Geol. Mag. **153** (*1*), *2016, pp. 38–60.* © *Cambridge University Press 2015*
doi:10.1017/S001675681500028X

Relationships between syn-orogenic sedimentation and nappe emplacement in the hinterland of the Variscan belt in NW Iberia deduced from detrital zircons

JOSÉ R. MARTÍNEZ CATALÁN*†, EMILIO GONZÁLEZ CLAVIJO‡, CARLOS MEIRELES§, RUBÉN DÍEZ FERNÁNDEZ¶ & JAMES BEVIS||

*Departamento de Geología, Universidad de Salamanca, 37008 Salamanca, Spain
‡Instituto Geológico y Minero de España, Azafranal, 48, 37001 Salamanca, Spain
§Laboratório Nacional de Energia e Geologia (LNEG), Rua da Amieira, Apartado 1089, 4466–956 S. Mamede de Infesta, Portugal
¶Departamento de Petrología y Geoquímica and Instituto de Geociencias (UCM, CSIC), Universidad Complutense de Madrid, 28040 Madrid, Spain
||GEMOC, Department of Earth and Planetary Sciences, Macquarie University, Sydney, NSW 2109, Australia

(*Received* 24 April 2015; *accepted* 28 April 2015; *first published online* 10 June 2015)

Abstract – Flysch-type, syn-orogenic deposits of Carboniferous age occur in relation to the emplacement of a large allochthonous nappe stack in the Variscan belt of NW Iberia. New U–Pb age populations of detrital zircons obtained using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) are considered together with others from previously dated samples to establish the relationships between sedimentation and thrusting. The age populations of four syn-orogenic formations are compared with those of the pre-orogenic sequence in the Autochthon and Parautochthon, representing the Gondwanan passive margin, and in the Allochthon, formed by peri-Gondwanan and oceanic terranes. In addition, a new structural study has been carried out to understand the relationships between the syn-orogenic deposits and the development of Variscan structures. The aims are to identify the sources of sediments and to establish the relationship between Variscan structural evolution and syn-orogenic sedimentation. Development of a forebulge outwards from the allochthonous front, deduced from the structural study, suggests the existence of depocentres that hosted the syn-orogenic sediments. Together with the trend shown by the more recent zircons in each formation, that are younger towards the external zones, the data suggest that sedimentation occurred in progressively migrating depocentres formed in front of the allochthonous wedge during its emplacement. The zircon age populations point to the Allochthon as the main source of detritus for the syn-orogenic basins, with perhaps a limited participation of the Parautochthon and Autochthon in the younger formations.

Keywords: syn-orogenic deposits, detrital zircon ages, nappe emplacement, Iberian Massif, Variscan belt.

1. Introduction

Syn-orogenic flysch-type deposits derived from the hinterland of the orogen are a characteristic of the Variscan belt, where they are widely referred to as culm (Suess, 1888), and are frequently involved in thrust sheets (Franke & Engel, 1986). In the Iberian Massif, flysch deposits of Carboniferous age are preserved in stripes in the internal zones, corresponding to late Variscan synforms. In the external zones flanking the Iberian Massif, both flysch and molasse-type sediments occur in large areas, and were deposited during late Namurian to early Westphalian times in the Cantabrian Zone (Marcos & Pulgar, 1982; Pérez-Estaún *et al*. 1988), and late Visean to early Westphalian times in the South Portuguese Zone (Schermerhorn, 1971; Oliveira, 1990).

The Iberian Massif also shares with other massifs of the Variscan belt the presence of remnants of a large nappe stack formed by peri-Gondwanan terranes and ophiolitic units. Referred to as the Allochthon, the stack includes the suture of an ocean opened around the Cambro-Ordovician boundary. It could be that of the Rheic Ocean or of a narrower peri-Gondwanan ocean, but in any case with a living time span similar to that of the Rheic (Martínez Catalán *et al*. 2009; Ballèvre *et al*. 2014).

In NW Iberia, syn-orogenic flysch-type deposits appear in close relation to a set of allochthonous terranes, and are mostly preserved in the Parautochthon, an imbricated thrust sheet separating the Allochthon and the Autochthon (Fig. 1).

To establish the relationships between sedimentation and nappe emplacement would require the dating of the syn-orogenic deposits, but this is hindered by the poor preservation of plant debris (Teixeira & Pais, 1973) and the scarcity of palynomorphs, which have been recycled in many cases (Pereira, Meireles & Pereira, 1999). Dating of detrital zircons would help to

†Author for correspondence: jrmc@usal.es

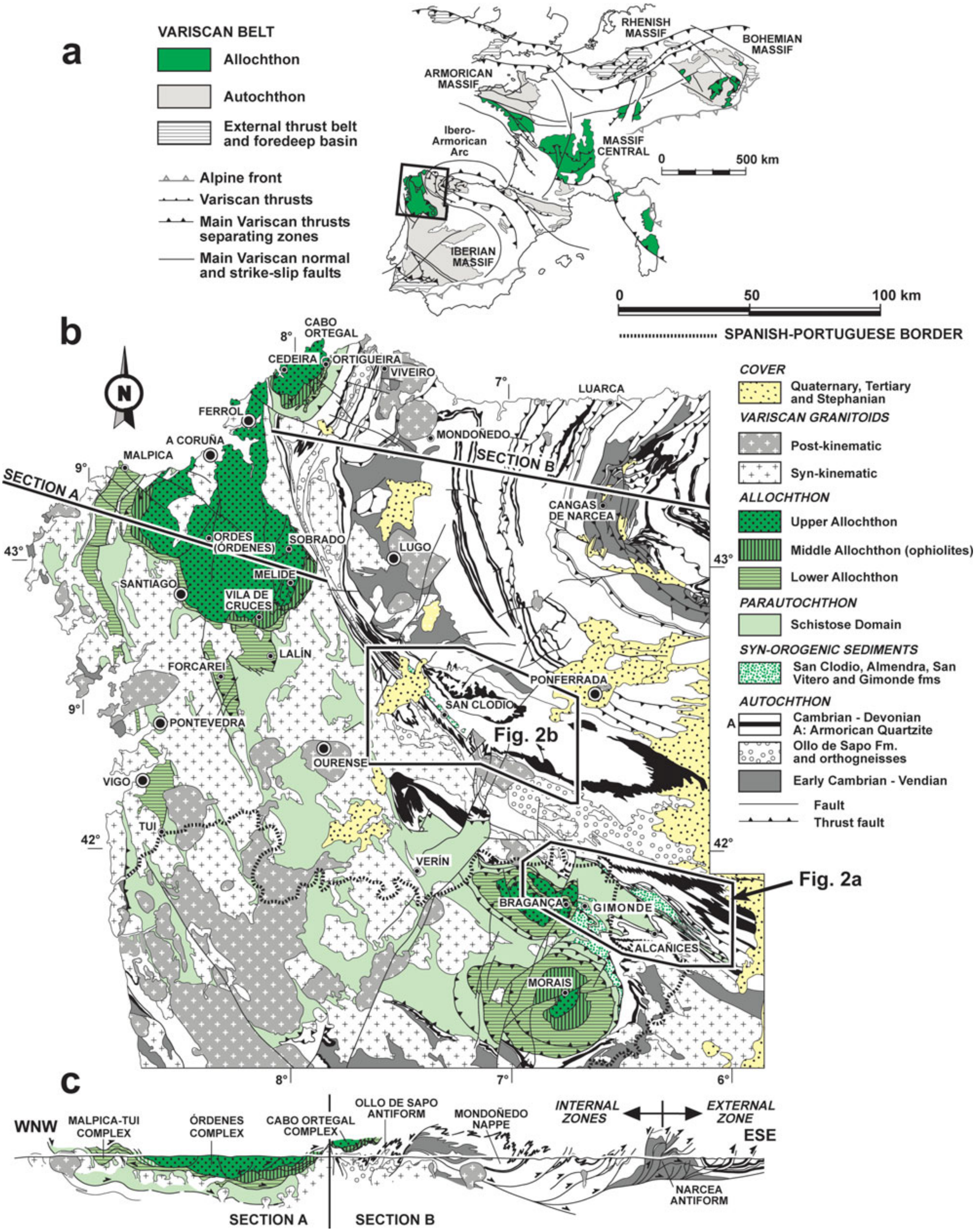

Figure 1. (Colour online) (a) Location of the study area in the Variscan belt. (b) Geological sketch map of the NW Iberian Massif showing the analysed syn-orogenic deposits and the domains discussed in the text (Allochthon, Parautochthon and Autochthon). The location of the maps in Figure 2 is shown. (c) Schematic composite cross-section.

constrain the timing of deformation by establishing the maximum depositional ages of the sedimentary units. Furthermore, the age clusters can be compared with those of the pre-orogenic sequence in the Autochthon and Parautochthon, representing the Gondwanan passive margin, and with the Allochthon, thus providing new insights into the orogenic evolution of this part of the belt.

https://doi.org/10.1017/S001675681500028X Published online by Cambridge University Press

In this study, we report new results of U–Pb zircon dating of five syn-orogenic metagreywackes imbricated in the Parautochthon and at the boundary with the Autochthon. Another two samples of pre-orogenic sedimentary rocks collected in the Parautochthon were dated to improve our knowledge about the possible sources and help to determine the provenance of the syn-orogenic sediments. The new age populations are considered together with previously published data in an attempt to (i) constrain the age of thrusting, (ii) evaluate its diachronism and that of the syn-orogenic sequences, (iii) establish the probable source areas, and (iv) show the relationship with the earlier Variscan structures.

2. Geological setting

The Autochthon of NW Iberia consists of a thick Neoproterozoic siliciclastic sequence overlain by pre-orogenic Palaeozoic clastic rocks, carbonates and volcanic rocks. During late Proterozoic time, it formed part of the Gondwanan continental active margin involved in the Cadomian–Avalonian–Pan-African orogeny (Murphy & Nance, 1991). Magmatism related to the Cadomian event was voluminous and scattered in the Autochthon (Bea *et al*. 2006; Rubio-Ordóñez *et al*. 2015). In Cambro-Ordovician times, that continental margin experienced rifting followed by the opening of the Rheic Ocean, which implied the splitting of the Avalon microcontinent and other peri-Gondwanan terranes (Fortey & Cocks, 1988; Soper, 1988). The resulting passive margin was stable until Early Devonian time, although the occurrence of minor amounts of basic and acid volcanic rocks indicates moderate extensional processes during Silurian and Devonian times (Ancochea *et al*. 1988; González Clavijo & Martínez Catalán, 2002; Gutiérrez-Alonso *et al*. 2003, 2008).

The Allochthon is exposed as klippen in five large synformal structures in NW Iberia, both in Spain and Portugal (Fig. 1). It is formed by a stack of structural units which from top to bottom includes pieces of a peri-Gondwanan continental magmatic arc of Cambro-Ordovician age (Upper Allochthon or Continental Allochthonous Terrane), units of oceanic affinity, including supra-subduction type ophiolites of Cambro-Ordovician and Early Devonian age (Middle Allochthon or Northern Ophiolitic Terrane), and parts of the thinned, outer margin of northern Gondwana (Lower Allochthon or Allochthonous Thrust Complex; Marques, Ribeiro & Pereira, 1991–1992; Marques, Ribeiro & Munhá, 1996; Ballèvre *et al*. 2014). The Cambro-Ordovician magmatic arc developed by subduction of the Iapetus Ocean under Gondwana, according to Martínez Catalán *et al*. (2007, 2009). The back-arc basin opened behind it is thought to have widened giving rise to the Cambro-Ordovician ophiolites and the extended continental margin presently forming the Lower Allochthon.

The Allochthon is separated from the Autochthon by a thrust sheet several kilometres thick called the Parautochthon (Ribeiro, Pereira & Dias, 1990; Ribeiro *et al*. 2007) or Schistose Domain (Marquínez García, 1984; Farias *et al.* 1987; Farias & Marcos, 2004; Valverde-Vaquero *et al.* 2005). Its sequence is comparable to that of the underlying Autochthon, although showing a more distal character, and consists of pre-orogenic Cambrian to Lower Devonian metasedimentary rocks and volcanic rocks, and of younger syn-orogenic flysch deposits (Farias *et al.* 1987; Gallastegui *et al*. 1988; Pereira, Meireles & Pereira, 1999; González Clavijo & Martínez Catalán, 2002; Piçarra *et al*. 2006*a*,*b*; Dias da Silva, 2014). The Parautochthon represents a palaeogeographic domain of northern Gondwana situated between the Autochthon and the Lower Allochthon (Díez Fernández *et al*. 2012*a*).

Several units of the Allochthon underwent an early Variscan pre-collisional evolution characterized by subduction and related high-pressure metamorphism, not seen in the Parautochthon or Autochthon. The three groups of allochthonous units were stacked following a piggy-back sequence of thrusting. First, the more distal Upper Allochthon formed the upper part of an accretionary wedge. Subsequently, the Middle and Lower allochthons were incorporated into the wedge during and after the closure of the intervening ocean (Martínez Catalán *et al*. 2007, 2009; Ballèvre *et al*. 2014).

Accretion took place during Devonian time, accommodating plate convergence essentially by subduction. But at the transition to the Carboniferous, and after limited subduction of the continental margin of Gondwana, the regime changed to continental collision. This marked the transition from early Variscan to Variscan shortening, and during Carboniferous time, deformation propagated into the inner parts of the continental margin. The accretionary wedge built previously was emplaced above the future Parautochthon, and then, above the Autochthon carrying the Allochthon piggy-back. The whole allochthonous wedge reached a thickness of up to *c*. 30 km, as estimated from the maximum thickness preserved in allochthonous units and by the pressure registered in the Autochthon underneath (Rubio Pascual *et al*. 2013; Martínez Catalán *et al*. 2014).

In the Autochthon, Variscan deformation involved several tectonic events that gave rise to characteristic macrostructures and associated cleavages. Compressional stresses related to plate convergence produced recumbent folds (C_1, S_1) in the Autochthon, followed by the emplacement of large thrust sheets (C_2, S_2; Figs 2, 3). The Parautochthon was emplaced along a detachment developed in Silurian carbonaceous slates which acted as a weak layer favouring slip (Farias Arquer, 1990; González Clavijo & Martínez Catalán, 2002).

Events C_1 and C_2 were diachronous, and progressively younger towards the external zones of the belt, situated to the east or northeast in present coordinates (Pérez-Estaún, Martínez Catalán & Bastida, 1991; Dallmeyer *et al*. 1997; Martínez Catalán *et al*. 2008). The recumbent folds and thrusts produced

https://doi.org/10.1017/S001675681500028X Published online by Cambridge University Press

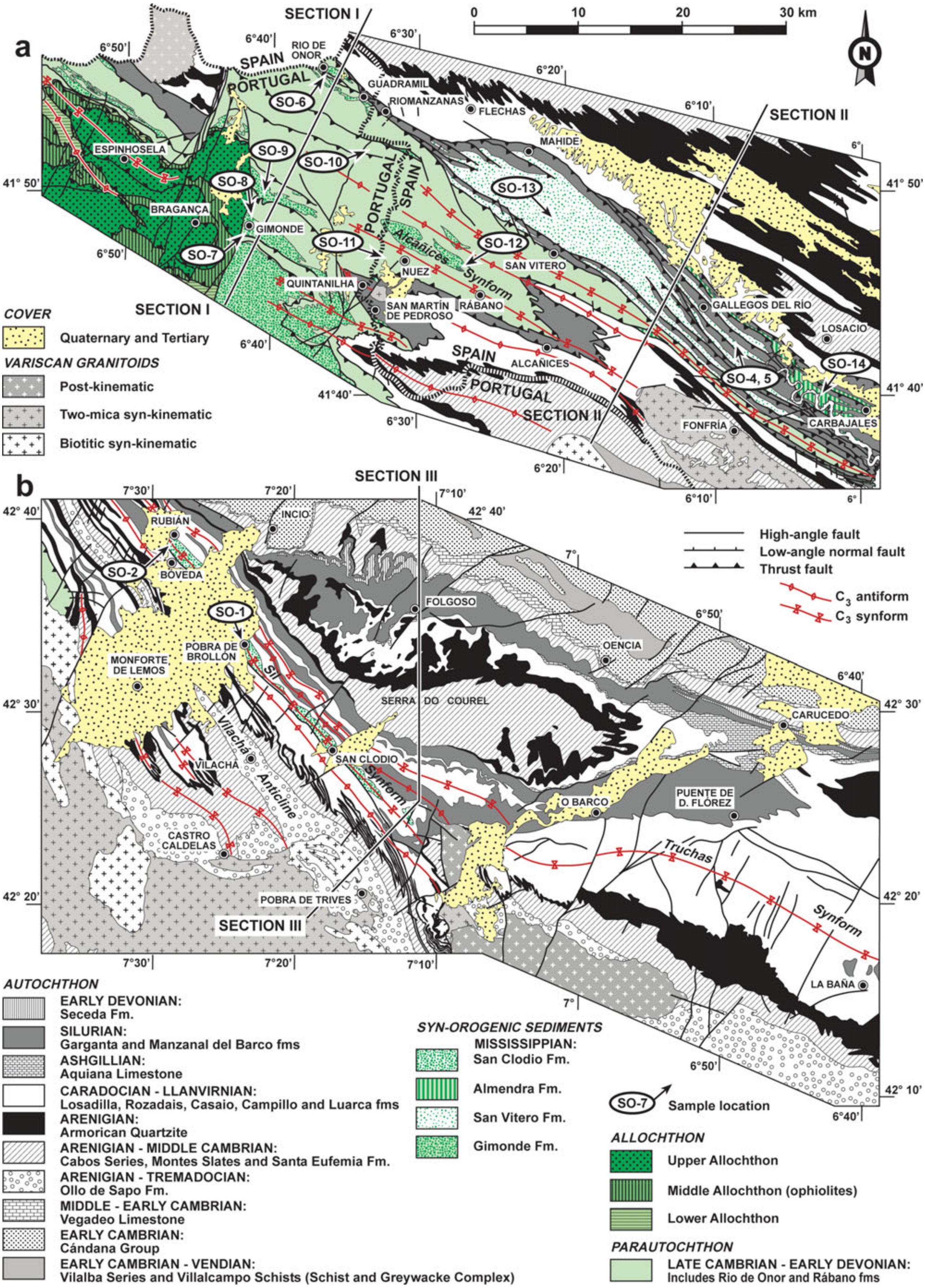

Figure 2. (Colour online) (a) Geological map of the Alcañices synform showing the Gimonde, San Vitero and Almendra syn-orogenic formations and their relationship with the large Variscan structures. (b) Geological map of the Serra do Courel and the Truchas and Sil synforms, showing the occurrence of the syn-orogenic San Clodio Fm. Also shown are the localities where the new and previously dated samples were collected, as well as the locations of the sections shown in Figure 3.

https://doi.org/10.1017/S001675681500028X Published online by Cambridge University Press

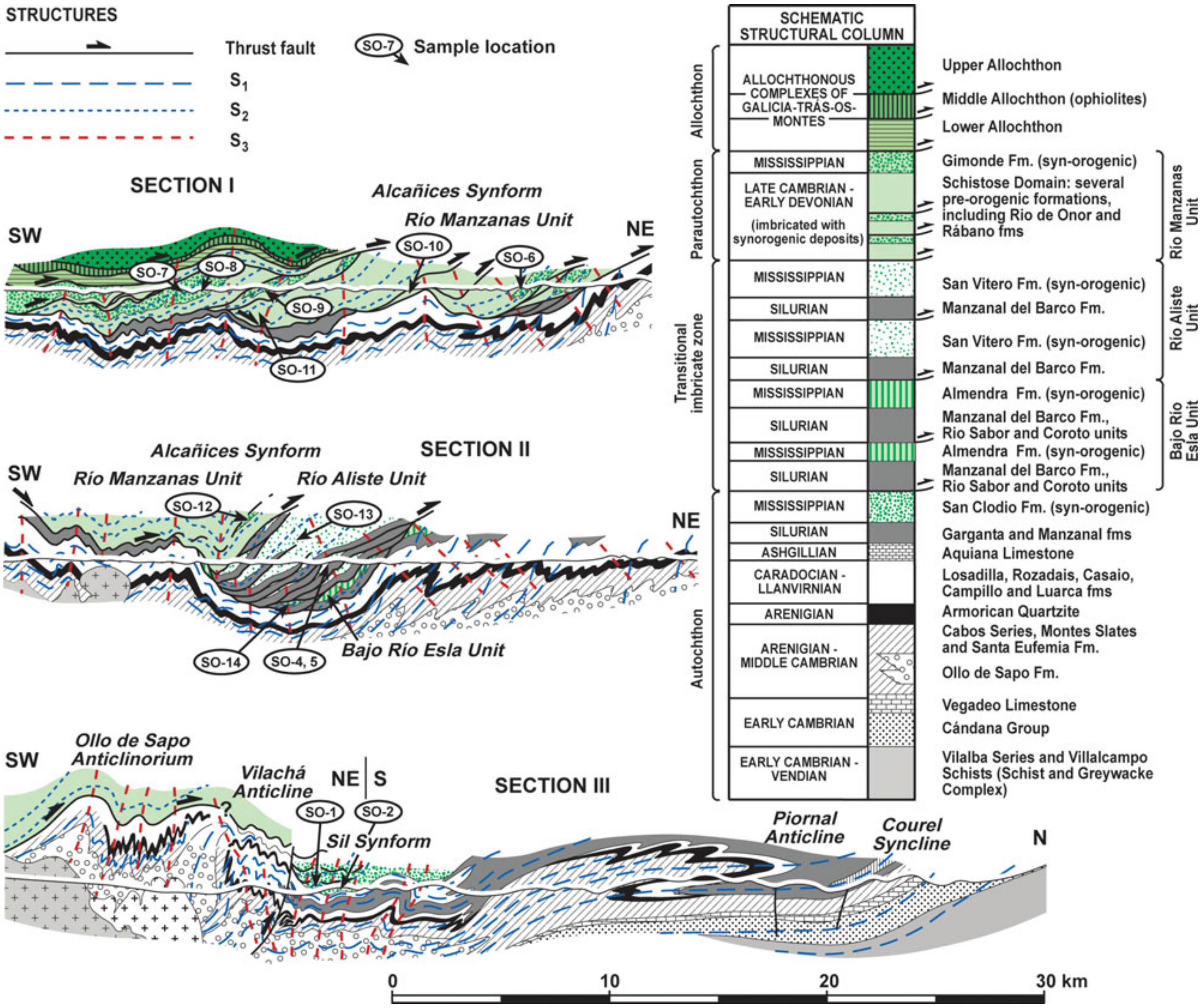

Figure 3. (Colour online) Geological sections across the Alcañices and Sil synforms. For location, see Figure 2. The structural column is simplified and depicts the main units of the different domains, although there are more imbricates, as shown in the cross-sections. The sampling localities have been projected onto the closest section to show their structural position. Recumbent folds (C_1) are cut by thrusts (C_2) and both are folded by later upright folds (C_3). Dashed lines represent the cleavages associated with each deformation event.

significant crustal thickening during early Carboniferous time, which was followed by thermal relaxation, weakening of the orogenic crust and collapse. Crustal extension took place during middle and late Carboniferous times, and is recorded in the internal zones of the orogen by the development of gneiss domes and extensional detachments (Escuder Viruete, Arenas & Martínez Catalán, 1994; Arenas & Martínez Catalán, 2003; Díez Fernández *et al*. 2012*b*). Afterwards, a new compressional event (C_3, S_3) of late Carboniferous age generated upright folds that overprinted the previous recumbent folds and thrusts, the extensional domes and detachments, and the isograds of regional metamorphism (Martínez Catalán *et al*. 2007).

3. Outline of the formations sampled

Sampling for this study was carried out in the core of the Alcañices synform, a C_3 structure which straddles the Spanish–Portuguese border and in Portugal is replaced en échelon by another synform that hosts at its core the allochthonous Bragança Complex (Figs 1, 2a). For detailed information on the geology of the Alcañices synform, see González Clavijo & Martínez Catalán (2002), González Clavijo (2006) and Meireles (2013).

In previous works, we also sampled and dated synorogenic deposits in the Alcañices synform (Martínez Catalán *et al*. 2008) as well as in the Sil synform (Martínez Catalán *et al*. 2004), situated to the north and shown with its regional context in Figures 1 and 2b.

The Alcañices synform folds several imbricates bounded by a sole thrust or detachment developed in Silurian carbonaceous slates. From top to bottom, three main imbricate units are recognized in Spain: Río Manzanas, Río Aliste and Bajo Río Esla (Fig. 3; González Clavijo & Martínez Catalán, 2002). The latter includes the Portuguese subautochthonous units of Rio Sabor and Coroto, which represent the Silurian slates (Meireles, 2013). The following sections describe the

https://doi.org/10.1017/S001675681500028X Published online by Cambridge University Press

formations and domains where the samples were collected.

3.a. Parautochthon

The Río Manzanas Unit belongs to the Parautochthon, and directly underlies the Allochthon of the Bragança Complex (Figs 2a, 3, Section I). Most of it consists of low-grade metasedimentary rocks including slates, carbonaceous slates, quartzites, greywackes, lydites and limestones. Mafic and felsic volcanic rocks are common, generally as thin lenses.

Several formations have been defined inside this unit, interpreted as pre-orogenic and of Silurian–Early Devonian age (Fig. 3). But these alternate with olistostromes formed by fragments of quartzites, lydites and limestones embedded in a slaty or sandy matrix. These olistostromes are lens shaped, a few to hundreds of metres thick, and show limited lateral continuity, although they may reach up to 3 km in length. They are syn-orogenic deposits interpreted as channel infillings. Large and small olistoliths are also found, and one olistolith of massive meta-rhyolites and metatuffs, 4 km long and dated as late Cambrian, has been reported near Nuez (Dias da Silva *et al*. 2014*a*). These deposits indicate basin instability, and herald Variscan deformation in nearby areas.

Sample SO-10 is a siltstone of the Vale Andrês Member of the Rio de Onor Fm, stratigraphically on top of dated Silurian slates and of probable Silurian age, as indicated by acritarchs of that age occurring together with reworked Cambrian and Ordovician acritarchs (Meireles, 2013). SO-11 is from a folded lens of quartzite 2 km long, surrounded by the Rábano Fm, defined in Spain by González Clavijo (2006), and partially equivalent to the Rio de Onor Fm defined in Portugal. Its age is imprecise. Conodonts and spores in nearby slates are Silurian–Early Devonian in age, but the quartzite might represent a large olistolith.

3.b. Gimonde Formation

The syn-orogenic sediments of the Gimonde Fm may occur as lenses tectonically sandwiched among the lithologies described in the Parautochthon, but are massively represented towards the top of the Río Manzanas Unit, where the Gimonde Fm has been defined and mapped (Pereira, Meireles & Pereira, 1999; Meireles, 2013). Based on the vergence to the northeast of the thrust faults, the structurally upper occurrences are interpreted as more internal than those tectonically imbricated in the middle and lower parts of the Parautochthon of the Alcañices synform.

The formation is a flysch-like, rhythmic sequence made of alternating slates, siltites and greywackes, which may include pebbles of various sizes and locally grade into microconglomerates and conglomerates containing fragments of metamorphic rocks, or even to large olistostromes. The conglomerates include meso- and catazonal gneisses, derived from the Allochthon, and low-grade metasandstones, metacherts, metatuffs, phyllites and quartzites possibly derived from the surrounding pre-orogenic Parautochthon (Ribeiro & Ribeiro, 1974; Meireles, 2000).

The Gimonde Fm overlies unconformably the pre-orogenic sequence of the Parautochthon, and both were affected by post-C_1 recumbent folds with NE vergence related to C_2 thrusting and imbrication (Fig. 3, Section I). In the metapelites, a fine-grained slaty cleavage (the first, although equivalent to S_2 in pre-orogenic formations) developed, associated with the folds and thrusts, and was in turn overprinted by a steeply dipping crenulation cleavage (S_3) axial planar in relation to late folding (C_3).

The age was considered Late Devonian by Teixeira & Pais (1973) based on poorly preserved plant debris. Palynological studies point to a Givetian–Frasnian age in the south (around Gimonde) and slightly younger (Frasnian) to the north (Pereira, Meireles & Pereira, 1999). However, all these seem to correspond to reworked populations, as shown by detrital zircons dated in the present study.

Previously dated samples SO-6 and SO-7 were collected close to the sole and in the upper part of the Río Manzanas Unit, respectively (Figs 2a, 3, Section I), and the results were presented by Martínez Catalán *et al.* (2008). Sample SO-6, representing the external part of the Gimonde Fm, yielded nine early Variscan zircons ranging in age from 404 to 378 Ma.

New samples SO-8 and SO-9 come from the upper imbricates in Portugal. The first was collected in a normal position in one of the upper thrust sheets, and the second in the reverse limb of a major recumbent syncline facing NE in the underlying imbricate. The new sample SO-12 was collected in the Spanish part of the Parautochthon, at the contact of a map-scale olistostrome that probably overlies unconformably the Rábano Fm but is also imbricated with it (González Clavijo & Martínez Catalán, 2002). It is ascribed to the Gimonde Fm by correlation with the Portuguese Parautochthon, where such imbricates are common (Meireles, 2013).

3.c. San Vitero Formation

The Río Aliste Unit is the imbricate stack occupying an intermediate position in the northern limb of the Alcañices synform (Figs 2a, 3, Section II). It overlies tectonically the Bajo Río Esla Unit in the southeast, but in the northwest it lies directly above the Autochthon, where it cuts across overturned C_1 folds.

The unit is formed by two contrasting sequences separated by an unconformity, the syn-orogenic San Vitero Fm and a pre-orogenic Silurian sequence formed by slates, carbonaceous slates and lydites, similar to the Manzanal del Barco Fm described by Vacas & Martínez Catalán (1987) in the underlying Bajo Río Esla Unit and in the Autochthon. The Silurian fossil associations are comparable and shared a similar palaeogeographic location (Piçarra *et al*. 2006*a*,*b*), and for that reason, the

https://doi.org/10.1017/S001675681500028X Published online by Cambridge University Press

Río Aliste and Bajo Río Esla units are considered transitional to the Autochthon and relatively little displaced in relation to it.

The San Vitero Fm is a syn-orogenic deposit with many characteristics of the culm facies of the Variscan belt, such as a turbiditic character and the existence of plant debris and pebbles of metamorphic rocks. It consists of terrigenous turbidites with decimetre- to metre-thick alternations of greywackes and slates. Microconglomerates occur at the base of some coarse greywacke levels. Scarce and thin alternations of carbonaceous cherts have been observed near the base, which is an erosive surface underlying the first turbiditic cycle (Martínez García, 1972; Antona & Martínez Catalán, 1990; González Clavijo & Martínez Catalán, 2002). Although the top of the formation is not seen, its thickness is at least several hundred metres.

Recumbent folds with an axial planar slaty cleavage are common in the San Vitero Fm, and appear in close relation to thrust faults. Both are folded by upright folds with a fine axial planar crenulation cleavage (S_3). The imbricated character of the Río Aliste Unit is highlighted by several repetitions of its two formations. The unit is possibly a duplex, or forms part of a large duplex which encompasses the three units being described, but the map does not prove that it is bounded by a roof thrust. The metamorphic grade of the San Vitero Fm corresponds to the lower epizone, near the anchizone, according to a study on illite crystallinity (Antona & Martínez Catalán, 1990).

The age of the San Vitero Fm remains uncertain because only unclassifiable plant debris has been found. Based on the stratigraphic position and correlation, several ages were proposed: Silurian (Martínez García, 1973), Devonian (J. L. Quiroga de la Vega, unpub. Ph.D. thesis, Univ. Oviedo, 1981) and uppermost Silurian – Middle Devonian (González Clavijo & Martínez Catalán, 2002). However, U–Pb detrital zircon dating in two samples (SO-4 and SO-5; Martínez Catalán *et al.* 2008; location in Figs 2a, 3, Section II), yielded two ages of 355 ± 8 and 360 ± 6 Ma, thus pointing to a Carboniferous age.

A new sample, SO-13, was collected in a microconglomeratic greywacke in the core of the Río Aliste Unit (Figs 2a, 3, Section II), to the north of San Vitero, in a position structurally higher than that of samples SO-4 and SO-5.

3.d. Almendra Formation

The lowermost imbricate preserved at the core of the Alcañices synform forms the Bajo Río Esla Unit, a duplex that occupies the more external part of the synform, resting directly above the Autochthon (Fig. 3, Section II). Together with the Río Aliste Unit, it traces the imbricate zone transitional between the Parautochthon and the Autochthon.

The imbricates share a Silurian condensed sequence at their base, the Manzanal del Barco Fm, consisting of slates, carbonaceous slates and lydites. Graptolites record the whole Silurian with the exception of the Pridoli (González Clavijo, 2006). Locally towards the top, small lenses of dark limestones yielding Pridolian–Lockhovian fauna occur in Portugal (Sarmiento *et al.* 1999).

Overlying the Manzanal del Barco Fm is the Almendra Fm (Vacas & Martínez Catalán, 1987), an alternation of calcarenites and grey slates at least 200 m thick, whose top is always cut by thrust faults. Discontinuous beds of calcarenite contain abundant bioclasts of corals, *Scyphocrinus*, bivalves, gastropods and calcarenite autoclasts up to 10 cm in size. The slates include clasts of diverse size (up to metric) of several lithologies, mainly belonging to the Manzanal del Barco Fm, and sometimes calcarenites of the Almendra Fm itself.

Some thin, discontinuous levels of conglomerate also exist that strongly resemble those described in the San Vitero Fm. They contain abundant pebbles, generally small but reaching up to 6 cm occasionally, of white quartz, quartzite, lydite, greywacke, slate displaying one or two tectonic foliations, strongly foliated orthogneiss and fragments of microconglomerate. The metamorphic clasts were interpreted as evidence of pre-Variscan events (Aldaya *et al.* 1973, 1976), but lately the Almendra Fm has been considered a deposit formed at the continental slope (González Clavijo & Martínez Catalán, 2002). The ages obtained from conodonts range from Pridoli to Emsian (Sarmiento, Calvo & González Clavijo, 1997), but the nature of the rocks and the presence of bioclasts strongly suggest they are inherited specimens. On the other hand, the metamorphic pebbles, including relatively soft slates, suggest a source area undergoing deformation nearby. Consequently, the Almendra Fm is interpreted as a syn-orogenic deposit, probably distal in relation to the source area, and derived mostly from erosion of the upper part of the Autochthon and/or Parautochthon weakly metamorphosed sequence, but yet with some participation of metamorphic rocks of higher grade derived from the Allochthon.

The new sample SO-14 was collected for this study from a level of conglomerates less than 3 m thick close to the upper part of the formation, inside one of the lower imbricated horses of the Bajo Río Esla Unit (Figs 2a, 3, Section II).

3.e. San Clodio Formation

Syn-orogenic turbidites consisting of pelites and greywackes identical to those of the San Vitero Fm crop out in the core of the Sil synform, a C_3 structure that folds the Autochthon to the east of the present front of the Allochthon. The synform is a narrow NW–SE structure, bounded to the west by a high-angle reverse fault, situated between the Ollo de Sapo anticlinorium (C_3) and the C_1 recumbent folds of the Serra do Courel (Figs 2b, 3, Section III). The San Clodio Fm was first studied by Riemer (1963, 1966), who described

https://doi.org/10.1017/S001675681500028X Published online by Cambridge University Press

carbonaceous cherts at the base of the formation, thin coal veins, poorly preserved plant debris, and pebbles of quartzite, slate, gneiss and granite. He suggested a Carboniferous pre-Stephanian age, based on the fact that deposits were folded, but noticed that deformation was weaker than in the underlying Ordovician slates. Matte (1968) discussed the deformation, and found no appreciable differences in metamorphism and cleavage development between the San Clodio Fm and older strata. He did not conclude whether or not the turbidites post-dated the first Variscan recumbent folds and cleavage. Pérez-Estaún (1974) described typical turbiditic sedimentary structures such as groove and flute casts, and prod marks, as well as trace fossils in the pelites, and established that the formation is not older than Late Devonian in age on the basis of plant debris content.

Samples SO-1 and SO-2 were collected for U–Pb detrital zircon dating at two localities, Pobra de Brollón and Bóveda (Fig. 2b), and the results published by Martínez Catalán *et al*. (2004). No new samples have been dated, but a detailed structural study has been carried out to establish the relationships between the syn-orogenic deposits and the Variscan structures.

The region to the east of the Sil synform is characterized by large C_1 recumbent folds, and a couple of such folds, the Piornal anticline and the Courel syncline (Matte, 1968), occur not far from the syn-orogenic deposits (Fig. 3, Section III). These folds form part of the larger Mondoñedo fold nappe, a huge recumbent structure with a reverse limb reaching between 15 and 30 km in length (Martínez Catalán, Arenas & Díez Balda, 2003).

To the west, the structure is complicated by overprinting of large C_3 upright folds. The San Clodio Fm rests usually on middle to upper Ordovician slates, but below them, a strip of Silurian rocks up to 1000 m thick forms the core of a recumbent syncline with a reverse limb of *c*. 10 km (Fig. 3, Section III). The C_1 syncline is re-folded by C_3, and the synform hosting at its core the syn-orogenic deposits delineates on the map a hook-type fold interference to the southeast of San Clodio (Fig. 2b).

The San Clodio Fm was deposited unconformably over the reverse limb of a C_1 recumbent fold. Later, the syn-orogenic deposits were affected by small recumbent folds associated with thrust faults directed to the NE attributed to late stages of C_2, and folded by steep C_3 folds. The unconformity was locally reactivated by thrusting, but not systematically. Where this happened, a few metres of carbonaceous slates and cherts between the turbidites and the underlying Ordovician slates were sheared and phyllonitized.

4. Description of new samples

Sample SO-08 (UTM: Datum ED 50, zone 29T, E691908, N4631397), from the Gimonde Fm, is a microconglomeratic low-grade metagreywacke formed by angular to poorly rounded grains. Detrital grains are of all sizes with a population of large clasts (1–3 mm) embedded in a fine-grained mass of quartz, plagioclase, muscovite, minor chlorite and opaques, and a micaceous matrix. The larger grains are rock fragments of slate, quartzitic schist, quartz mylonite, polycrystalline aggregates of quartz derived from quartzite and deformed quartz veins, carbonaceous chert and carbonate. A crenulation cleavage folding a previous low-grade tectonic foliation is often preserved in the metamorphic clasts. The whole rock is deformed, with a rough cleavage marked by the statistically preferred orientation of the elongated grains, and dark, irregular pressure-solution seams.

Sample SO-09 (E692833, N4633617), from the Gimonde Fm, is a low-grade metagreywacke formed by angular to poorly rounded grains of quartz, plagioclase, muscovite, rare biotite and opaques. Grains are of all sizes up to a maximum of 0.6 mm, embedded in a fine-grained matrix of white mica and chlorite, with some porphyroblastic grains of the latter. A rough cleavage is marked by the statistically preferred orientation of the elongate grains, pressure-solution seams and the orientation of the new grains in the matrix.

Sample SO-10 (E701239, N4639620), from the pre-orogenic Parautochthon (Rio de Onor Fm), is a siltstone formed by angular to sub-rounded detrital grains, up to 0.4 mm long. Quartz is the main detrital component, but white mica, and a few grains of greenish biotite and tourmaline also occur. The grains are elongated parallel to a low-temperature, anastomosing cleavage, probably formed by pressure solution, where opaque minerals concentrate. Tiny, apparently new white mica also occurs statistically oriented parallel to the cleavage seams, pointing to recrystallization of the very scarce pelitic matrix.

Sample SO-11 (E704003, N4628578), from the pre-orogenic Parautochthon near Nuez (Rábano Fm), probably a glided block, is a fine-grained, rather equigranular quartzite consisting of grains of 0.1 to 0.2 mm long quartz. Opaque minerals are present in a limited amount, as well as detrital muscovite, and a few grains of plagioclase and zircon have been recognized. The matrix is almost inexistent. A rough cleavage is defined by the weak to moderately elongated quartz and opaque grains, and by poorly developed and anastomosing seams of phyllitic material. Growth of pyrite in polycrystalline aggregates occurred in a post-kinematic stage.

Sample SO-12 (E712015, N4627466), from the Gimonde Fm, is a medium-grained lithic-wacke containing some clasts up to 3 mm, and includes scarce quartz grains displaying volcanic embayments. The clasts are subangular to sub-rounded and predominantly of monomineralic quartz. A previous tectonic foliation was identified inside some rock fragments, clearly bearing different attitudes, and in some cases crenulated. Deformation of the greywacke is very weak, only indicated by scarce narrow pressure-solution seams, and

https://doi.org/10.1017/S001675681500028X Published online by Cambridge University Press

no tectonic foliation is developed. The matrix is formed by fine-grained detritals and tiny white mica and chlorite crystals distributed in narrow and irregular seams among the monomineralic and rock fragments. The metamorphic grade is very low, displaying scarce muscovite and new chlorite crystals. Growth of idiomorphic pyrite post-dates deformation.

Sample SO-13 (E720718, N4632658), from the San Vitero Fm, is a microconglomeratic greywacke consisting of subangular to rounded clasts less than 2 mm long of quartz, plagioclase, microcline, muscovite, carbonate, as well as of polymineralic quartz grains and low-grade metapelites. Scarce volcanic quartz crystals have been identified, and some cryptocrystalline grains possibly represent vitric fragments of pyroclastic rocks. Several clasts display a tectonic foliation, which may appear crenulated by a later deformation. Both occurred previously to the weak deformation shown by the whole rock, indicated by the poor statistically preferred orientation of grains without pressure-solution seams.

Sample SO-14 (E745723, N4616813), from the Almendra Fm, can be classified as a coarse-grained microconglomerate or lithic-wacke. Rock fragments are of all sizes with a population of large clasts up to 20 mm long, embedded in a fine-grained mass of small grains of quartz, plagioclase, muscovite, tourmaline, chlorite, opaques and a micaceous matrix. Large fragments consist of single grains of quartz, or of rock fragments. The latter include low-grade metapelites and quartzitic schists, polycrystalline aggregates of quartz derived from quartzite and deformed quartz veins, and very fine-grained foliated rocks that probably represent vitric volcanic fragments (shards). Very few quartz grains show corrosion embayments. No carbonates have been found although the microconglomerate is intercalated in limestones. A crenulation cleavage folds a previous low-grade tectonic foliation in some clasts of metamorphic rock, but in other cases, crenulation cleavage in the clasts is parallel to cleavage in the matrix, suggesting contemporaneity. The whole rock is strongly deformed, with a cleavage marked by the preferred orientation of the elongated detrital grains and the small recrystallized phyllosilicates of the matrix. Also, dark, irregular but rather continuous pressure-solution seams occur. The metamorphic grade is low, anchizone–epizone, according to the colour alteration index in conodonts (Sarmiento, Calvo & González Clavijo, 1997). This fact is consistent with the microscopic observations of quartz grains showing undulatory extinction, recovery, serrate grain boundaries, subgrains and Boehm lamellae. Single crystals or aggregates of pyrite grew after deformation, partially replacing the detrital grains and the foliated matrix.

5. Zircon geochronology

5.a. Dating procedure

Mineral separation was carried out at the Universidad Complutense (Madrid) following conventional techniques. Zircons were hand-picked in alcohol under a binocular microscope and chosen to represent all types found in the samples in terms of size, length to breadth ratio, roundness, colour and other salient morphological features.

Zircon dating was done at GEMOC, Department of Earth and Planetary Sciences, Macquarie University, Sydney, Australia. The grains selected for U–Pb, laser ablation, inductively coupled plasma mass spectrometry (LA-ICP-MS) dating were mounted in epoxy discs and polished. Of the seven samples, 60 analyses were performed on single grains from six samples, while one sample (SO-11) was limited to 20 analyses owing to insufficient zircon recovery.

U–Pb dating was performed using an Agilent 7500 quadrupole ICP-MS system, attached to a New Wave UP213 laser ablation system ($\lambda = 213$ nm). The analyses were carried out with a beam diameter of *c.* 30–50 μm with a 5 Hz repetition rate. The analytical procedures for the U–Pb dating have been described in detail previously (Belousova *et al.* 2001; Griffin *et al.* 2004; Jackson *et al.* 2004). A very fast scanning data acquisition protocol was employed to minimize signal noise. Data acquisition for each analysis took 3 min (1 min on background, 2 min on signal). Ablation was carried out in He to improve sample transport efficiency, provide more stable signals and give more reproducible Pb/U fractionation. Provided that constant ablation conditions are maintained, accurate correction for U/Pb fractionation can then be achieved using an isotopically homogeneous zircon standard.

Samples were analysed in runs of 16 analyses, which included 12 unknown points, bracketed beginning and end by pairs of analyses of the GEMOC GJ-1 zircon standard. This standard is slightly discordant, and has yielded an isotope dilution thermal ionization mass spectrometry ^{207}Pb–^{206}Pb age of 608.5 Ma (Jackson *et al.* 2004). Two other well-characterized zircons, 91500 (Wiedenbeck *et al.* 1995) and Mud Tank (Black & Gulson, 1978), were analysed within each run as an independent control on reproducibility and instrument stability.

U–Pb ages were calculated from the raw signal data using the online software package GLITTER (www.mq.edu.au/GEMOC; van Achterbergh, Ryan & Griffin, 1999; van Achterbergh *et al.* 2001). GLITTER calculates the relevant isotopic ratios for each mass sweep and displays them as time-resolved data. This allows isotopically homogeneous segments of the signal to be selected for integration. GLITTER then corrects the integrated ratios for ablation-related fractionation and instrumental mass bias by calibration of each selected time segment against the identical time segments for the standard zircon analyses.

The common-Pb correction procedure of Andersen (2002) was used assuming recent lead loss. A common lead composition corresponding to present-day average orogenic lead is given by the second-stage growth curve of Stacey & Kramers (1975) for $^{238}U/^{204}Pb = 9.74$. No correction has been applied to analyses that are concordant within 2σ of analytical error, or that have less than 0.2 % common lead. Only 19 analyses needed to be corrected for common lead. Concordia diagrams and probability density distribution plots were generated using the Isoplot software, version 3.0 (Ludwig, 2003).

5.b. Dating results

Data from LA-ICP-MS of detrital zircon grains for U, Pb and Th can be seen in Tables S1 to S7 in the online Supplementary Material available at http://journals.cambridge.org/geo.

The concordia plots of syn-orogenic samples are shown in Figure 4, with insets representing the Palaeozoic and Neoproterozoic zircons. Figure 5 shows the probability density distribution of ages together with the percentage of significant age populations of detrital zircon grains for concordant or subconcordant analyses.

The samples are characterized by one or more Archaean populations up to 3.4 Ga old (11–25 % of the age spectra), a Palaeoproterozoic population concentrated between 1.7 and 2.3 Ga (27–44 %), a small representation of Mesoproterozoic zircons (2–5 %, absent in SO-8), and a representative Neoproterozoic group mostly younger than 0.7 Ga (20–39 %). Palaeozoic zircons are absent in SO-8 and variably represented in the other samples, and have been divided into pre-Variscan (older than 400 Ma; 12–20 %), and early Variscan and Variscan (4–15 %).

Figure 6 depicts the concordia plots and the probability density distribution of ages and percentage of significant age populations for the two samples of the pre-orogenic Parautochthon. SO-10, from the Rio de Onor Fm, includes a representation of all ages present in the syn-orogenic samples except Variscan, with zircons of Neoproterozoic age representing 51 % and Palaeozoic zircons 17 %. Sample SO-15, from the quartzite, has a higher percentage of Neoproterozoic zircons and lacks the Archaean and Palaeozoic populations, but it is little representative as it has supplied only 15 concordant ages.

6. Age summary and geological interpretation

In order to establish the sources of syn-orogenic sediments, Figure 7 shows a synthesis of published zircon age data as probability density plots, together with time intervals representing significant events of crustal accretion or rifting.

The results of samples from the syn-orogenic San Vitero and Gimonde fms have been combined with previous data on the same formations, and are shown in the central part of Figure 7 together with those of the Almendra and San Clodio fms. For the Gimonde Fm, samples from the upper imbricates in the Parautochthon of the Alcañices synform, corresponding to internal parts of the sedimentary basin, have been separated from samples collected lower in the section and representing more external parts.

The right part of Figure 7 shows probability density plots from published data of the pre-orogenic Autochthon, obtained in greywacke and quartzite samples of Neoproterozoic, Cambrian, Ordovician, Silurian and Early Devonian ages (Gutiérrez-Alonso *et al.* 2003; Martínez Catalán *et al.* 2004). New data from Ediacaran and early Cambrian samples (Fernández-Suárez *et al.* 2014) and from early Ordovician quartzites (Shaw *et al.* 2014) of NW and Central Iberia confirm the patterns of zircon age populations in the Autochthon. The left part of Figure 7 depicts zircon age populations of representative units of the Allochthon.

6.a. Precambrian populations

In the Autochthon, the age spectra include Archaean zircons, Palaeoproterozoic ages in the range 2.25–1.7 Ga (Orosirian–Rhyacian), Mesoproterozoic–Neoproterozoic ages covering the interval 1.2–0.85 Ga (Tonian–Stenian) and Neoproterozoic ages younger than 850 Ma (Cryogenian–Ediacaran). These populations are compatible with a palaeoposition of the Iberian Autochthon close to present northern Africa, with the Orosirian–Rhyacian population being characteristic of the West African craton and the Cryogenian–Ediacaran zircons derived from northern Gondwana.

The Mesoproterozoic population was first related to NE African sources by Gómez Barreiro *et al.* (2007) and later by Bea *et al.* (2010). Current views support that near sources for the Tonian–Stenian population are the Saharan craton, the Arabian–Nubian shield, the Hoggar megasuture or Trans-Saharan fold belt, and the East African orogen (Bea *et al.* 2010; Díez Fernández *et al.* 2010; Dias da Silva *et al.* 2014*b*; Fernández-Suárez *et al.* 2014). Far sources related to far-travelled clastic sediments include terranes exposed to the south of the Saharan craton and the Arabian–Nubian shield (Shaw *et al.* 2014).

The Palaeoproterozoic and Archaean populations are common to the three domains represented in Figure 7, although the Archaean seems better represented in the Autochthon. The Mesoproterozoic population is clearly more abundant in the Autochthon, but it also exists in the Middle and Lower allochthons (Sánchez Martínez, 2009; Díez Fernández *et al.* 2010, 2012*a*) and is absent or nearly so in the Upper Allochthon (Fernández-Suárez *et al.* 2003; Albert *et al.* 2015). The decreasing amount of Mesoproterozoic zircons upwards in the nappe pile has been related to the palaeoposition of the peri-Gondwanan allochthons to the west of the Autochthon, closer to present NW Africa (Díez Fernández *et al.* 2010, 2012*a*). There, they would have registered a progressively larger influence from the West African craton and a minor to zero influence from central and eastern sources of the northern margin of Gondwana.

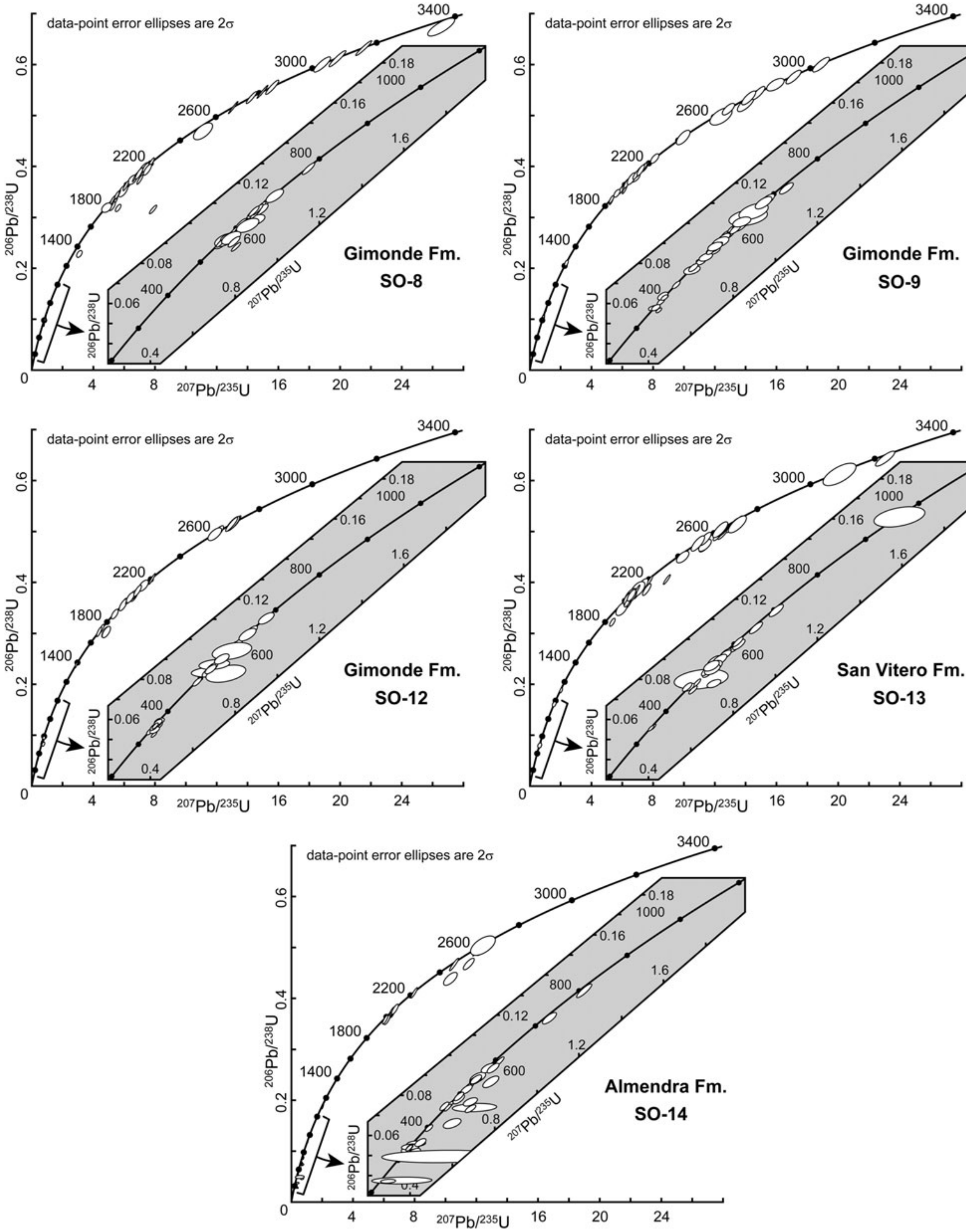

Figure 4. U–Pb concordia diagrams with the results of LA-ICP-MS zircon dating of new samples from the Gimonde, Alcañices and Almendra fms. Error ellipses represent 2σ uncertainties. The enlarged regions show the Palaeozoic, Neoproterozoic and Stenian zircons.

The Neoproterozoic populations of the three domains are similar, reflecting the overwhelming influence of pan-African sources in both the Autochthon and the Allochthon.

For the syn-orogenic deposits, sources are probably local as creation of relief is etymologically and by definition a consequence of orogenesis. The scarcity or absence of the Mesoproterozoic population in the

https://doi.org/10.1017/S001675681500028X Published online by Cambridge University Press

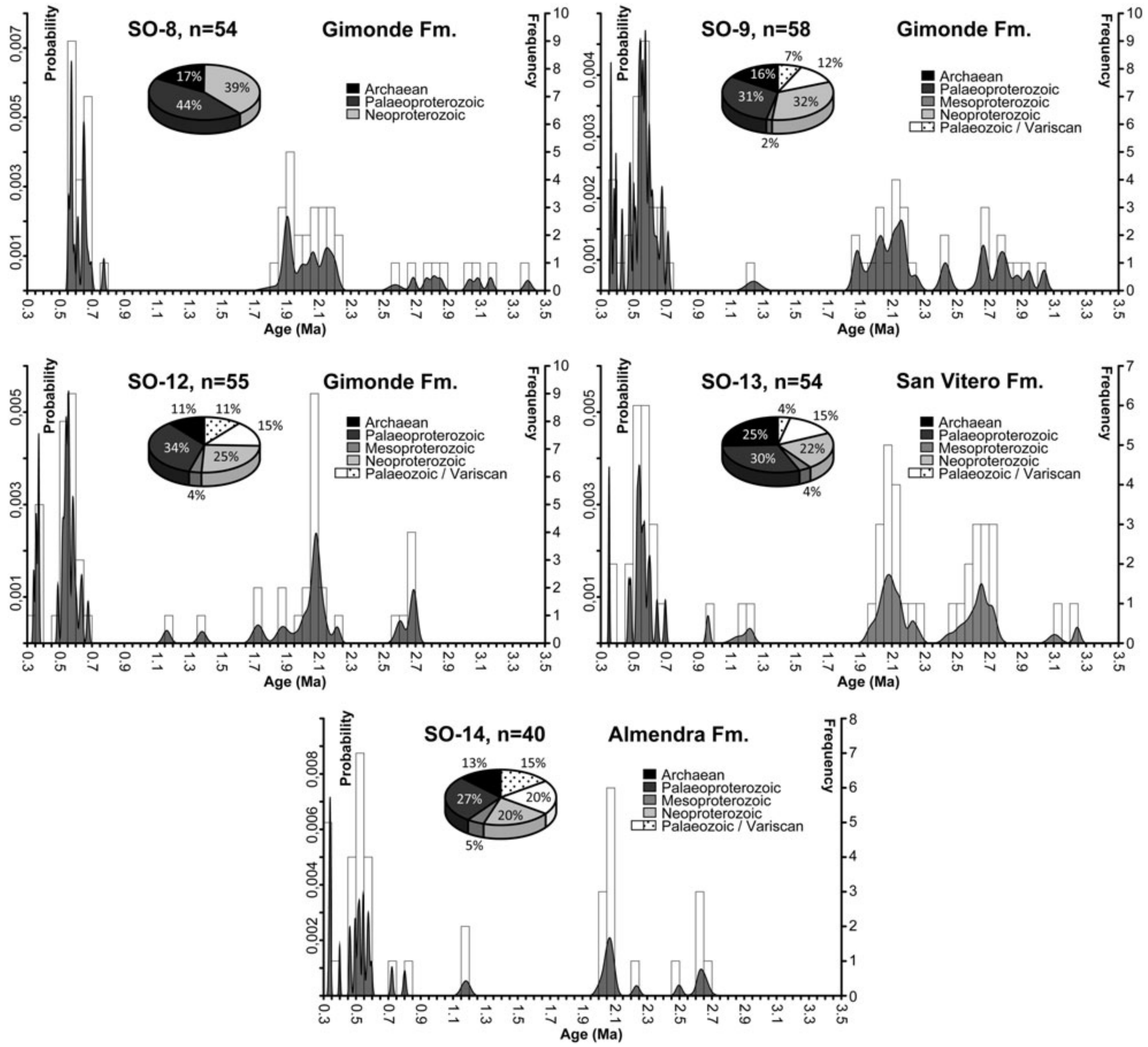

Figure 5. Probability density distribution (curves) and frequency (bars) of ages and percentage of significant age populations of detrital zircon grains for the samples whose ages are shown in Figure 4. Only concordant or subconcordant analyses (<10 % discordant) have been plotted. n – number of analyses with <10 %.discordance.

syn-orogenic sediments suggests a derivation from the Allochthon, where that population is small to inexistent.

6.b. Palaeozoic pre-Variscan population

Pre-Variscan, Palaeozoic zircons reflect the magmatic activity related to the Cambro-Ordovician rifting, which in turn has been related to the pulling apart of some peri-Gondwanan terrane driven by subduction of the Iapetus oceanic lithosphere beneath Gondwana (Fernández *et al*. 2008; Martínez Catalán *et al*. 2009; Díez Montes, Martínez Catalán & Bellido Mulas, 2010).

Significant to voluminous late Cambrian to early Ordovician magmatism characterizes the different domains, although its signature differs from one domain to the other. In the Autochthon and Parautochthon, the magmatism is mostly felsic, includes volcanic rocks and intrusive granitoids, and is coeval with shallow-water, platform-facies clastic deposits (Gutiérrez Marco, de San José & Pieren, 1990; Pérez-Estaún *et al*. 1990). Magmatism there was related to extension of the northern Gondwanan passive margin, and its calc-alkaline and ferrosilicic signature is interpreted as being derived from its source rocks, the Cadomian arc-related magmatism or lower crustal equivalents (Fernández *et al*. 2008; Díez Montes, Martínez Catalán & Bellido Mulas, 2010; Ballèvre *et al*. 2012; Dias da Silva *et al*. 2014*c*).

In the Lower Allochthon, magmatism is bimodal, although the felsic rocks dominate. Rocks similar to those of the underlying domains coexist with alkaline and peralkaline magmatism (Floor, 1966; Montero *et al*. 2009*a*; Rodríguez Aller, 2005; Díez Fernández, Castiñeiras & Gómez Barreiro, 2012). The latter points

https://doi.org/10.1017/S001675681500028X Published online by Cambridge University Press

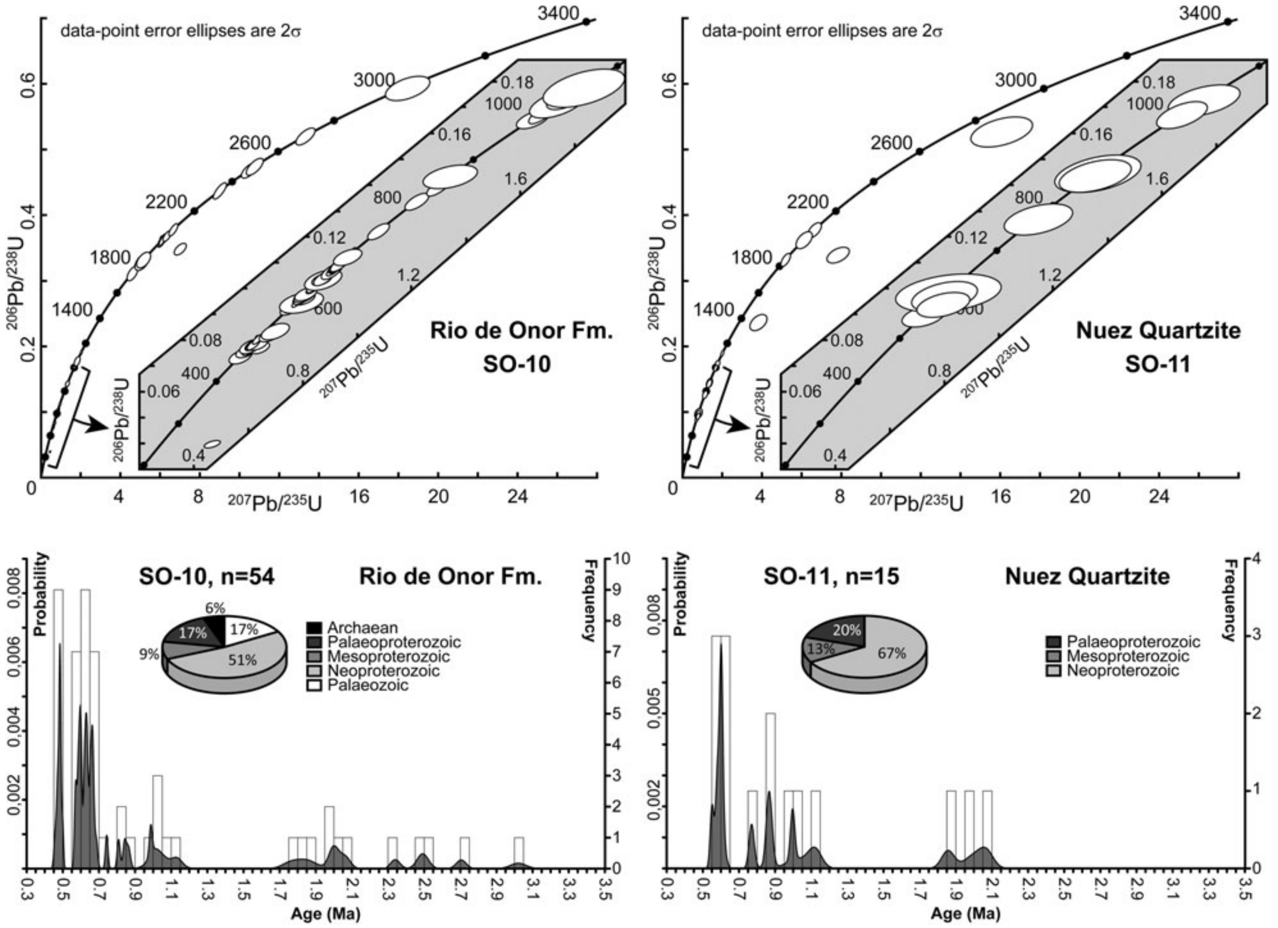

Figure 6. Above: U–Pb concordia diagrams with the results of LA-ICP-MS zircon dating of new samples in the Rio de Onor and Rábano fms. Error ellipses represent 2σ uncertainties. The enlarged regions show the Palaeozoic, Neoproterozoic and Stenian zircons. Below: Probability density distribution (curves) and frequency (bars) of ages, and percentage of significant age populations of detrital zircon grains. Only concordant or subconcordant analyses (< 10 % discordant) have been plotted. n – number of analyses with < 10 % discordance.

to a continental rift, related to the opening of the oceanic domain represented in the ophiolitic Middle Allochthon (Arenas *et al*. 2007*a,b*; Sánchez Martínez *et al*. 2007*a,b*).

In the Upper Allochthon, plutonism is bimodal, with large bodies of granitoids and gabbros, and with characteristics reflecting arc-type magmatism in the uppermost units of the group (Andonaegui *et al*. 2002, 2012), and continental extension in the structurally lower units (Galán & Marcos, 1997).

Voluminous magmatism is somewhat older in the Upper Allochthon (510–490 Ma; Abati *et al*. 1999; Castiñeiras, Díaz García & Gómez Barreiro, 2010; Andonaegui *et al*. 2012) than in the Lower Allochthon (500–470 Ma; Abati *et al.* 2010; Díez Fernández, Castiñeiras & Gómez Barreiro, 2012), the Parautochthon (493–483 Ma; Dias da Silva *et al*. 2014*c*) and the Autochthon (495–470 Ma; Bea *et al*. 2006; Montero *et al*. 2007, 2009*b*; Díez Montes, Martínez Catalán & Bellido Mulas, 2010), with alkaline and peralkaline magmatism in the Lower Allochthon having started slightly later (485–470 Ma; Díez Fernández & Martínez Catalán, 2009; Montero *et al*. 2009*a*; Díez Fernández, Castiñeiras & Gómez Barreiro, 2012). Massive basic volcanism related to the opening of the oceanic realm has been dated at *c*. 500–495 Ma (Arenas *et al*. 2007*b*).

Palaeozoic zircons are very scarce in the sediments of the Autochthon, owing to the rather continuous sedimentation that buried the volcanic rocks and the intrusive character of granitoids. And the same holds for the Parautochthon. Comparing the new results (Fig. 6) with previous data on the Parautochthon of NW Iberia (Fig. 7), sample SO-10 shows a small population of pre-Variscan, Palaeozoic zircons covering the 500–460 Ma interval. But this is the exception, as the Palaeozoic population was neither found in samples dated by Díez Fernández *et al*. (2012*a*), nor in sample SO-11.

Conversely, 540–400 Ma old zircons are well represented in some allochthonous units owing to deposition coeval with the activity and dismantling of a Cambro-Ordovician volcanic arc. As seen in Figure 7, this is the case for low-grade metagreywackes of the Upper Allochthon (Fernández-Suárez *et al*. 2003; Fuenlabrada *et al*. 2010) and the upper sequence of the Lower Allochthon (Díez Fernández *et al*. 2010). Moreover, early Palaeozoic zircons have been found in Early Devonian

https://doi.org/10.1017/S001675681500028X Published online by Cambridge University Press

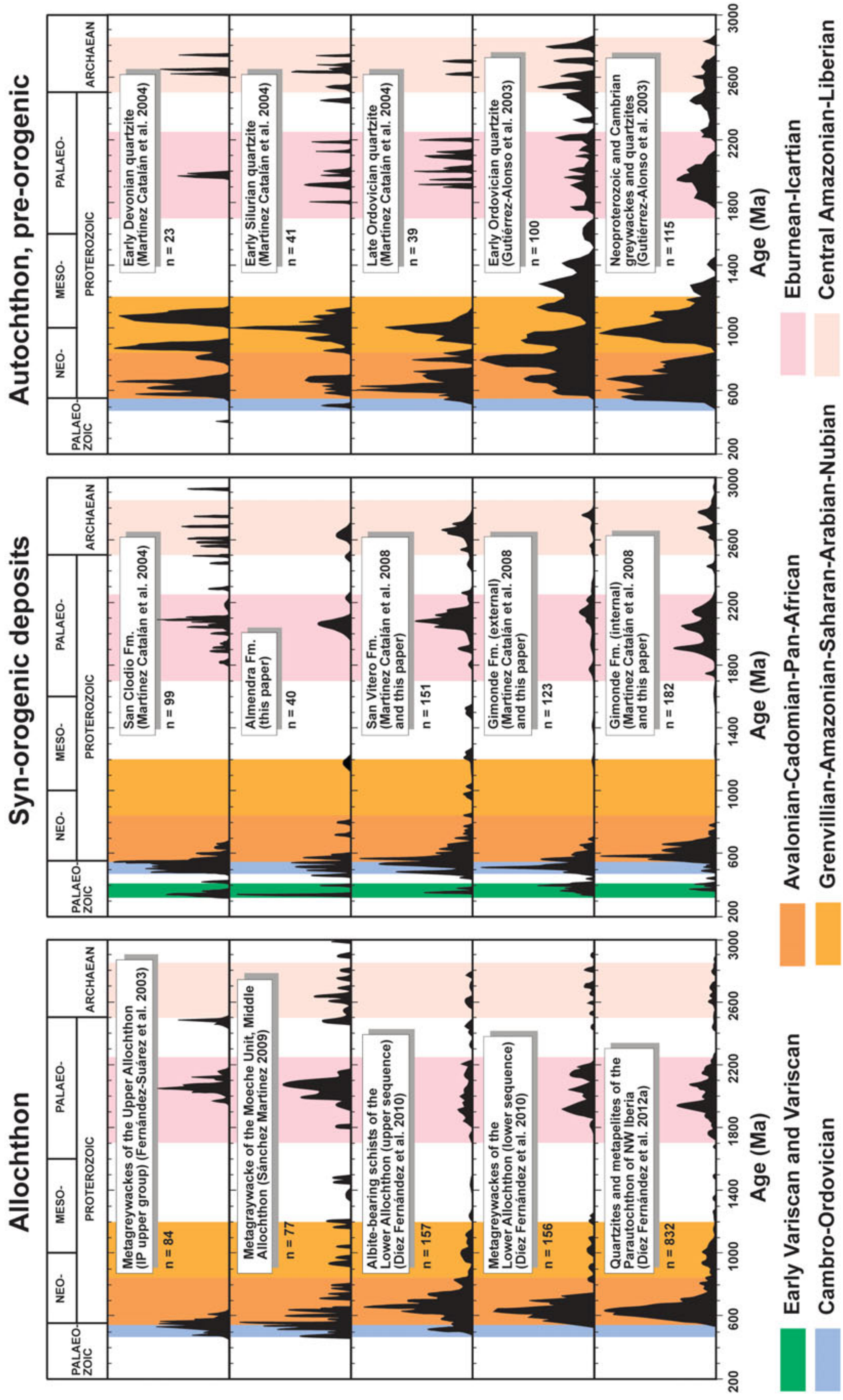

Figure 7. (Colour online) Synthesis of several published zircon age data as probability density plots, together with time intervals representing significant events of crustal growth or recycling. New data from the San Vitero and Gimonde fms have been combined with previous data on the same formations, and are shown in the central column together with age spectra of the Almendra and San Clodio fms. The right column shows probability density plots from published data of the pre-orogenic Autochthon, and the left column depicts populations of representative units of the Allochthon.

https://doi.org/10.1017/S001675681500028X Published online by Cambridge University Press

ophiolitic rocks of the Moeche Unit, in the Middle Allochthon (Sánchez Martínez, 2009; Arenas *et al.* 2014).

In addition to early Palaeozoic igneous rocks, some units of the Upper and Middle allochthons registered a Cambro-Ordovician, granulite-facies metamorphism at *c.* 495 Ma and 475 Ma, respectively (Abati *et al.* 1999; Martínez *et al.* 2012).

Concerning the syn-orogenic deposits, the probability that their Palaeozoic zircons derive from the Autochthon are scarce, because neither massive volcanic rocks such as the Ollo de Sapo Fm nor the Cambro-Ordovician granitoids were apparently exposed to erosion during the emplacement of the Allochthon. Conversely, not only are Palaeozoic zircons more abundant in sediments of the Allochthon, but there is a high probability that its abundant Cambro-Ordovician igneous and high-grade metamorphic rocks were exposed during the emplacement. Again, this points to the Allochthon as the main source of detritals for the syn-orogenic basins.

A similar situation, with detritals and olistoliths derived from nearby, contemporaneous thrust sheets, has been described in the Montagne Noire (Engel, Feist & Franke, 1982). But other, more external Variscan syn-orogenic deposits contain an important component of recycled passive margin components of the relative autochthon, as for instance, the Rhenish Massif (Engel, Flehmig & Franke, 1983; Franke & Engel, 1986).

In NW Iberia, lower and middle Pennsylvanian sediments in the external Cantabrian Zone have yielded detrital zircon populations that reflect the erosion of the recently formed Variscan edifice (Galán *et al.* 2012). They include sources from both the Autochthon and the Allochthon, the latter indicated by late Ordovician, Silurian and Devonian zircons. These are, however, small populations, whereas for instance, the Tonian–Stenian population is always present and more significant, suggesting a larger contribution from the Autochthon.

In the South Portuguese Zone, far from the NW Iberian Allochthon, dominant syn-orogenic sediments are probably linked to the collision between Gondwana and Laurussia. There, zircon populations in middle Mississippian turbidites probably derived from a Devonian magmatic arc, as suggested by the almost total absence of pre-Devonian zircons (Pereira *et al.* 2012, 2014). Younger turbidites, however, contain significant pre-Devonian populations. Those in upper Mississippian turbidites are derived from recycled Gondwanan basement whereas in middle Pennsylvanian turbidites, late Ordovician and Silurian detrital zircons suggest an additional Laurussian source (Pereira *et al.* 2014).

6.c. Early Variscan and Variscan populations

Accretion of the units forming the Allochthon occurred progressively from the Upper to the Lower, following in each case a previous history of metamorphism and deformation. Early evidence of convergence related to the Variscan cycle is the generation of intraoceanic, supra-subduction zone ophiolites (upper units of the Middle Allochthon) at 405–395 Ma (Díaz García *et al.* 1999; Pin *et al.* 2002, 2006).

More important from the point of view of zircon generation is the high-pressure and high-temperature metamorphism producing eclogites and granulites in the Upper Allochthon at 400–390 Ma (Santos Zalduegui *et al.* 1996; Ordóñez Casado *et al.* 2001; Fernández-Suárez *et al.* 2007). This Early–Middle Devonian metamorphic event implied subduction of part of the continental arc. For that reason, we consider 400 Ma as the time when early Variscan convergence began, or at least, zircons reflecting convergence grew. Subduction was followed by underthrusting and imbrication of the young supra-subduction zone ophiolites at 390–375 Ma. This produced decompression and partial melting of the overlying Upper Allochthon, followed by the development of an amphibolite-facies foliation dated at 390–370 Ma (Peucat *et al.* 1990; Dallmeyer, Ribeiro & Marques, 1991; Dallmeyer *et al.* 1997; Díaz García *et al.* 1999; Gómez Barreiro *et al.* 2006).

Continuation of convergence accreted the Cambro-Ordovician ophiolites that had remained close to the margin of Gondwana, while extension and exhumation of the Upper Allochthon continued. Then, the Lower Allochthon underwent subduction and eclogitization at *c.* 375–365 Ma (Santos Zalduegui, Schärer & Gil Ibarguchi, 1995; Rodríguez *et al.* 2003; Abati *et al.* 2010).

Continental subduction, necessarily limited, gave way to continental collision, a change that took place roughly at the Devonian–Carboniferous boundary and marked the transition from early Variscan to Variscan convergence. The Parautochthon and Autochthon were involved in the deformation while the Allochthon kept undergoing deformation during its emplacement. According to ^{49}Ar–^{39}Ar dating of foliations (Dallmeyer *et al.* 1997), recumbent folds (C_1) developed between *c.* 360 and 335 Ma progressing from the hinterland outwards, whereas an age of *c.* 340 Ma was obtained for thrusting of the Parautochthon (C_2). Retrogradation of the Allochthon started before. Rb–Sr ages of 355–345 Ma in the Upper Allochthon (Ordóñez Casado *et al.* 2001) and ^{49}Ar–^{39}Ar ages ranging from *c.* 360–340 Ma in the Lower Allochthon (Rodríguez *et al.* 2003) reflect recumbent folding, thrusting and extension, all related to the emplacement of the allochthonous wedge. Partial melting occurred locally at 345 Ma in the Lower Allochthon (Abati & Dunning, 2002).

Crustal thickening was followed by a period of thermal relaxation and then by extensional collapse, reflected in a high-temperature and low-pressure metamorphic event whose main phase took place at 325–315 Ma (Martínez Catalán *et al.* 2009, 2014). Migmatization in extensional domes and anatectic granites have yielded ages between 330 and 315 Ma (Valverde-Vaquero *et al.* 2007). Syn-kinematic Variscan granitoids in NW Iberia crystallized between 325 and 305 Ma, and were deformed

https://doi.org/10.1017/S001675681500028X Published online by Cambridge University Press

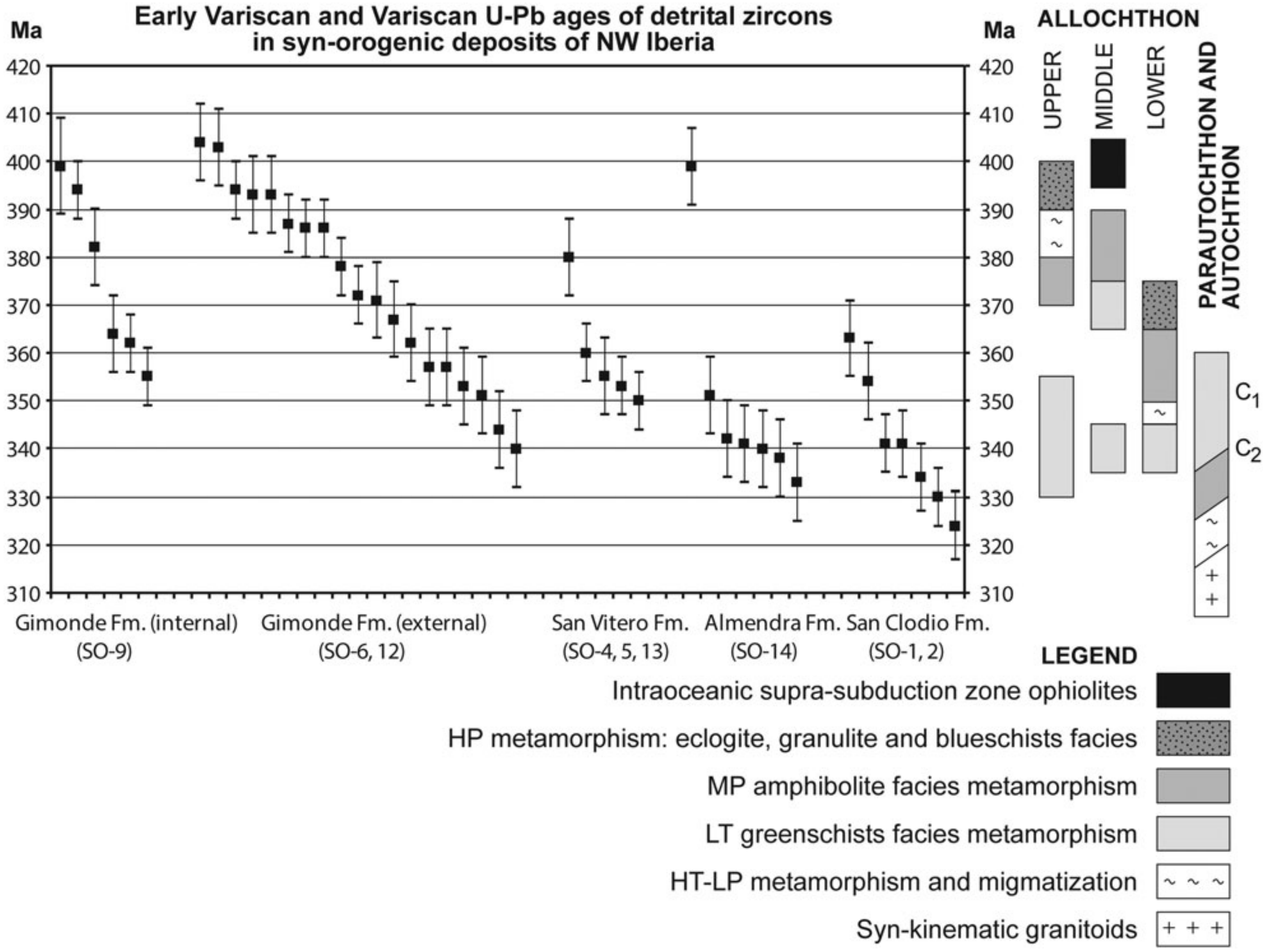

Figure 8. Early Variscan and Variscan zircon ages with bars of 2σ standard deviation from the Sil and Alcañices synforms, grouped by formations. These are ordered from top (left) to bottom (right) of the structural sequence. To the right, bars show ranges of published age data for the events registered in the different domains that are potential sources for syn-orogenic zircons. Their meaning is indicated in the legend, and a description of the ages and references can be read in the text.

by C_3, responsible also for steep folds and dated at *c.* 315–305 Ma (Capdevila & Vialette, 1970; Dallmeyer *et al.* 1997). Late- to post-kinematic granitoids continued to be emplaced until 286 Ma (Fernández-Suárez *et al.* 2000; Valle Aguado *et al.* 2005; Gutiérrez-Alonso *et al.* 2011).

The Allochthon was the main source for syn-orogenic sediments around it during its emplacement and shortly after. However, in areas far from it, such as the two external zones of the Iberian Massif, the Autochthon was the main source of detritals. This is shown by the Gondwanan populations recycled several times, the last of which is Variscan, and by a possible Laurussian contribution in the South Portuguese Zone.

Proximity and the huge relief of the area covered by the Allochthon at the time of nappe emplacement explain its dominant role in feeding the surrounding syn-orogenic basins. But as extensional collapse proceeded, relief was considerably lowered in the hinterland, and the erosion of the domes and frontal parts of the Allochthon allowed the erosion of the Autochthon, which then contributed also to feeding the basins.

7. Nappe emplacement and syn-orogenic sedimentation

Early Variscan and Variscan zircons represent a small population, sometimes missing, in the syn-orogenic samples (Figs 4, 5, 7). Figure 8 depicts all dated zircons from the Sil and Alcañices synforms whose ages, including 2σ confidence bars, are 400 Ma or younger. They are grouped by the formations from where they have been collected, which in turn are ordered from top to bottom of the imbricated sequence. The bars to the right show time intervals of published ages corresponding to the main tectonic and metamorphic events that might produce zircon growth, as described in Section 6.

In the Sil synform, where erosion removed the upper part of the pre-orogenic autochthonous sequence, only greenschist-facies metamorphic rocks, mainly slates, were uncovered. There is little possibility that these rocks developed new zircons during C_1, and in any case they would be younger than 360 Ma. This can be generalized to the whole surrounding Autochthon, so that the presence of Variscan and early Variscan zircons points once again to the Allochthon as the main source of detritals.

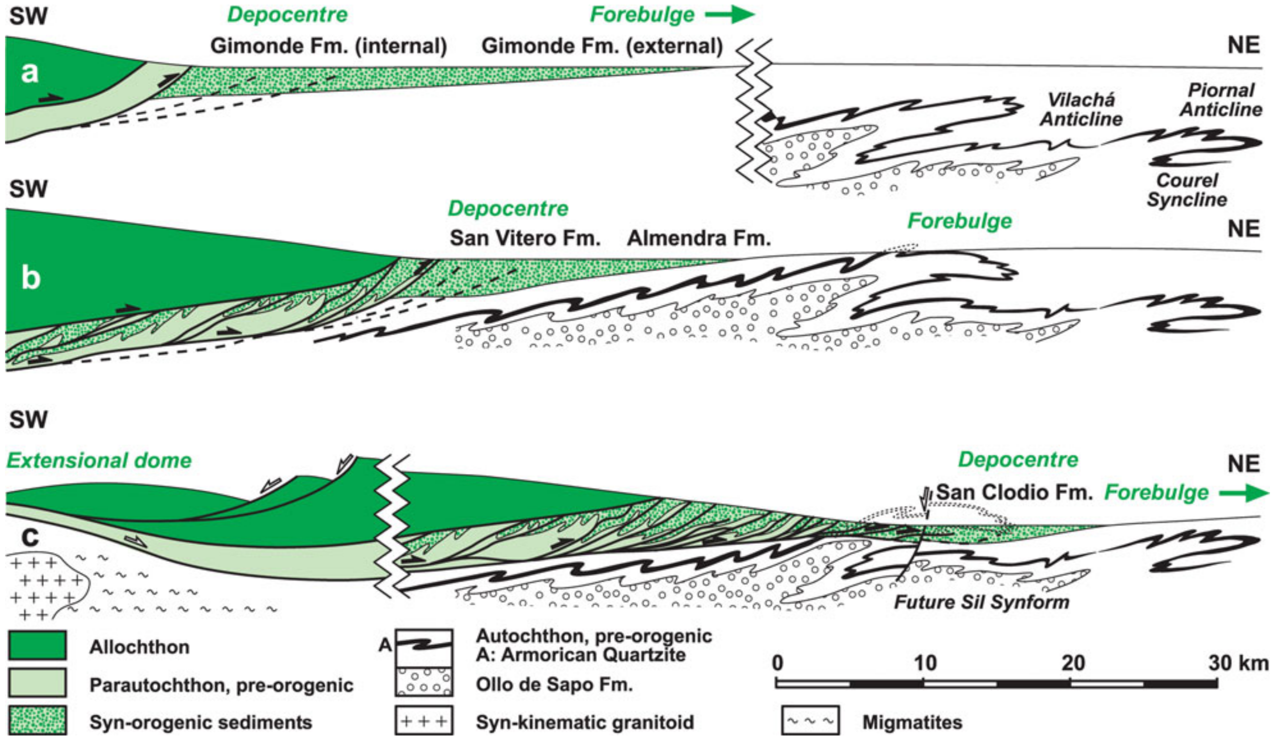

Figure 9. (Colour online) Sketch showing the evolution of the studied syn-orogenic deposits as deduced from structural fieldwork and detrital zircon ages. The Parautochthon was built by progressive incorporation of the Autochthon into the allochthonous wedge. Sedimentation occurred in depocentres developed in front of the allochthonous wedge that migrated during its emplacement, and was followed by imbrication and incorporation into the wedge. In the younger deposits, deformation was probably coeval with extensional doming in more internal areas, which might have unroofed the Autochthon.

For the youngest zircons in each formation, there is a tendency to be younger towards the lower imbricates in the Alcañices synform and the autochthonous San Clodio Fm of the Sil synform (Fig. 8). This suggests a progressively younger age of the syn-orogenic deposits towards the external zones. Additional support is provided by a syn-orogenic olistostrome sampled in the continuation to the south of the upper imbricates of the Gimonde Fm (Dias da Silva *et al.* 2014*b*). Its age populations are similar to those shown in Figures 5 and 7, and the youngest population is formed by four early Variscan zircons of 401–385 Ma.

As most syn-orogenic deposits were imbricated in the Parautochthon, or at the boundary with the Autochthon, a model based on the relationships found in the Sil synform is proposed (Fig. 9). According to it, sedimentation took place in depocentres developed in front of the allochthonous wedge during its emplacement. Subsidence of a foreland basin at the wedge front, caused by isostatic adjustments and lithosphere flexure, would explain the migration of the peripheral syn-orogenic basin with time. The forebulge created by the elastic behaviour of the lithosphere outwards from the depocentre would have been eroded, as in the Sil synform, and later occupied by the migrating depocentre. The new deposits were then progressively incorporated into the allochthonous wedge, together with slivers of the underlying pre-orogenic sequence.

The youngest zircon in each imbricated formation would mark its maximum depositional age, but also that of thrusting. For the Gimonde and San Vitero fms their ages agree with the assumed 340 Ma age for the end of emplacement of the Parautochthon (Dallmeyer *et al.* 1997). For the Almendra Fm, imbricated at the boundary between the Parautochthon and Autochthon, a somewhat younger age of thrusting (*c.* 335–330 Ma) is possible, and for the San Clodio Fm, sedimentation at *c.* 325 Ma is reasonable considering its youngest zircon. The latter is the most external of the preserved syn-orogenic formations, and its deformation was probably coeval with extension in more internal areas (Fig. 9c).

The reverse fault bounding the San Clodio Fm to the SW in the Sil synform (Figs 2, 3, Section III) is possibly inherited from the time of syn-orogenic sedimentation, when it might have moved as a normal fault developed at the currently active depocentre.

In the Almendra and San Clodio fms, a supply of Variscan zircons from the Autochthon is conceivable, as the younger of them may derive from the high-temperature event post-dating crustal thickening, which produced migmatization in the Autochthon and Parautochthon, and the intrusion of syn-kinematic granitoids.

8. Conclusions

Zircon age populations show that syn-orogenic culm deposits in NW Iberia are related to the Variscan emplacement of a thick and huge nappe stack formed

https://doi.org/10.1017/S001675681500028X Published online by Cambridge University Press

by peri-Gondwanan and oceanic terranes. The Allochthon was the main source of detritals, as shown by the scarcity of Mesoproterozoic zircons, the relative abundance of Palaeozoic, pre-Variscan zircons, and the presence of early Variscan and Variscan zircons in the syn-orogenic sediments. The relationship with earlier Variscan structures shows that sedimentation was structurally related to thrusting via the formation of peripheral troughs where the flysch-type deposits accumulated.

According to the youngest zircons, all syn-orogenic formations are early Carboniferous (Mississippian) in age and reflect the collisional stage of Variscan convergence in the region. Younging of the Variscan populations downwards in the structural pile suggests progressive migration of the depocentre towards the foreland during nappe emplacement. Sedimentation was followed by imbrication of the syn-orogenic deposits and their incorporation into the allochthonous wedge, and by late Variscan folding.

Thrusting occurred during Mississippian time. A maximum Tournaisian–Visean age (355–350 Ma) is indicated by the youngest zircons in the internal imbricates of the Gimonde Fm, whereas those of the San Clodio Fm suggest that thrusting was active in the area until the end of Serpukhovian (323 Ma) time.

Acknowledgements. This contribution has been funded by the Sección de Cartografía of the Consejería de Fomento, Junta de Castilla y León, and by the research projects CGL2007–65338-C02–02/BTE and CGL2011–22728 of the Spanish Ministry of Science and Innovation, as part of the National Programme of Projects in Fundamental Research, in the frame of the National Plans of Scientific Research, Development and Technologic Innovation 2004–2007 and 2008–2011. W. Franke and an anonymous referee are kindly acknowledged for detailed reviews of the manuscript.

References

ABATI, J. & DUNNING, G. R. 2002. Edad U–Pb en monacitas y rutilos de los paragneises de la Unidad de Agualada (Complejo de Órdenes, NW del Macizo Ibérico). *Geogaceta* **32**, 95–8.

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**, 213–28.

ABATI, J., GERDES, A., FERNÁNDEZ-SUÁREZ, J., ARENAS, R., WHITEHOUSE, M. J. & DÍEZ FERNÁNDEZ, R. 2010. Magmatism and early-Variscan continental subduction in the northern Gondwana margin recorded in zircons from the basal units of Galicia, NW Spain. *Geological Society of America Bulletin* **122**, 219–35.

ALBERT, R., ARENAS, R., GERDES, A., SÁNCHEZ MARTÍNEZ, S., FERNÁNDEZ-SUÁREZ, J. & FUENLABRADA, J. M. 2015. Provenance of the Variscan Upper Allochthon (Cabo Ortegal Complex, NW Iberian Massif). *Gondwana Research*. Published online 15 November 2014. doi: 10.1016/j.gr.2014.10.016.

ALDAYA, F., ARRIBAS, A., GONZÁLEZ LODEIRO, F., IGLESIAS, M., MARTÍNEZ CATALÁN, J. R. & MARTÍNEZ-GARCÍA, E. 1973. Presencia de una nueva fase de deformación, probablemente prehercínica en el Noroeste y Centro de la Península Ibérica. *Stvdia Geologica Salmanticensia* **6**, 29–48.

ALDAYA, F., CARLS, P., MARTÍNEZ-GARCÍA, E. & QUIROGA, J. L. 1976. Nouvelles précisions sur la série de San Vitero (Zamora, nord-ouest de l'Espagne). *Comptes Rendus de l'Académie des Sciences*, Paris, Série D **283**, 881–3.

ANCOCHEA, E., ARENAS, R, BRANDLE, J. L., PEINADO, M. & SAGREDO, J. 1988. Caracterización de las rocas metavolcánicas silúricas del Noroeste del Macizo Ibérico. *Geociências, Aveiro*, **3**, 23–34.

ANDERSEN, T. 2002. Correction of common-lead in U–Pb analyses that do not report 204Pb. *Chemical Geology* **192**, 59–79.

ANDONAEGUI, P., GONZÁLEZ DEL TÁNAGO, J., 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 *Variscan–Appalachian Dynamics: The Building of the Late Paleozoic Basement* (eds J. R. Martínez Catalán, R. D. Hatcher Jr., R. Arenas & F. Díaz García), pp. 37–56. Geological Society of America, Special Paper no. 364.

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.

ANTONA, J. F. & MARTÍNEZ CATALÁN, J. R. 1990. Interpretación de la Formación San Vitero en relación con la Orogenia Hercínica. *Cuadernos do Laboratorio Xeolóxico de Laxe* **15**, 257–69.

ARENAS, R. & MARTÍNEZ CATALÁN, J. R. 2003. Low-P metamorphism following a Barrovian-type evolution. Complex tectonic controls for a common transition, as deduced in the Mondoñedo thrust sheet (NW Iberian Massif). *Tectonophysics* **365**, 143–64.

ARENAS, R., MARTÍNEZ CATALÁN, J. R., SÁNCHEZ MARTÍNEZ, S., DÍAZ GARCÍA, F., ABATI, J., FERNÁNDEZ-SUÁREZ, J., ANDONAEGUI, P. & GÓMEZ-BARREIRO, J. 2007a. Paleozoic ophiolites in the Variscan suture of Galicia (northwest Spain): distribution, characteristics and meaning. In *4-D Framework of Continental Crust* (eds R. D. Hatcher Jr., M. P. Carlson, J. H. McBride & J. R. Martínez Catalán), pp. 425–44. Geological Society of America, Memoir no. 200.

ARENAS, R., MARTÍNEZ CATALÁN, J. R., SÁNCHEZ MARTINEZ, S., FERNÁNDEZ-SUÁREZ, J., ANDONAEGUI, P., PEARCE, J. A. & CORFU, F. 2007b. The Vila de Cruces Ophiolite: a remnant of the early Rheic Ocean in the Variscan suture of Galicia (NW Iberian Massif). *Journal of Geology* **115**, 129–48.

ARENAS, R., SÁNCHEZ MARTÍNEZ, S., GERDES, A., ALBERT, R., DÍEZ FERNÁNDEZ, R. & ANDONAEGUI, P. 2014. 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**, 1385–402.

BALLÈVRE, M., FOURCADE, S., CAPDEVILA, R., PEUCAT, J. -J., COCHERIE, A. & FANNING, C. M. 2012. Geochronology and geochemistry of Ordovician felsic volcanism in the Southern Armorican Massif (Variscan belt, France): implications for the breakup of Gondwana. *Gondwana Research* **21**, 1019–36.

Ballèvre, M., Martínez Catalán, J. R., López-Carmona, A., Pitra, P., Abati, J., Díez Fernández, R., Ducassou, C., Arenas, R., Bosse, V., Castiñeiras, P., Fernández-Suárez, J., Gómez Barreiro, J., Paquette, J. L., Peucat, J. J., Poujol, M., Ruffet, G. & Sánchez Martínez, S. 2014. Correlation of the nappe stack in the Ibero-Armorican arc across the Bay of Biscay: a joint French-Spanish project. In *The Variscan Orogeny: Extent, Timescale and the Formation of the European Crust* (eds K. Schulmann, J. R. Martínez Catalán, J. M. Lardeaux, V. Janousek & G. Oggiano), pp. 77–113. Geological Society of London, Special Publication no. 405.

Bea, F., Montero, P., Talavera, C & Zinger, T. 2006. A revised Ordovician age for the Miranda do Douro orthogneiss, Portugal. Zircon U–Pb ion-microprobe and LA-ICPMS dating. *Geologica Acta* **4**, 395–401.

Bea, F., Montero, P., Talavera, C., Abu Anbar, M., Scarrow, J. H., Molina, J. F. & Moreno, J. A. 2010. The palaeogeographic position of Central Iberia in Gondwana during the Ordovician: evidence from zircon chronology and Nd isotopes. *Terra Nova* **22**, 341–6.

Belousova, E., Griffin, W. L., Shee, S. R., Jackson, S. E. & O'Reilly, S. Y. 2001. Two age populations of zircons from the Timber Creek kimberlites, Northern Territory, as determined by laser-ablation ICPMS analysis. *Australian Journal of Earth Sciences* **48**, 757–65.

Black, L. P. & Gulson, B. L. 1978. The age of the Mud Tank carbonatite, Strangways Range, Northern Territory. *BMR Journal of Australian Geology and Geophysics* **3**, 227–32.

Capdevila, R. & Vialette, Y. 1970. Estimation radiométrique de l'âge de la deuxième phase tectonique hercynienne en Galice Moyenne (Nord-Ouest de l'Espagne). *Comptes Rendus de l'Académie des Sciences, Paris* **270**, 2527–30.

Castiñeiras, P., Díaz García, F. & Gómez Barreiro, J. 2010. REE-assisted U–Pb zircon age (SHRIMP) of an anatectic granodiorite: constraints on the evolution of the A Silva granodiorite, Iberian Allochthonous Complexes. *Lithos* **116**, 153–66.

Dallmeyer, R. D., Ribeiro, A. & Marques, F. 1991. Polyphase Variscan emplacement of exotic terranes (Morais and Bragança Massifs) onto Iberian successions: evidence from 40Ar/39Ar mineral ages. *Lithos* **27**, 133–44.

Dallmeyer, R. D., Martínez Catalán, J. R., Arenas, R., Gil Ibarguchi, J. I., Gutiérrez Alonso, G., Farias, P., Aller, J. & Bastida, F. 1997. Diachronous Variscan tectonothermal activity in the NW Iberian Massif: evidence from 40Ar/39Ar dating of regional fabrics. *Tectonophysics* **277**, 307–37.

Dias da Silva, Í. 2014. *Geología de las Zonas Centro Ibérica y Galicia – Trás-os-Montes en la parte oriental del Complejo de Morais, Portugal/España*. Laboratorio Xeolóxico de Laxe, Instituto Universitario de Xeoloxía, A Coruña, Spain. Serie Nova Terra no. 45, 424 pp.

Dias da Silva, I. F., González Clavijo, E., Gutiérrez Alonso, G. & Gómez Barreiro, J. 2014a. Large Upper Cambrian rhyolite olistoliths locked in the Early Carboniferous Variscan syn-orogenic melange of the parautochthonous realm of the NW Iberian Massif. In *Gondwana 15. North Meets South* (eds R. J. Pankhurst, P. Castiñeiras & S. Sánchez Martínez), p. 52. Abstracts Book.

Dias da Silva, Í., Linnemann, U., Hofmann, M., González Clavijo, E., Díez-Montes, A. & Martínez Catalán, J. R. 2014b. Detrital zircon and tectonostratigraphy of the Parautochthon under the Morais Complex (NE Portugal): implications for the Variscan accretionary history of the Iberian Massif. *Journal of the Geological Society, London*. **172**, 45–61.

Dias da Silva, I., Valverde-Vaquero, P., González-Clavijo, E., Díez-Montes, A. & Martínez Catalán, J. R. 2014c. Structural and stratigraphical significance of U–Pb ages from the Mora and Saldanha volcanic complexes (NE Portugal, Iberian Variscides). In *The Variscan Orogeny: Extent, Timescale and the Formation of the European Crust* (eds K. Schulmann, J. R. Martínez Catalán, J. M. Lardeaux, V. Janousek & G. Oggiano), pp. 115–35. Geological Society of London, Special Publication no. 405.

Díaz García, F., Arenas, R., Martínez Catalán, J. R., González del Tánago, J. & Dunning, G. 1999. Tectonic evolution of the Careón ophiolite (Northwest Spain): a remnant of oceanic lithosphere in the Variscan belt. *Journal of Geology* **107**, 587–605.

Díez Fernández, R., Castiñeiras, P. & Gómez Barreiro, J. 2012. Age constraints on Lower Paleozoic convection system: magmatic events in the NW Iberian Gondwana margin. *Gondwana Research* **21**, 1066–79.

Díez Fernández, R. & Martínez Catalán, J. R. 2009. 3D analysis of an Ordovician igneous ensemble: a complex magmatic structure hidden in a polydeformed allochthonous Variscan unit. *Journal of Structural Geology*, **31**, 222–36.

Díez Fernández, R., Martínez Catalán, J. R., Arenas, R., Abati, J., Gerdes, A. & Fernández-Suárez, J. 2012a. 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, London* **169**, 655–65.

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**, 385–99.

Díez Fernández, R., Martínez Catalán, J. R., Gómez Barreiro, J. & Arenas, R. 2012b. Extensional flow during gravitational collapse: a tool for setting plate convergence (Padrón migmatitic dome, Variscan belt, NW Iberia). *Journal of Geology* **120**, 83–103.

Díez Montes, A., Martínez Catalán, J. R. & Bellido Mulas, F. 2010. Role of the Ollo de Sapo massive felsic volcanism of NW Iberia in the Early Ordovician dynamics of northern Gondwana. *Gondwana Research* **17**, 363–76.

Engel, W., Feist, R. & Franke, W. 1982. Le Carbonifère ante-Stéphanien de la Montagne Noire: raports entre mise en place des nappes et sédimentation. *Bulletin du Bureau de Recherches Géologiques et Minières* **2**, 341–89.

Engel, W., Flehmig, W. & Franke, W. 1983. The mineral composition of Rhenohercynian flysch sediments and its tectonic significance. In *Intracontinental Fold Belts – Case Studies in the Variscan Belt of Europe and the Damara Belt in Namibia* (eds H. Martin & W Eder), pp. 171–84. Berlin: Springer-Verlag.

Escuder Viruete, J., Arenas, R. & Martínez Catalán, J. R. 1994. Tectonothermal evolution associated with Variscan crustal extension in the Tormes Gneiss Dome

(NW Salamanca, Iberian Massif, Spain). *Tectonophysics* **238**, 117–38.

FARIAS ARQUER, P. 1990. *La Geología de la Región del Sinforme de Verín (Cordillera Herciniana, NW de España)*. Laboratorio Xeolóxico de Laxe, A Coruña, Spain. Serie Nova Terra no. 2, 201 pp.

FARIAS, P., GALLASTEGUI, G., GONZÁLEZ-LODEIRO, F., MARQUÍNEZ, J., MARTÍN PARRA, L. M., MARTÍNEZ CATALÁN, J. R., PABLO MACIÁ, J. G. DE, & RODRÍGUEZ FERNÁNDEZ, L. R. 1987. Aportaciones al conocimiento de la litoestratigrafía y estructura de Galicia Central. *Memórias da Faculdade de Ciências, Universidade do Porto* **1**, 411–31.

FARIAS, P. & MARCOS, A. 2004. Dominio Esquistoso de Galicia-Trás-os-Montes. In *Geología de España* (ed. J. A. Vera), pp. 135–8. Madrid: SGE-IGME.

FERNÁNDEZ, C., BECCHIO, R., CASTRO, A., VIRAMONTE, J. M., MORENO-VENTAS, I. & CORRETGÉ, L. G. 2008. Massive generation of atypical ferrosilicic magmas along the Gondwana active margin: implications for cold plumes and back-arc magma generation. *Gondwana Research* **14**, 451–73.

FERNÁNDEZ-SUÁREZ, J., ARENAS, R., ABATI, J., MARTINEZ CATALÁN, J. R., WHITEHOUSE, M. J. & JEFFRIES, T. 2007. U–Pb chronometry of polymetamorphic high-pressure granulites: an example from the allochthonous terranes of the NW Iberian Varsican belt. In *4-D Framework of Continental Crust* (eds R. D. Hatcher, Jr., M. P. Carlson, J. H. McBride & J. R. Martínez Catalán), pp. 469–88. Geological Society of America, Memoir no. 200.

FERNÁNDEZ-SUÁREZ, J., DÍAZ GARCÍA, F., JEFFRIES, T., 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**, 138–44.

FERNÁNDEZ-SUÁREZ, J., DUNNING, G. R., JENNER, G. A. & GUTIÉRREZ-ALONSO, G. 2000. Variscan collisional magmatism and deformation in NW Iberia: constraints from U–Pb geochronology of granitoids. *Journal of the Geological Society, London* **157**, 565–76.

FERNÁNDEZ-SUÁREZ, J., GUTIÉRREZ-ALONSO, G., PASTOR-GALÁN, D., HOFMANN, M., MURPHY, J. B. & LINNEMANN, U. 2014. The Ediacaran-Early Cambrian detrital zircon record of NW Iberia: possible sources and paleogeographic constraints. *International Journal of Geological Sciences* **103**, 1335–57.

FLOOR, P. 1966. Petrology of an aegirine-riebeckite gneiss-bearing part of the Hesperian Massif: the Galiñeiro and surrounding areas, Vigo, Spain. *Leidse Geologische Mededelingen* **36**, 1–204.

FORTEY, R. A. & COCKS, L. R. M. 1988. Arenig to Llandovery faunal distributions in the Caledonides. In *The Caledonian–Appalachian Orogen* (eds A. L. Harris & D. J. Fettes), pp. 233–46. Geological Society of London, Special Publication no. 38.

FRANKE, W. & ENGEL, W. 1986. Synorogenic sedimentation in the Variscan Belt of Europe. *Bulletin de la Société Géologique de France* **2**, 25–33.

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 to the origin of the arc – a sedimentary approach. *Gondwana Research* **17**, 338–51.

GALÁN, D., GUTIÉRREZ-ALONSO, G., MURPHY, J. B., FERNÁNDEZ-SUÁREZ, J., HOFMANN, M. & LINNEMANN, U. 2012. Provenance analysis of the Paleozoic sequences of the northern Gondwana margin in NW Iberia: passive margin to Variscan collision and orocline development. *Gondwana Research* **23**, 1089–103.

GALÁN, G. & MARCOS, A. 1997. Geochemical evolution of high-pressure mafic granulites from the Bacariza formation (Cabo Ortegal complex, NW Spain): an example of a heterogeneous lower crust. *Geologische Rundschau* **86**, 539–55.

GALLASTEGUI, G., MARTÍN PARRA, L. M., PABLO MACIÁ, J. G. DE & RODRÍGUEZ FERNÁNDEZ, L. R. 1988. Las metavulcanitas del Dominio Esquistoso de Galicia-Tras-os-Montes: petrografía, geoquímica y ambiente geotectónico (Galicia, NO de España). *Cuadernos do Laboratorio Xeolóxico de Laxe, A Coruña, Spain* **12**, 127–39.

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 *The Evolution of the Rheic Ocean: From Avalonian–Cadomian Active Margin to Alleghenian–Variscan Collision* (eds U. Linnemann, R. D. Nance, P. Kraft & G. Zulauf), pp. 315–32. Geological Society of America, Special Paper no. 423.

GÓMEZ-BARREIRO, J., WIJBRANS, J. R., CASTIÑEIRAS, P., MARTÍNEZ CATALÁN, J. R., ARENAS, R., DÍAZ GARCÍA, F. & ABATI, J. 2006. 40Ar/39Ar laserprobe dating of mylonitic fabrics in a polyorogenic terrane of NW Iberia. *Journal of the Geological Society, London* **163**, 61–73.

GONZÁLEZ CLAVIJO, E. 2006. *La Geología del Sinforme de Alcañices, Oeste de Zamora*. Laboratorio Xeolóxico de Laxe, A Coruña, Spain. Serie Nova Terra no. 31, 238 pp

GONZÁLEZ CLAVIJO, E. & MARTÍNEZ CATALÁN, J. R. 2002. Stratigraphic record of preorogenic to synorogenic sedimentation, and tectonic evolution of imbricate units in the Alcañices synform (northwestern Iberian Massif). In *Variscan–Appalachian Dynamics: The Building of the Late Paleozoic Basement* (eds J. R. Martínez Catalán, R. D. Hatcher Jr., R. Arenas & F. Díaz García), pp. 17–35. Geological Society of America, Special Paper no. 364.

GRIFFIN, W. L., BELOUSOVA, E. A., SHEE, S. R., PEARSON, N. J. & O'REILLY, S. Y. 2004. Archean crustal evolution in the northern Yilgarn Craton: U–Pb and Hf-isotope evidence from detrital zircons. *Precambrian Research* **131**, 231–82.

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**, 221–32.

GUTIÉRREZ-ALONSO, G., FERNÁNDEZ-SUÁREZ, J., JEFFRIES, T. E., JOHNSTON, S. T., PASTOR-GALÁN, D., MURPHY, J. B., M. FRANCO, P. & GONZALO, J. C. 2011. Diachronous post-orogenic magmatism within a developing orocline in Iberia, European Variscides. *Tectonics* **30**, TC5008, 1–17, doi: 10.1029/2010TC002845.

GUTIÉRREZ-ALONSO, G., MURPHY, J. B., FERNÁNDEZ-SUÁREZ, J. & HAMILTON, M. A. 2008. Geocronología de las rocas volcánicas de El Castillo (Salamanca, Zona Centroibérica). *Geogaceta* **44**, 3–6.

GUTIÉRREZ MARCO, J. C., DE SAN JOSÉ, M. A. & PIEREN, A. P. 1990. Central-Iberian Zone. Post-Cambrian Palaeozoic stratigraphy. In *Pre-Mesozoic Geology of Iberia* (eds R. D. Dallmeyer & E. Martínez García), pp. 160–71. Berlin: Springer-Verlag.

JACKSON, S. E., PEARSON, N. J., GRIFFIN, W. L. & BELOUSOVA, E. A. 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology. *Chemical Geology* **211**, 47–69.

LUDWIG, K. R. 2003. *User's Manual for Isoplot 3.00 – A Geochronological Toolkit for Microsoft Excel*. Berkeley Geochronology Center Special Publication no. 4, 72 pp.

MARCOS, A. & PULGAR, J. A. 1982. An approach to the tectonostratigraphic evolution of the Cantabrian Foreland thrust and fold belt, Hercynian Cordillera of NW Spain. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen* **163**, 256–60.

MARQUES, F. O., RIBEIRO, A. & MUNHÁ, J. M. 1996. Geodynamic evolution of the Continental Allochthonous Terrane (CAT) of the Bragança Nappe Complex, NE Portugal. *Tectonics* **15**, 747–62.

MARQUES, F. O., RIBEIRO, A. & PEREIRA, E. 1991–1992. Tectonic evolution of the deep crust: Variscan reactivation by extension and thrusting of Precambrian basement in the Bragança and Morais massifs (Trás-os-Montes, NE Portugal). *Geodinamica Acta* **5**, 135–51.

MARQUÍNEZ GARCÍA, J. L. 1984. La geología del área esquistosa de Galicia Central (Cordillera Herciniana, NW de España). *Memorias del Instituto Geológico y Minero de España* **100**, 1–231.

MARTÍNEZ, S. S., GERDES, A., ARENAS, R. & ABATI, J. 2012. The Bazar Ophiolite of NW Iberia: a relic of the Iapetus-Tornquist Ocean in the Variscan suture. *Terra Nova* **24**, 283–94.

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**, 114–26.

MARTÍNEZ CATALÁN, J. R., ARENAS, R., DÍAZ GARCÍA, F., GONZÁLEZ CUADRA, P., GÓMEZ-BARREIRO, J., ABATI, J., CASTIÑEIRAS, P., FERNÁNDEZ-SUÁREZ, J., SÁNCHEZ-MARTÍNEZ, S., ANDONAEGUI, P., GONZÁLEZ CLAVIJO, E., DÍEZ MONTES, A., RUBIO PASCUAL, F. J. & VALLE AGUADO, B. 2007. Space and time in the tectonic evolution of the northwestern Iberian Massif: implications for the Variscan belt. In *4-D Framework of Continental Crust* (eds R. D. Hatcher, Jr., M. P. Carlson, J. H. McBride & J. R. Martínez Catalán), pp. 403–23. Geological Society of America, Memoir no. 200.

MARTÍNEZ CATALÁN, J. R., ARENAS, R. & DÍEZ BALDA, M. A. 2003. Large extensional structures developed during emplacement of a crystalline thrust sheet: the Mondoñedo nappe (NW Spain). *Journal of Structural Geology* **25**, 1815–39.

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 Paleozoic plate configuration and Variscan evolution. *Journal of the Geological Society, London* **161**, 463–76.

MARTÍNEZ CATALÁN, J. R., FERNÁNDEZ-SUÁREZ, J., MEIRELES, C., GONZÁLEZ CLAVIJO, E., BELOUSOVA, E. & SAEED, A. 2008. U–Pb detrital zircon ages in synorogenic deposits of the NW Iberian Massif (Variscan belt): interplay of Devonian–Carboniferous sedimentation and thrust tectonics. *Journal of the Geological Society, London* **165**, 687–98.

MARTÍNEZ CATALÁN, J. R., RUBIO PASCUAL, F. J., DÍEZ MONTES, A., DÍEZ FERNÁNDEZ, R., GÓMEZ BARREIRO, J., DIAS DA SILVA, I., GONZÁLEZ CLAVIJO, E., AYARZA, P. & ALCOCK, J. E. 2014. The late Variscan HT/LP metamorphic event in NW and Central Iberia: relationships to crustal thickening, extension, orocline development and crustal evolution. In *The Variscan Orogeny: Extent, Timescale and the Formation of the European Crust* (eds K. Schulmann, J. R. Martínez Catalán, J. M. Lardeaux, V. Janousek, & G. Oggiano), pp. 225–47. Geological Society of London, Special Publication no. 405.

MARTÍNEZ GARCÍA, E. 1972. El Silúrico de San Vitero (Zamora). Comparación con las series vecinas e importancia orogénica. *Acta Geológica Hispánica* **7**, 104–8.

MARTÍNEZ GARCÍA, E. 1973. Deformación y metamorfismo en la zona de Sanabria. *Stvdia Geologica Salmanticensia* **5**, 7–106.

MATTE, PH. 1968. La structure de la virgation hercynienne de Galice (Espagne). *Revue de Géologie Alpine* **44**, 1–128.

MEIRELES, C. A. P. 2000. *Carta Geológica de Portugal, 1:50.000, Folha 3-D, Espinhosela*, 64 pp. Lisbon: Instituto Geológico e Mineiro.

MEIRELES, C. A. P. 2013. *Litoestratigrafía do Paleozóico do Sector a Nordeste de Bragança (Trás-os-Montes)*. Laboratorio Xeolóxico de Laxe, A Coruña, Spain. Serie Nova Terra no. 42, 471 pp.

MONTERO, P., BEA, F., CORRETGÉ, L. G., FLOOR, P. & WHITEHOUSE, M. J. 2009a. U–Pb ion microprobe dating and Sr and Nd isotope geology of the Galiñeiro Igneous Complex: a model for the peraluminous/peralkaline duality of the Cambro-Ordovician magmatism of Iberia. *Lithos* **107**, 227–38.

MONTERO, P., BEA, F., GONZÁLEZ-LODEIRO, F., TALAVERA, C. & WHITEHOUSE, M. J. 2007. Zircon ages of the metavolcanic rocks and metagranites of the Ollo de Sapo Domain in central Spain: implications for the Neoproterozoic to Early Palaeozoic evolution of Iberia. *Geological Magazine* **144**, 963–76.

MONTERO, P., TALAVERA, C., BEA, F., LODEIRO, F. G. & WHITEHOUSE, M. J. 2009b. Zircon geochronology of the Ollo de Sapo Formation and the age of the Cambro-Ordovician rifting in Iberia. *Journal of Geology* **117**, 174–91.

MURPHY, J. B. & NANCE, R. D. 1991. Supercontinent model for the contrasting character of Late Proterozoic orogenic belts, Geology **19**, 469–72.

OLIVEIRA, J. T. 1990. South Portuguese Zone. Stratigraphy and synsedimentary tectonism. In *Pre-Mesozoic Geology of Iberia* (eds R. D. Dallmeyer & E. Martínez García), pp. 334–47. Berlin: Springer-Verlag.

ORDÓÑEZ CASADO, B., GEBAUER, D., SCHÄFER, 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**, 359–85.

PEREIRA, M. F., CHICHORRO, M., JOHNSTON, S. T., GUTIÉRREZ-ALONSO, G., SILVA, J. B., LINNEMANN, U., HOFMANN, M. & DROST, K. 2012. The missing Rheic Ocean magmatic arcs: provenance analysis of Late Paleozoic sedimentary clastic rocks of SW Iberia. *Gondwana Research* **22**, 882–91.

PEREIRA, Z., MEIRELES, C. & PEREIRA, E. 1999. Upper Devonian palynomorphs of NE sector of Trás-os-Montes (Central Iberian Zone). In *XV Reunión de Geología del Oeste Peninsular – International Meeting on Cadomian Basement* (eds G. Vintaned, L. Eguíluz & T. Palacios), pp. 201–6. Badajoz, Spain.

PEREIRA, M. F., RIBEIRO, C., VILALLONGA, F., CHICHORRO, M., DROST, K., SILVA, J. B., ALBARDEIRO, L., HOFMANN, M. & LINNEMANN, U. 2014. Variability over time in the sources of South Portuguese Zone turbidites: evidence of denudation of different crustal blocks during the assembly of Pangaea. *International Journal of Earth Sciences* **103**, 1453–70.

PÉREZ-ESTAÚN, A. 1974. Aportaciones al conocimiento del Carbonífero de San Clodio (Prov. de Lugo). *Breviora Geologica Asturica* **18**, 3–8.

PÉREZ-ESTAÚN, A., BASTIDA, F., ALONSO, J. L., MARQUÍNEZ, J., ALLER, J., ÁLVAREZ-MARRÓN, J., MARCOS, A. & PULGAR, J. A. 1988. A thin-skinned tectonics model for an arcuate fold and thrust belt: the Cantabrian Zone (Variscan Ibero-Armorican Arc). *Tectonics* **7**, 517–37.

PÉREZ-ESTAÚN, A., BASTIDA, F., MARTÍNEZ CATALÁN, J. R., GUTIERREZ MARCO, J. C., MARCOS, A. & PULGAR, J. A. 1990. West Asturian-Leonese Zone. Stratigraphy. In *Pre-Mesozoic Geology of Iberia* (eds R. D. Dallmeyer & E. Martínez García), pp. 92–102. Berlin: Springer-Verlag.

PÉREZ-ESTAÚN, A., MARTÍNEZ CATALÁN, J. R. & BASTIDA, F. 1991. Crustal thickening and deformation sequence in the footwall to the suture of the Variscan Belt of northwest Spain. *Tectonophysics* **191**, 243–53.

PEUCAT, J. J., BERNARD-GRIFFITHS, J., GIL IBARGUCHI, J. I., DALLMEYER, R. D., MENOT, R. P., CORNICHET, J. & IGLESIAS PONCE DE LEÓN, M. 1990. Geochemical and geochronological cross-section of the deep Variscan crust: the Cabo Ortegal high-pressure nappe (northwestern Spain). *Tectonophysics* **177**, 263–92.

PIÇARRA, J. M., GUTIÉRREZ-MARCO, J. C., SÁ, A. A., MEIRELES, C. & GONZÁLEZ-CLAVIJO, E. 2006a. Silurian graptolite biostratigraphy of the Galicia-Trás-os-Montes Zone (Spain and Portugal). *Journal of the Geological Society of Sweden (Geologiska Foreningen)*, **128**, 185–8.

PIÇARRA, J. M., GUTIÉRREZ-MARCO, J. C., SARMIENTO, C. & SÁ, A. A. 2006b. Novos dados de conodontes e graptólitos no Paleozóico parautóctone da Zona Galiza–Trás-os-Montes (Espanha e Portugal). In *VII Cogresso Nacional de Geologia* (eds J. Mirão, J. & A. Balbino), pp. 653–6. Universidade de Évora, Abstracts no. 2.

PIN, C., PAQUETTE, J. L., ÁBALOS, B., SANTOS, F. J. & GIL IBARGUCHI, J. I. 2006. Composite origin of an early Variscan transported suture: ophiolitic units of the Morais Nappe Complex (north Portugal). *Tectonics* **25**, TC5001, 1–19, doi: 10.1029/2006TC001971.

PIN, C., PAQUETTE, J. L., SANTOS ZALDUEGUI, J. F. & GIL IBARGUCHI, J. I. 2002. Early Devonian supra-subduction zone ophiolite related to incipient collisional processes in the Western Variscan Belt: the Sierra de Careón unit, Ordenes Complex, Galicia. In *Variscan–Appalachian Dynamics: The Building of the Late Paleozoic Basement* (eds J. R. Martínez Catalán, R. D. Hatcher Jr., R. Arenas & F. Díaz García), pp. 57–71. Geological Society of America, Special Paper no. 364.

RIBEIRO, A., MUNHÁ, J., DIAS, R., MATEUS, A., PEREIRA, E., RIBEIRO, L., FONSECA, P., ARAÚJO, A., OLIVEIRA, T., ROMÃO, J., CHAMINÉ, H., COKE, C. & PEDRO, J. 2007. Geodynamic evolution of the SW Europe Variscides. *Tectonics* **26**, 1–24, TC6009, doi: 10.1029/2006TC002058.

RIBEIRO, A., PEREIRA, E. & DIAS, R. 1990. Central-Iberian Zone. Allochthonous Sequences. Structure in the northwest of the Iberian Peninsula. In *Pre-Mesozoic Geology of Iberia* (eds R. D. Dallmeyer, & E. Martínez García), pp. 220–36. Berlin: Springer-Verlag.

RIBEIRO, M. L. & RIBEIRO, A. 1974. Signification paléogéographique et tectonique de la présence de galets de roches métamorphiques dans un flysch d'âge dévonien supérieur du Tras-os-Montes oriental (Nord-Est du Portugal). *Comptes Rendues de l'Académie des Sciences, Paris* **278**, 3161–3.

RIEMER, W. 1963. Entwicklung des Paläozoikums in der Südlichen Provinz Lugo (Spanien). *Neues Jarbuch für Geologie und Paläontologie, Abhandlungen* **117**, 273–85.

RIEMER, W. 1966. Datos para el conocimiento de la estratigrafía de Galicia. *Notas y Comunicaciones del Instituto Geológico y Minero de España* **81**, 7–20.

RODRÍGUEZ ALLER, J. 2005. *Recristalización y Deformación de Litologías Supracorticales Sometidas a Metamorfismo de Alta Presión (Complejo de Malpica-Tuy, NO del Macizo Ibérico)*. Laboratorio Xeolóxico de Laxe, A Coruña, Spain. Serie Nova Terra no. 29, 572 pp.

RODRÍGUEZ, J., COSCA, J. I., GIL IBARGUCHI, J. I. & DALLMEYER, R. D. 2003. Strain partitioning and preservation of 40Ar/39Ar ages during Variscan exhumation of a subducted crust (Malpica-Tui Complex, NW Spain). *Lithos* **70**, 111–39.

RUBIO-ORDÓÑEZ, A., GUTIÉRREZ-ALONSO, G., VALVERDE-VAQUERO, P., CUESTA, A., GALLASTEGUI, G., GERDES, A. & CÁRDENES, V. 2015. Arc-related Ediacaran magmatism along the northern margin of Gondwana: geochronology and isotopic geochemistry from northern Iberia. *Gondwana Research*, **27**, 216–27.

RUBIO PASCUAL, F. J., ARENAS, R., MARTÍNEZ CATALÁN, J. R., RODRÍGUEZ FERNÁNDEZ, L. R. & WIJBRANS, J. 2013. Thickening and exhumation of the Variscan roots in the Iberian Central System: tectonothermal processes and 40Ar/39Ar ages. *Tectonophysics* **587**, 207–21.

SÁNCHEZ MARTÍNEZ, S. 2009. *Geoquímica y Geocronología de las Ofiolitas de Galicia*. Laboratorio Xeolóxico de Laxe, A Coruña, Spain. Serie Nova Terra no. 37, 351 pp.

SÁNCHEZ MARTÍNEZ, S., ARENAS, R., ANDONAEGUI, P., MARTÍNEZ CATALÁN, J. R. & PEARCE, J. A. 2007a. Geochemistry of two associated ophiolites from the Cabo Ortegal complex (Variscan belt of northwest Spain). In *4-D Framework of Continental Crust* (eds R. D. Hatcher Jr., M. P. Carlson, J. H. McBride & J. R. Martínez Catalán), pp. 445–67. Geological Society of America, Memoir no. 200.

SÁNCHEZ MARTÍNEZ, S., ARENAS, R., DÍAZ GARCÍA, F., MARTÍNEZ CATALÁN, J. R., GÓMEZ-BARREIRO, J. & PEARCE, J. A. 2007b. Careón Ophiolite, NW Spain: suprasubduction zone setting for the youngest Rheic Ocean floor. *Geology* **35**, 53–6.

SANTOS ZALDUEGUI, J. F., SCHÄRER, U. & GIL IBARGUCHI, J. I. 1995. Isotope constraints on the age and origin of magmatism and metamorphism in the Malpica-Tuy allochthon, Galicia, NW-Spain. *Chemical Geology* **121**, 91–103.

SANTOS ZALDUEGUI, J. F., SCHÄRER, U., GIL IBARGUCHI, J. I. & GIRARDEAU, J. 1996. Origin and evolution of the Paleozoic Cabo Ortegal ultramafic-mafic complex (NW Spain): U–Pb, Rb–Sr and Pb–Pb isotope data. *Chemical Geology* **129**, 281–304.

SARMIENTO, G. N., CALVO, A. A. & GONZÁLEZ CLAVIJO, E. 1997. Conodontos paleozoicos (Ashgill-Emsiense) del Sinforme de Alcañices (oeste de Zamora, España). In *Paleozoico Inferior del Noroeste de Gondwana* (eds A. Grandal D'Anglade, J. C. Gutiérrez-Marco & L. Santos Fidalgo), pp. 108–11. V Reunión Internacional del Proyecto 351 PICG, Libro de Resúmenes y Excursiones.

Sarmiento, G. N., Piçarra, J. M., Rebelo, J. A., Robardet, M., Gutíerrez-Marco, J. C., Storch, P. & Rábano, I. 1999. Le Silurien du Synclinorium de Moncorvo (NE du Portugal): bioestratigraphie et importance paléógéographique. *Geobios* **32**, 749–67.
Schermerhorn, L. J. G. 1971. An outline of the stratigraphy of the Iberian pyrite belt. *Boletín Geológico y Minero* **82**, 239–68.
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.
Soper, N. J. 1988. Timing and geometry of collision, terrane accretion and sinistral strike-slip events in the British Caledonides. In *The Caledonian–Appalachian Orogen* (eds A. L. Harris & D. J. Fettes), pp. 481–92. Geological Society of London, Special Publication no. 38.
Stacey, J. S. & Kramers, J. D. 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth and Planetary Science Letters* **26**, 207–21.
Suess, E. 1888. *Das Antlitz der Erde*. Vol. II. Wien: Tempsky, 508 pp.
Teixeira, C. & Pais, J. 1973. Sobre a presença de Devónico na região da Bragança (Guadramil e Mofreita) e de Alcañices (Zamora). *Boletim da Sociedade Geológica de Portugal* **18**, 199–202.
Vacas, J. M. & Martínez Catalán, J. R. 1987. El Sinforme de Alcañices en la transversal de Manzanal del Barco. *Stvdia Geologica Salmanticensia* **24**, 151–75.
Valle Aguado, B., Azevedo, M. R., Schaltegger, U., Martínez Catalán, J. R. & Nolan, J. 2005. U–Pb zircon and monazite geochronology of Variscan magmatism related to syn-convergence extension in Central Northern Portugal. *Lithos* **82**, 169–84.
Valverde-Vaquero, P., Díez Balda, M. A., Díez Montes, A., Dörr, W., Escuder Viruete, J., González Clavijo, E., Maluski, H., Rodríguez-Fernández, L. R., Rubio, F. & Villar, P. 2007. The "hot orogen": two separate Variscan low-pressure metamorphic events in the Central Iberian Zone. In *Mechanics of Variscan Orogeny: A Modern View on Orogenic Research* (eds M. Faure, J. M. Lardeaux, P. Ledru, A. Peschler & K. Schulmann), p. 168. Géologie de la France, 2007, no. 2. Societé Géologique de France and Bureau de Recherches Géologiques et Minières.
Valverde-Vaquero, P., Marcos, A., Farias, P. & Gallastegui, G. 2005. U–Pb dating of Ordovician felsic volcanism in the Schistose Domain of the Galicia-Trás-os-Montes Zone near Cabo Ortegal (NW Spain). *Geológica Acta* **3**, 27–37.
van Achterbergh, E., Ryan, C. G. & Griffin, W. L. 1999. GLITTER: on-line interactive data reduction for the laser ablation ICP-MS microprobe. In *Proceedings of the 9th V.M. Goldschmidt Conference*, p. 305. Cambridge, Massachusetts.
van Achterbergh, E., Ryan, C., Jackson, S. & Griffin, W. 2001. Appendix 3 Data reduction software for LA-ICP-MS. In *Laser-Ablation-ICPMS in the Earth Sciences* (ed. P. Sylvester), pp. 239–43. Mineralogical Association of Canada Short Course no. 29.
Wiedenbeck, M., Alle, P., Corfu, F., Griffin, W. L., Meier, M., Oberli, F., Von Quart, A., Roddick, J. C. & Spiegel, W. 1995. Three natural zircon standards for U–Th–Ph, Lu–Th, trace element and REE analyses. *Geostandards Newsletter* **19**, 1–23.