus.

Comparison with the Órdenes Complex uppermost unit reveals that the IP Upper Allochthon is heterogeneous. This unit, which was thought to correlate with the Cariño Gneiss unit, has yielded a MDA of 510-530 Ma and was intruded by a swarm of dykes with protolith ages of c. 510 Ma ([Fernández-Suárez et al., 2003](#); [Díaz García et al., 2010](#); [Fuenlabrada et al., 2010](#)). Its zircon population ($n = 85$) has 81 % of Paleozoic-Neoproterozoic zircons, 0 % are Mesoproterozoic, 19 % are Paleoproterozoic and 0 % are Archean ones. This unit has a higher Paleozoic-Neoproterozoic zircon input and younger Nd DM model ages ($\text{TDM}_{\text{mean}} = 1 \text{ Ga}$) than the Cariño Gneisses ($\text{TDM}_{\text{mean}} = 1.73 \text{ Ga}$, Fig. 9). Therefore the IP Upper Allochthon of the NW Iberian complexes is interpreted to represent different stages and positions within the peri-Gondwanan back-arc basin, where the Cariño Gneisses were deposited closer to the stable metacraton (WAC) and the Órdenes Complex Upper Allochthon unit was deposited closer to the arc.

A paleogeographical sketch map of the peri-Gondwanan region at c. 500 Ma is presented in Fig. 10. The sedimentary series included in the upper units were deposited close to a long lived volcanic arc. The Cariño Gneiss protoliths were probably formed in a back-arc basin, in a sedimentary basin with abundant detritus coming from the most active part of the arc and from the mainland. Other siliciclastic series from the Upper Allochthon, such as the Órdenes Complex top metagreywackes, were deposited closer to the active part of the arc, in a domain of the sedimentary basin where the arc was the main sediment supplier. The basal units of the allochthonous complexes contain siliciclastic metagreywacke series with MDA in the range of c.

560 - 517 Ma and detrital zircon maximum abundance age of c. 650 Ma ([Díez Fernández et al., 2010](#)). These siliciclastic series are characterized by Nd TDM model ages in the range of 1.74 - 2.22 Ga ([Fuenlabrada et al., 2012](#)), the oldest model ages reported so far in the NW Iberian terranes, including both the autochthonous and allochthonous domains. These relatively old isotopic sources strongly suggest deposition in a tectonic setting where detritus were sourced dominantly from the Gondwana mainland (Fig. 10). The most frequent siliciclastic series included in the basal units ([Díez Fernández et al., 2010](#)) seems to be older than those forming part of the Upper Allochthon. They were deposited closer to the mainland and they do not reflect the most recent activity of the arc during the Middle Cambrian. Finally, according to available zircon data and the dynamic evolution of the Variscan belt, the original setting of the Iberian Autochthon was probably located further to the East, in any transitional region between the West African Craton and the Sahara Craton (Fig. 10; [Gómez Barreiro et al., 2007](#); [Díez Fernández et al., 2010](#); [Shaw et al., 2014](#)), or even further East, in the vicinity of the present day Jordan-Israel region ([Fernández-Suárez et al., 2013](#)).

7. Conclusions

The protoliths of the Cariño Gneiss formation, the intermediate pressure Upper Allochthon included in the Cabo Ortegal Complex, are formed by siliciclastic series that represent the deposition of greywackes by turbidity currents at c. 510 Ma (maximum depositional age from detrital zircons). Considering the high proportion of Eburnean zircon input and its relatively old whole rock Nd TDM values, the siliciclastic series were deposited in a peripheral back-arc basin somewhere between an active volcanic arc and the Northern margin of the West Africa Craton (WAC). In this tectonic setting, detritus arrived both from the active part of the volcanic arc and from the mainland. These metasedimentary rocks record Archean, Eburnean, and late or post Cadomian - Pan-African crust formation events, with a 3.6 % Mesoproterozoic zircon input.

In the source region of the gneiss formation, the Archean crust formation event is roughly dated at c. 3.3 - 2.9 Ga, which is represented by zircons with c. 3.0 - 2.2 Ga crystallization ages. These Archean materials suffered important crustal reworking processes without any mixing with other materials supporting an intracratonic or a passive margin setting.

The recorded Eburnean events represent the intrusion of Eburnean juvenile magmas into an Archean basement, most probably the Archean basement represented by the Cariño Gneiss Archean zircons. The most probable geodynamic setting is a volcanic arc at the margin of a pre-existing Archean craton.

Archean and Paleoproterozoic (Eburnean) zircon populations seem to be derived from the WAC. The Cambrian events recorded in the Cariño Gneisses represent a magmatic arc at the periphery of the North Gondwana margin, specifically the North WAC. This arc records the intrusion of c. 525 Ma juvenile magmas into the Eburnean and Archean basement of Gondwana. The first stages of the arc were probably linked to the Cadomian arc system, defined in other parts of Europe as to have an activity bracketed between 750 Ma and 540 Ma, and so it could represent a long lasting volcanic-magmatic arc system.

Taking into account the Nd TDM model ages published from other metagreywacke series included in the NW Iberian Upper Allochthon, it can be concluded that this terrane contains heterogeneous isotopic sources. These varied sources indicate that different parts of the peri-Gondwanan arc system may be preserved in the Upper Allochthon.

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References

- Ábalos, B., Puellas, P., Gil Ibarguchi, J.I., 2003. Structural assemblage of high-pressure mantle and crustal rocks in a subduction channel (Cabo Ortegal, NW Spain). *Tectonics* 22.
- Abati, J., Dunning, G.R., Arenas, R., Díaz García, F., González Cuadra, P., Martínez Catalán, J.R., Andonaegui, P., 1999. Early Ordovician orogenic event in Galicia (NW Spain): evidence from U-Pb ages in the uppermost unit of the Ordenes Complex. *Earth and Planetary Science Letters* 165, 213-228.
- Abati, J., Arenas, R., Martínez Catalán, J.R., Díaz Garca, F., 2003. Anticlockwise P-T path of granulites from the Monte Castelo Gabbro (Ordenes Complex, NW Spain). *Journal of Petrology* 44, 305-327.
- Abati, J., Castiñeiras, P., Arenas, R., Fernández-Suárez, J., Gómez Barreiro, J., Wooden, J.L., 2007. Using SHRIMP zircon dating to unravel tectonothermal events in arc environments. The early Palaeozoic arc of NW Iberia revisited. *Terra Nova* 19, 432-439.
- Abati, J., Aghzer, A.M., Gerdes, A., Ennih, N., 2010a. Detrital zircon ages of Neoproterozoic sequences of the Moroccan Anti-Atlas belt. *Precambrian Research* 181, 115-128.
- Abati, J., Gerdes, A., Fernández-Suárez, J., Arenas, R., Whitehouse, M.J., Díez Fernández, R., 2010b. Magmatism and early-Variscan continental subduction in the northern Gondwana margin recorded in zircons from the basal units of Galicia, NW Spain. *Geological Society of America Bulletin* 122, 219-235.
- Abati, J., Aghzer, A.M., Gerdes, A., Ennih, N., 2012. Insights on the crustal evolution of the West African Craton from Hf isotopes in detrital zircons from the Anti-Atlas belt. *Precambrian Research* 212, 263-274.
- Andonaegui, P., del Tánago, J.G., Arenas, R., Abati, J., Martínez Catalán, J.R., Peinado, M., Díaz García, F., 2002. Tectonic setting of the Monte Castelo gabbro (Ordenes Complex, northwestern Iberian Massif): Evidence for an arc-related terrane in the hanging wall to the Variscan suture. In: Martínez Catalán, J.R., Hatcher, R.D., Arenas, R., Díaz García, F. (Eds.), *Variscan-Appalachian Dynamics: The Building of the Late Paleozoic Basement: Boulder, Colorado. Geological Society of America Special Paper* 364, pp. 37-56.
- Andonaegui, P., Castiñeiras, P., González Cuadra, P., Arenas, R., Sánchez Martínez, S., Abati, J., Díaz García, F., Martínez Catalán, J.R., 2012. The Corredoiras orthogneiss (NW Iberian Massif): Geochemistry and geochronology of the Paleozoic magmatic suite developed in a peri-Gondwanan arc. *Lithos* 128-131, 84-99.
- Arenas, R., 1988. Evolución petrológica y geoquímica de la unidad alóctona inferior del complejo metamórfico básico-ultrabásico de Cabo Ortegal (Unidad de Moeche) y del Silúrico paraautoctono, Cadena Hercínica Ibérica (NW de España). *Corpus Geologicum Gallaeciae* 4, Laboratorio Xeolóxico de Laxe. Phd thesis., p. 543.
- Arenas, R., Rubio Pascual, F.J., Díaz García, F., Martínez Catalán, J.R., 1995. High-pressure micro-inclusions and development of an inverted metamorphic gradient in the Santiago Schists (Ordenes Complex, NW Iberian Massif, Spain): evidence of subduction and syncollisional decompression. *Journal of Metamorphic Geology* 13, 141-164.
- 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). *Journal of Geology* 115, 129-148.
- Arenas, R., Sánchez Martínez, S., Gerdes, A., Albert, R., Díez Fernández, R., Andonaegui, P., 2013. Re-interpreting the Devonian ophiolites involved in the Variscan suture: U-Pb and Lu-Hf zircon data of the Moeche Ophiolite (Cabo Ortegal Complex, NW Iberia). *International Journal of Earth Sciences* 103, 1385-1402.
- Arenas, R., Díez Fernández, R., Sánchez Martínez, S., Gerdes, A., Fernández-Suárez, J., Albert, R., 2014. Two-stage collision: Exploring the birth of Pangea in the Variscan terranes. *Gondwana Research* 25, 756-763.
- Avigad, D., Gerdes, A., Morag, N., Bechstädt, T., 2012. Coupled U-Pb-Hf of detrital zircons of Cambrian sandstones from Morocco and Sardinia: Implications for provenance and Precambrian crustal evolution of North Africa. *Gondwana Research* 21, 690-703.
- Begemann, F., Ludwig, K.R., Lugmair, G.W., Min, K., Nyquist, L.E., Patchett, P.J., Renne, P.R., Shih, C.Y., Villa, I.M., Walker, R.J., 2001. Call for an improved set of decay constants for geochronological use. *Geochimica Et Cosmochimica Acta* 65, 111-121.
- Bouvier, A., Vervoort, J.D., Patchett, P.J., 2008. The Lu-Hf and Sm-Nd isotopic composition of CHUR: Constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets. *Earth and Planetary Science Letters* 273, 48-57.
- Castiñeiras, P., 2005. Origen y evolución tectonotermal de las unidades de O Pino y Cariño (Complejos Alóctonos de Galicia). *Nova Terra* 28, Laboratorio Xeolóxico de Laxe. Phd thesis., p. 279.
- Cawood, P.A., Hawkesworth, C.J., Dhuime, B., 2012. Detrital zircon record and tectonic setting. *Geology* 40, 875-878.
- Chauvel, C., Blichert-Toft, J., 2001. A hafnium isotope and trace element perspective on melting of the depleted mantle. *Earth and Planetary Science Letters* 190, 137-151.
- Chauvel, C., Lewin, E., Carpentier, M., Arndt, N.T., Marini, J.C., 2008. Role of recycled oceanic basalt and sediment in generating the Hf-Nd mantle array. *Nature Geoscience* 1, 64-67.

- DePaolo, D.J., Wasserburg, G.J., 1976. Inferences about magma sources and mantle structure from variations of $^{143}\text{Nd}/^{144}\text{Nd}$. *Geophysical Research Letters* 3, 743-746.
- DePaolo, D.J., 1981. 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, 470-488.
- Díaz García, F., 1990. La geología del sector occidental del Complejo de Órdenes, (Cordillera Hercínica, Noroeste de España). *Nova Terra* 3, Laboratorio Xeológico de Laxe. Phd thesis., p. 290.
- Díaz García, F., Arenas, R., Martínez Catalán, J.R., González del Tánago, J., Dunning, G.R., 1999. Tectonic evolution of the Careón ophiolite (northwest Spain). A remnant of oceanic lithosphere in the Variscan belt. *Journal of Geology* 107, 587-605.
- Díaz García, F., Sánchez Martínez, S., Castiñeiras, P., Fuenlabrada, J.M., Arenas, R., 2010. A peri-Gondwanan arc in NW Iberia. II: Assessment of the intra-arc tectonothermal evolution through U-Pb SHRIMP dating of mafic dykes. *Gondwana Research* 17, 352-362.
- Dickinson, W.R., Gehrels, G.E., 2009. Use of U-Pb ages of detrital zircons to infer maximum depositional ages of strata: A test against a Colorado Plateau Mesozoic database. *Earth and Planetary Science Letters* 288, 115-125.
- Díez Fernández, R., Martínez Catalán, J.R., Gerdes, A., Abati, J., Arenas, R., Fernández-Suárez, J., 2010. U-Pb ages of detrital zircons from the Basal allochthonous units of NW Iberia: Provenance and paleoposition on the northern margin of Gondwana during the Neoproterozoic and Paleozoic. *Gondwana Research* 18, 385-399.
- Díez Fernández, R., Martínez Catalán, J.R., Arenas, R., Abati, J., 2011. Tectonic evolution of a continental subduction-exhumation channel: Variscan structure of the basal allochthonous units in NW Spain. *Tectonics* 30, 1-22.
- Díez Fernández, R., Castiñeiras, P., Gómez Barreiro, J., 2012a. Age constraints on Lower Paleozoic convection system: Magmatic events in the NW Iberian Gondwana margin. *Gondwana Research* 21, 1066-1079.
- Díez Fernández, R., Martínez Catalán, J.R., Arenas, R., Abati, J., Gerdes, A., Fernández-Suárez, J., 2012b. U-Pb detrital zircon analysis of the lower allochthon of NW Iberia: age constraints, provenance and links with the Variscan mobile belt and Gondwanan cratons. *Journal of the Geological Society* 169, 655-665.
- Egal, E., Thieblemont, D., Lahondere, D., Guerrot, C., Costea, C.A., Iliescu, D., Delor, C., Goujou, J.C., Lafon, J.M., Tegye, M., Diaby, S., Kolie, P., 2002. Late Eburnean granitization and tectonics along the western and northwestern margin of the Archean Kenema-Man domain (Guinea, West African Craton). *Precambrian Research* 117, 57-84.
- Ennih, N., Liégeois, J.-P., 2008. The boundaries of the West African craton, with special reference to the basement of the Moroccan metacratonic Anti-Atlas belt. *Geological Society, London, Special Publications* 297, 1-17.
- Fernández-Suárez, J., Gutiérrez-Alonso, G., Jenner, G.A., Tubrett, M.N., 1999. Crustal sources in Lower Palaeozoic rocks from NW Iberia: insights from laser ablation U-Pb ages of detrital zircons. *Journal of the Geological Society* 156, 1065-1068.
- 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.
- Fernández-Suárez, J., Díaz García, F., Jeffries, T.E., Arenas, R., Abati, J., 2003. Constraints on the provenance of the uppermost allochthonous terrane of the NW Iberian Massif: inferences from detrital zircon U-Pb ages. *Terra Nova* 15, 138-144.
- Fernández-Suárez, J., Arenas, R., Abati, J., Martínez Catalán, J.R., Whitehouse, M.J., Jeffries, T.E., 2007. U-Pb chronometry of polymetamorphic high-pressure granulites: An example from the allochthonous terranes of the NW Iberian Variscan belt, In: Hatcher Jr, R.D., Carlson, M.P., McBride, J.H., Martínez Catalán, J.R. (Eds.), 4-D Framework of Continental Crust. *Geological Society of America Memoir* 200, pp. 469-488.
- Fernández-Suárez, J., Gutiérrez-Alonso, G., Pastor-Galán, D., Hofmann, M., Murphy, J., Linnemann, U., 2013. The Ediacaran–Early Cambrian detrital zircon record of NW Iberia: possible sources and paleogeographic constraints. *International Journal of Earth Sciences* 103, 1335-1357.
- Fuenlabrada, J.M., Arenas, R., Sánchez Martínez, S., Díaz García, F., Castiñeiras, P., 2010. A peri-Gondwanan arc in NW Iberia I: Isotopic and geochemical constraints on the origin of the arc-A sedimentary approach. *Gondwana Research* 17, 338-351.
- Fuenlabrada, J.M., Arenas, R., Díez Fernández, R., Sánchez Martínez, S., Abati, J., López Carmona, A., 2012. Sm-Nd isotope geochemistry and tectonic setting of the metasedimentary rocks from the basal allochthonous units of NW Iberia (Variscan suture, Galicia). *Lithos* 148, 196-208.
- Gerdes, A., Zeh, A., 2006. Combined U-Pb and Hf isotope LA-(MC-)ICP-MS analyses of detrital zircons: Comparison with SHRIMP and new constraints for the provenance and age of an Armorican metasediment in Central Germany. *Earth and Planetary Science Letters* 249, 47-61.
- Gerdes, A., Zeh, A., 2009. Zircon formation versus zircon alteration - New insights from combined U-Pb and Lu-Hf in-situ LA-ICP-MS analyses, and consequences for the interpretation of Archean zircon from the Central Zone of the Limpopo Belt. *Chemical Geology* 261, 230-243.

- Gil Ibarguchi, J.I., Ortega Gironés, E., 1985. Petrology, structure and geotectonic implications of glaucophane-bearing eclogites and related rocks from the Malpica—Tuy (MT) Unit, Galicia, northwest Spain. *Chemical Geology* 50, 145-162.
- Gil Ibarguchi, J.I., Mendia, M., Girardeau, J., Peucat, J.J., 1990. Petrology of eclogites and clinopyroxene-garnet metabasites from the Cabo Ortegal Complex (northwestern Spain). *Lithos* 25, 133-162.
- Gómez Barreiro, J., Martínez Catalán, J.R., Arenas, R., Castiñeiras, P., Abati, J., Díaz García, F., Wijbrans, J.R., 2007. Tectonic evolution of the upper allochthon of the Órdenes complex (northwestern Iberian Massif): Structural constraints to a polyorogenic peri-Gondwanan terrane. In: Linnemann, U., Nance, R.D., Kraft, P., Zulauf, G. (Eds.), *The evolution of the Rheic Ocean: From Avalonian-Cadomian active margin to Alleghenian-Variscan collision*. Geological Society of America Special Paper 423, pp. 315-332.
- Gutiérrez-Alonso, G., Fernández-Suárez, J., Jeffries, T.E., Jenner, G.A., Tubrett, M.N., Cox, R., Jackson, S.E., 2003. Terrane accretion and dispersal in the northern Gondwana margin. An Early Paleozoic analogue of a long-lived active margin. *Tectonophysics* 365, 221-232.
- Hamilton, P.J., O'Nions, R.K., Bridgwater, D., Nutman, A., 1983. Sm-Nd studies of Archaean metasediments and metavolcanics from West Greenland and their implications for the Earth's early history. *Earth and Planetary Science Letters* 62, 263-272.
- Hawkesworth, C.J., Dhuime, B., Pietranik, A.B., Cawood, P.A., Kemp, A.I.S., Storey, C.D., 2010. The generation and evolution of the continental crust. *Journal of the Geological Society* 167, 229-248.
- Jacobsen, S.B., Wasserburg, G.J., 1980. Sm-Nd isotopic evolution of chondrites. *Earth and Planetary Science Letters* 50, 139-155.
- Kemp, A.I.S., Wilde, S.A., Hawkesworth, C.J., Coath, C.D., Nemchin, A., Pidgeon, R.T., Vervoort, J.D., DuFrane, S.A., 2010. Hadean crustal evolution revisited: New constraints from Pb-Hf isotope systematics of the Jack Hills zircons. *Earth and Planetary Science Letters* 296, 45-56.
- Kretz, R., 1983. Symbols for rock-forming minerals. *American Mineralogist* 68, 277-279.
- Linnemann, U., McNaughton, N.J., Romer, R.L., Gehmlich, M., Drost, K., Tonk, C., 2004. West African provenance for Saxo-Thuringia (Bohemian Massif): Did Armorica ever leave pre-Pangean Gondwana? U/Pb-SHRIMP zircon evidence and the Nd-isotopic record. *International Journal of Earth Sciences* 93, 683-705.
- Linnemann, U., Pereira, F., Jeffries, T.E., Drost, K., Gerdes, A., 2008. The Cadomian Orogeny and the opening of the Rheic Ocean: The diachrony of geotectonic processes constrained by LA-ICP-MS U-Pb zircon dating (Ossa-Morena and Saxo-Thuringian Zones, Iberian and Bohemian Massifs). *Tectonophysics* 461, 21-43.
- Linnemann, U., Gerdes, A., Hofmann, M., Marko, L., 2014. The Cadomian Orogen: Neoproterozoic to Early Cambrian crustal growth and orogenic zoning along the periphery of the West African Craton—Constraints from U–Pb zircon ages and Hf isotopes (Schwarzburg Antiform, Germany). *Precambrian Research* 244, 236-278.
- López-Carmona, A., Abati, J., Pitra, P., Lee, J.K.W., 2014. Retrogressed lawsonite blueschists from the NW Iberian Massif: P-T-t constraints from thermodynamic modelling and Ar-40/Ar-39 geochronology. *Contributions to Mineralogy and Petrology* 167.
- Ludwig, K.R., 2012. User's Manual for Isoplot 3.75. A Geochronological Toolkit for Microsoft Excel. Berkeley Geochronology Center Special Publication No. 5, 75.
- Lugmair, G.W., Marti, K., 1978. Lunar initial $^{143}\text{Nd}/^{144}\text{Nd}$: Differential evolution of the lunar crust and mantle. *Earth and Planetary Science Letters* 39, 349-357.
- Lugmair, G.W., Shimamura, T., Lewis, R.S., Anders, E., 1983. Sm-146 in the early solar-system - Evidence from neodymium in the Allende meteorite. *Science* 222, 1015-1018.
- Marcos, A., Marquínez, J., Pérez-Estaún, A., Pulgar, J.A., Bastida, F., 1984. Nuevas aportaciones al conocimiento de la evolución tectonometamórfica del Complejo de Cabo Ortegal (NW de España). *Cadernos Laboratorio Xeolóxico de Laxe* 7, 125-137.
- Martínez Catalán, J.R., Fernández-Suárez, J., Jenner, G.A., Belousova, E., Díez Montes, A., 2004. Provenance constraints from detrital zircon U-Pb ages in the NW Iberian Massif: implications for Palaeozoic plate configuration and Variscan evolution. *Journal of the Geological Society* 161, 463-476.
- Martínez Catalán, J.R., Arenas, R., Abati, J., Sánchez Martínez, S., Díaz García, F., Fernández-Suárez, J., González Cuadra, P., Castiñeiras, P., Gómez Barreiro, J., Díez Montes, A., González Clavijo, E., Rubio Pascual, F.J., Andonaegui, P., Jeffries, T.E., Alcock, J.E., Díez Fernández, R., López Carmona, A., 2009. A rootless suture and the loss of the roots of a mountain chain: The Variscan belt of NW Iberia. *Comptes Rendus Geoscience* 341, 114-126.
- Martínez Catalán, J.R., 2011. Are the oroclines of the Variscan belt related to late Variscan strike-slip tectonics? *Terra Nova* 23, 241-247.
- McLennan, S.M., Hemming, S., 1992. Samarium/neodymium elemental and isotopic systematics in sedimentary rocks. *Geochimica Et Cosmochimica Acta* 56, 887-898.
- Millonig, L.J., Gerdes, A., Groat, L.A., 2012. U–Th–Pb geochronology of meta-carbonatites and meta-alkaline rocks in the southern Canadian Cordillera: A geodynamic perspective. *Lithos* 152, 202-217.

- Morag, N., Avigad, D., Gerdes, A., Harlavan, Y., 2012. 1000–580 Ma crustal evolution in the northern Arabian-Nubian Shield revealed by U–Pb–Hf of detrital zircons from late Neoproterozoic sediments (Elat area, Israel). *Precambrian Research* 208–211, 197–212.
- O’Nions, R.K., Hamilton, P.J., Evensen, N.M., 1977. Variations in $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ in oceanic basalts. *Earth and Planetary Science Letters* 34, 13–22.
- Ordóñez Casado, B., Gebauer, D., Schafer, H.J., Gil Ibarguchi, J.I., Peucat, J.J., 2001. A single Devonian subduction event for the HP/HT metamorphism of the Cabo Ortegal complex within the Iberian Massif. *Tectonophysics* 332, 359–385.
- Peucat, J.J., Bernard-Griffiths, J., Gil Ibarguchi, J.I., Dallmeyer, R.D., Menot, R.P., Cornichet, J., Ponce De León, M.I., 1990. Geochemical and geochronological cross section of the deep Variscan crust: The Cabo Ortegal high-pressure nappe (northwestern Spain). *Tectonophysics* 177, 263–292.
- Peucat, J.J., Capdevila, R., Drareni, A., Mahdjoub, Y., Kahoui, M., 2005. The Eglab massif in the West African Craton (Algeria), an original segment of the Eburnean orogenic belt: petrology, geochemistry and geochronology. *Precambrian Research* 136, 309–352.
- Potrel, A., Peucat, J.J., Fanning, C.M., 1998. Archean crustal evolution of the West African Craton: example of the Amsaga Area (Reguibat Rise). U–Pb and Sm–Nd evidence for crustal growth and recycling. *Precambrian Research* 90, 107–117.
- Rodríguez, J., Cosca, M.A., Gil Ibarguchi, J.I., Dallmeyer, R.D., 2003. Strain partitioning and preservation of $^{40}\text{Ar}/^{39}\text{Ar}$ ages during Variscan exhumation of a subducted crust (Malpica-Tui complex, NW Spain). *Lithos* 70, 111–139.
- Rudnick, R.L., Gao, S., 2003. 3.01 - Composition of the Continental Crust, In: Holland, H.D., Turekian, K.K. (Eds.), *Treatise on Geochemistry*. Pergamon, Oxford, pp. 1–64.
- Sánchez Martínez, S., Arenas, R., Díaz García, F., Martínez Catalán, J.R., Gómez-Barreiro, J., Pearce, J.A., 2007. Careón ophiolite, NW Spain: Suprasubduction zone setting for the youngest Rheic Ocean floor. *Geology* 35, 53–56.
- Sánchez Martínez, S., Arenas, R., Gerdes, A., Castiñeiras, P., Potrel, A., Fernández-Suárez, J., 2011. Isotope geochemistry and revised geochronology of the Purrido Ophiolite (Cabo Ortegal Complex, NW Iberian Massif): Devonian magmatism with mixed sources and involved Mesoproterozoic basement. *Journal of the Geological Society* 168, 733–750.
- Sánchez Martínez, S., Gerdes, A., Arenas, R., Abati, J., 2012. The Bazar Ophiolite of NW Iberia: a relic of the Iapetus–Torqu coast Ocean in the Variscan suture. *Terra Nova* 24, 283–294.
- Scherer, E., Munker, C., Mezger, K., 2001. Calibration of the lutetium-hafnium clock. *Science* 293, 683–687.
- Schofield, D.I., Horstwood, M.S.A., Pitfield, P.E.J., Gillespie, M., Darbyshire, F., O’Connor, E.A., Abdouloye, T.B., 2012. U–Pb dating and Sm–Nd isotopic analysis of granitic rocks from the Tiris Complex: New constraints on key events in the evolution of the Reguibat Shield, Mauritania. *Precambrian Research* 204–205, 1–11.
- Shaw, J., Gutiérrez-Alonso, G., Johnston, S.T., Pastor Galán, D., 2014. Provenance variability along the Early Ordovician north Gondwana margin: Paleogeographic and tectonic implications of U–Pb detrital zircon ages from the Armorican Quartzite of the Iberian Variscan belt. *Geological Society of America Bulletin* 126, 702–719.
- Slama, J., Kosler, J., Condon, D.J., Crowley, J.L., Gerdes, A., Hanchar, J.M., Horstwood, M.S.A., Morris, G.A., Nasdala, L., Norberg, N., Schaltegger, U., Schoene, B., Tubrett, M.N., Whitehouse, M.J., 2008. Plešovice zircon - A new natural reference material for U–Pb and Hf isotopic microanalysis. *Chemical Geology* 249, 1–35.
- Soderlund, U., Patchett, J.P., Vervoort, J.D., Isachsen, C.E., 2004. The Lu-176 decay constant determined by Lu–Hf and U–Pb isotope systematics of Precambrian mafic intrusions. *Earth and Planetary Science Letters* 219, 311–324.
- Thomas, R.J., Chevallier, L.P., Gresse, P.G., Harmer, R.E., Eglinton, B.M., Armstrong, R.A., de Beer, C.H., Martini, J.E.J., de Kock, G.S., Macey, P.H., Ingram, B.A., 2002. Precambrian evolution of the Sirwa Window, Anti-Atlas Orogen, Morocco. *Precambrian Research* 118, 1–57.
- Vermeesch, P., 2004. How many grains are needed for a provenance study? *Earth and Planetary Science Letters* 224, 441–451.
- Vermeesch, P., 2012. On the visualisation of detrital age distributions. *Chemical Geology* 312, 190–194.
- Vogel, D.E., 1967. Petrology of an eclogite- and pyrigarnite-bearing polymetamorphic rock complex at Cabo Ortegal, NW Spain., *Leidse Geol Mededelingen*, Phd thesis., pp. 121–213.
- Wiedenbeck, M., Alle, P., Corfu, F., Griffin, W.L., Meier, M., Oberli, F., Vonquadt, A., Roddick, J.C., Speigel, W., 1995. 3 natural zircon standards for U–Th–Pb, Lu–Hf, trace-element and REE analyses. *Geostandards Newsletter* 19, 1–23.
- Woodhead, J.D., Hergt, J.M., 2005. A preliminary appraisal of seven natural zircon reference materials for in situ Hf isotope determination. *Geostandards and Geoanalytical Research* 29, 183–195.

854 Zeh, A., Gerdes, A., Millonig, L., 2011. Hafnium isotope record of the Ancient Gneiss Complex, Swaziland,
855 southern Africa: evidence for Archaean crust-mantle formation and crust reworking between 3.66 and 2.73
856 Ga. Journal of the Geological Society 168, 953-963.
1 857 Zeh, A., Gerdes, A., 2012. U-Pb and Hf isotope record of detrital zircons from gold-bearing sediments of the
2 858 Pietersburg Greenstone Belt (South Africa)-Is there a common provenance with the Witwatersrand Basin?
3 859 Precambrian Research 204, 46-56.
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Figure captions:

Fig. 1. Geological map of the European Variscides (a) based on [Martínez Catalán \(2011\)](#). Geological map (b) and cross-section (c) of the NW Iberian Cabo Ortegal Complex. The location of Fig. 2 geological map is also shown. Based on [Vogel \(1967\)](#); [Marcos et al. \(1984\)](#); [Arenas \(1988\)](#); [Arenas et al. \(2013\)](#). The Upper Allochthon is formed by the intermediate –P upper units and the high-p – high-T upper units.

Fig. 2. Geological map of the Northern part of the Cariño Gneiss formation, with the location of the studied samples.

Fig. 3. U-Pb conventional concordia diagrams for samples GCH- 07, 08, 09, 10, 11, and 12. Ellipses represent combined 2σ uncertainties of $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ ratios.

Fig. 4. Kernel density estimation plots (continuous line enclosing the blue area) and probability density plots (dashed line) for all samples and for the combination of all Cariño Gneiss zircons studied.

Fig. 5. (a) Results of the Kolmogorov-Smirnoff (K-S) test. This K-S test compares the distribution of detrital zircon ages from detrital samples, and tests the null hypothesis that the distributions are the same. When $P < 0.05$ it is likely with a 95% confidence level that the samples derive from different populations. (b) Cumulative distribution function (CDF) plot, incorporating measurement uncertainty, showing the probability that a zircon will be younger than a certain age and the similarity between samples.

Fig. 6. Percentage of zircon populations represented as bar diagrams and circular plots.

Fig. 7. Maximum depositional ages for each Cariño Gneiss sample (see sections 4.2 and 5.1) and the weighted average of all samples, which gives a c. 510 Ma MDA for the Cariño Gneiss formation.

Fig. 8. (a) Hf isotope evolution diagram showing Cariño Gneiss zircon data. Kernel Density Estimation of analysed zircons with Lu-Hf systematics is represented in grey. See text for discussion (section 5.2) and for constants and parameters used (section 4.3). CHUR - chondritic uniform reservoir; DM - depleted mantle; MORB - mid ocean ridge basalt. (b) Hf isotope

evolution diagram of analysed zircon grains in the age range of 400 - 1000 Ma. See text for discussion, and for constants and parameters used.

Fig. 9. Sm-Nd isotope evolution diagram showing whole-rock data of 10 metasedimentary rock samples from the Cariño Gneiss formation (Cabo Ortegal Complex, NW Iberian Massif). Whole-rock Sm-Nd data (n = 20) of the uppermost greywackes of the Órdenes Complex (upper units; [Fuenlabrada et al., 2010](#)) are included for comparison. Rhombus and triangles show ϵ_{Nd} values at present day and at maximum depositional ages. See text for discussion (section 5.3) and for constants and parameters used (section 4.4). CHUR - chondritic uniform reservoir; DM - depleted mantle; MORB - mid ocean ridge basalt.

Fig. 10. Sketch showing the proposed paleogeographic position of the upper units and other terranes from the NW Iberian Massif. Paleogeographical context based on [Fernández-Suárez et al. \(2013\)](#). Numbers in squares are zircon ages in Ga from the cratons, from [Linnemann et al. \(2014\)](#) and references therein. New zircon ages have been added to the West African Craton ([Avigad et al., 2012](#)) and to the Arabian Nubian Shield ([Morag et al., 2012](#)).

Figure 1

EUROPEAN VARISCIDES

COVER

Quaternary

INTERMEDIATE-P UPPER UNITS (Upper Allochthon)

Amphibolite facies paragneisses (Cariño Gneisses)

HIGH-P-HIGH-T UPPER UNITS (Upper Allochthon)

Paragneisses with inclusions of eclogites (Banded Gneisses)

Eclogites (rare augengneiss alternations)

Mafic and intermediate granulites and amphibolites (Bacanza Fm.)

Ultramafic rocks (Limo, Herbeira and Uzal massifs)

Paragneisses with granulite facies mafic inclusions (Chimparra Gneisses)

Metagabbros

High T amphibolites, granulites and coronitic metagabbros (Candeira Fm.)

High temperature amphibolites (Peña Escrita Fm.)

UPPER OPHIOLITIC UNITS

Amphibolites

LOWER OPHIOLITIC UNITS

Greenschists

Phyllites and schists

Serpentinities

BASAL UNITS

Felsic orthogneisses and amphibolites (minor retroeclogites and schists)

MÉLANGE UNIT

Serpentine mélangé

Serpentine phyllite mélangé

High temperature tectonic blocks (orthogneisses and amphibolites)

LOWER ALLOCHTHON - PARAUTOCHTHON (SCHISTOSE DOMAIN)

Phyllites, phyllonites, sandstones carbonaceous schists and black cherts

Rhyolites and minor dacites

Quartzites

AUTOCHTHONOUS SEQUENCES

Greenschists facies metasediments

Variscan granitoids

(c)

Figure 2
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Figure 3

Figure 4
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Figure 5

a

	GCH-07	GCH-08	GCH-09	GCH-10	GCH-11	GCH-12
GCH-07		0.679	0.257	0.110	0.045	0.053
GCH-08	0.679		0.791	0.902	0.467	0.496
GCH-09	0.257	0.791		0.189	0.422	0.029
GCH-10	0.110	0.902	0.189		0.773	0.202
GCH-11	0.045	0.467	0.422	0.773		0.709
GCH-12	0.053	0.496	0.029	0.202	0.709	

b

Figure 6

Figure 7

Figure 8
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Figure 9

Figure 10

Table 1

Sample	Sm	Nd	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd _(o)	2SE(abs)*10 ⁻⁶	εNd _(t=0)	εNd _(t=510)	T _{DM}
GCH-07	2.99	16.27	0.1111	0.511841	3	-15.5	-10.0	1783
GCH-08	3.44	18.51	0.1124	0.511879	3	-14.8	-9.3	1751
GCH-09	3.24	17.40	0.1126	0.511876	3	-14.9	-9.4	1758
GCH-10	2.50	13.09	0.1155	0.511869	2	-15.0	-9.7	1821
GCH-11	3.26	18.57	0.1063	0.511856	3	-15.3	-9.4	1683
GCH-12	4.68	24.78	0.1142	0.511968	2	-13.1	-7.7	1645
GCH-27	7.20	36.68	0.1187	0.512054	2	-11.4	-6.3	1584
GCH-28	2.23	11.96	0.1126	0.511834	3	-15.7	-10.2	1821
GCH-29	5.48	27.90	0.1186	0.511962	3	-13.2	-8.1	1731
GCH-30	2.96	16.65	0.1073	0.511815	2	-16.0	-10.2	1757
Average								1733

Supplementary Electronic Materials

[Click here to download e-component: Suppl Electr Mat Tables 1-12.xls](#)