U–Pb detrital zircon ages in synorogenic deposits of the NW Iberian Massif (Variscan belt): interplay of Devonian–Carboniferous sedimentation and thrust tectonics

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Abstract: Detrital zircons from Devonian and Carboniferous synorogenic flysch deposits occurring in an imbricate stack have been dated by laser ablation-inductively coupled plasma mass spectrometry (LA-ICP-MS) to: (1) obtain a maximum depositional age to constrain the maximum age limit for thrusting of exotic terranes in the NW Iberian Massif; (2) correlate the zircon age populations with published ages in nearby units to establish their possible source areas. The maximum depositional ages are Late Devonian for rocks high in the structural nappe pile (Gimonde Formation), in accordance with palynomorph dating, and around the Devonian–Carboniferous boundary for structurally lower samples (San Vitero Formation). Used in conjunction with previously published ages, the new ages are interpreted in terms of the advance of the thrust system responsible for the emplacement of exotic terranes upon the Iberian autochthon during the Variscan collision. Early Variscan zircon population ages indicate the exotic terranes as the source of synorogenic sediments, whereas their scarcity suggests derivation from the Iberian autochthon. One of the samples analysed lacks Variscan detrital zircons; this feature, together with the absence of an Early Palaeozoic zircon age population, puts into question its synorogenic character and suggests that the sample may be representative of the preorogenic parautochthon.

The Iberian Massif formed during the Variscan continental collision between Laurussia and Gondwana. Deformation in NW Iberia started during the Middle–Late Devonian (Dallmeyer *et al*. 1997; Martínez Catalán *et al*. 1997, 2007; Rodríguez *et al*. 2003), and was accompanied by Devonian and Early Carboniferous synorogenic sedimentation, which is poorly preserved in the deeply eroded basement of this part of the Variscan belt.

Dating of detrital zircons in the synorogenic deposits may help to constrain the timing of deformation by establishing maximum depositional ages for these sedimentary units. Furthermore, the age clusters can be compared with those of the preorogenic sequence to establish which units supplied the detritus, thus providing valuable information on the orogenic evolution. In this paper we report and discuss the results of U–Pb zircon dating of four samples of the San Vitero and Gimonde synorogenic formations using laser ablation-inductively coupled plasma mass spectrometry (LA-ICP-MS), in an attempt to check the diachronous character of synorogenic sedimentation, relate it to the progression of Variscan deformation towards the foreland, and gain insights into their sources.

Geological setting and age data

Preorogenic history

The Variscan belt of NW Iberia is characterized by an autochthonous metasedimentary sequence, and several exotic, allochthonous terranes, separated by a parautochthonous thrust sheet (Fig. 1). In addition, there are abundant syn- to postorogenic granitoids and scarce synorogenic sediments.

The autochthonous sequence consists of thick and monotonous Neoproterozoic siliciclastic rocks and of Palaeozoic clastic rocks, carbonates, and volcanic and intrusive rocks. It is generally agreed that the autochthonous sedimentary sequences were deposited on the northern margin of Gondwana. During the late Proterozoic, the area was an active continental margin (Murphy & Nance 1991; Ochsner 1993) involved in the Cadomian–Avalonian–Pan-African orogeny. However, in Cambro-Ordovician times, what now forms the Iberian Massif was the site of continental rifting, which finally resulted in the opening of the Rheic Ocean, the separation of the Avalon microcontinent and other peri-Gondwanan terranes (Fortey & Cocks 1988; Soper 1988), and the formation of a passive margin that was stable from the Cambrian to the Early Devonian.

The Cadomian and Cambro-Ordovician events produced abundant granitoids and volcanic rocks, whose crystallization ages range from 620 to 470 Ma (Lancelot *et al*. 1985; Allegret & Iglesias Ponce de León 1987; Vialette *et al*. 1987; Gebauer 1993; Ochsner 1993; Fernández-Suárez *et al*. 1998; Valverde Vaquero & Dunning 2000; Bea *et al*. 2006; Díez Montes 2006). Older ages have been obtained from upper intercepts and inherited zircons from orthogneisses and volcaniclastic rocks. They include a population of 1180–1080 Ma (Fernández-Suárez *et al*. 1999), and the rest range between 3.2 and 1.8 Ga (Lancelot *et al*.

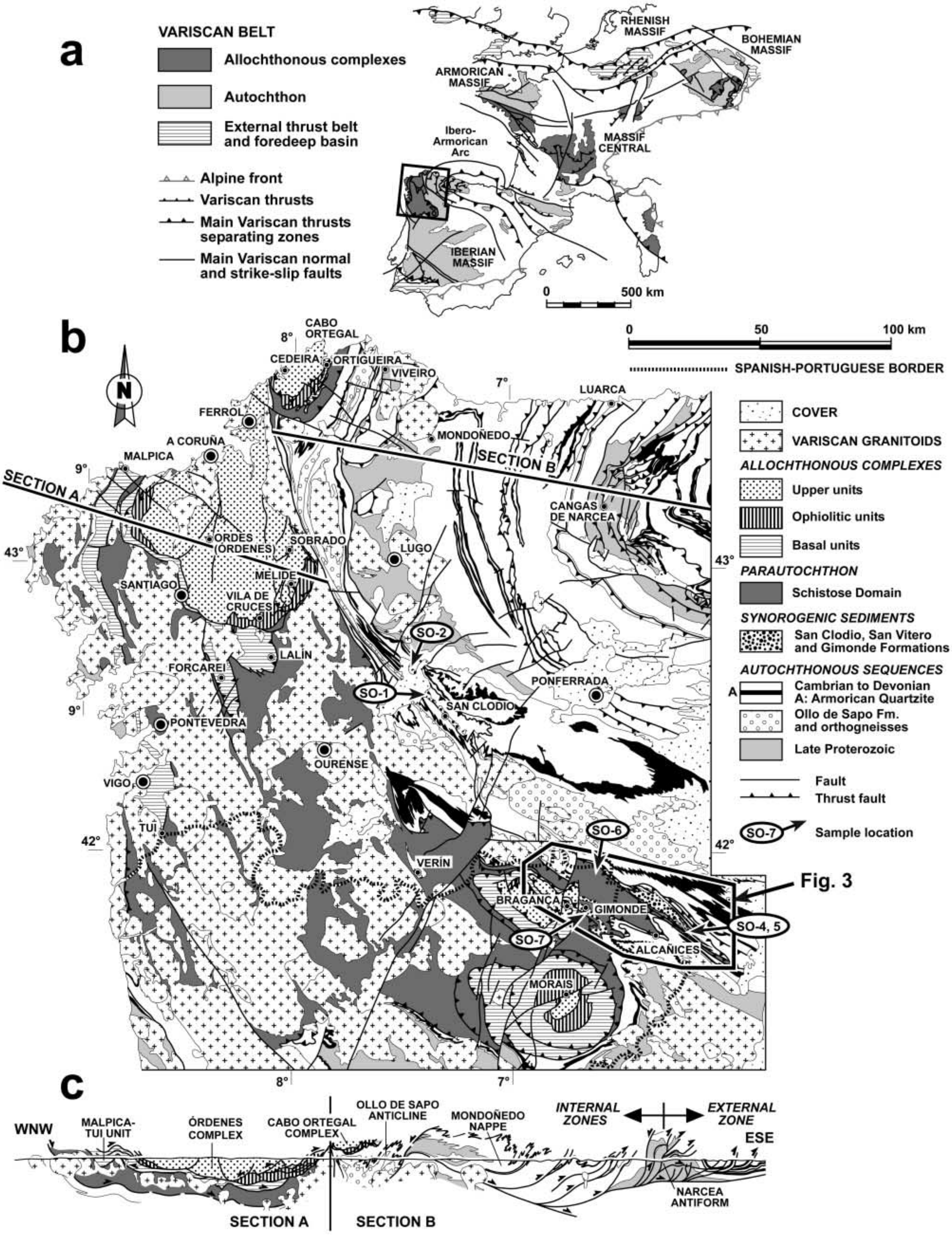

Fig. 1. (**a**) Location of the study area in the Ibero-Armorican arc, in the western part of the Variscan belt. (**b**) Geological sketch map of the NW Iberian Massif showing the main groups of rock units and the allochthonous complexes. Location of samples analysed in this work (SO-4 to SO-7) and others used in the interpretation (SO-1 and SO-2; Martínez Catalán *et al*. 2004) is shown, and the area shown in Figure 3 is outlined. (**c**) Schematic composite cross-section.

1985; Gebauer 1993; Bea *et al*. 2006). The older ages are similar to those of the West African craton (Bessoles 1977; Caby 1989), and suggest a link between the two areas. In Figure 2 the main populations of isotopic ages, representing igneous and metamorphic events, are shown.

U–Pb dating of detrital zircons from Neoproterozoic sedimentary rocks yielded four main age clusters (Fernández-Suárez *et al*. 2000*b*): Archaean (2.8–2.5 Ga), Palaeoproterozoic (2–1.8 Ga), Mesoproterozoic (1.2–0.9 Ga), and Neoproterozoic (800–640 Ma). U–Pb dating of detrital zircons from Early Palaeozoic sequences gave roughly the same clusters, plus a younger Neoproterozoic (620–550 Ma) population (Fernández-Suárez *et al*. 1999, 2000*b*, 2002*b*) and very few zircons with Palaeozoic ages ranging between 540 and 500 Ma (Martínez Catalán *et al*. 2004). As can be seen, the Cadomian events left an important imprint on the zircon population ages of contemporaneous and younger sequences, whereas the Cambro-Ordovician and younger magmatism, although voluminous, had a much weaker influence. This reflects lack of exposure as a result of continuous Palaeozoic sedimentation until the Early Devonian, which hindered the erosion of Early Palaeozoic intrusive and volcanic rocks.

The exotic terranes crop out in synforms forming five allochthonous complexes (Fig. 1). They consist of a stack of allochthonous units appearing in a constant structural order; the higher the position, the more exotic in character. The allochthonous units comprise fragments of a peri-Gondwanan terrane on top (upper units), several ophiolitic units in the middle, and parts of the subducted and exhumed outermost margin of Gondwana at the bottom (basal units). The upper, ophiolitic and basal units are known in Portugal as the Continental Allochthonous Terrane, Northern Ophiolitic Terrane, and Lower Allochthonous Thrust Complex, respectively (Marques *et al*. 1991–1992, 1996).

In the upper units, early Palaeozoic (500–480 Ma) U–Pb zircon ages obtained in metabasic rocks, orthogneisses and migmatites (Fig. 2) are interpreted as dating the igneous protoliths and low-pressure, high-temperature metamorphism (Kuijper 1980; Peucat *et al*. 1990; Dallmeyer & Tucker 1993; Abati *et al*. 1999). Upper intercepts give ages ranging between 2.5 and 1.9 Ga, similar to upper intercepts and inherited zircon ages from orthogneisses, and volcaniclastic and sedimentary rocks of the Iberian autochthon.

Greywackes from low-grade metasediments in the uppermost unit of the Órdenes Complex have been investigated for detrital zircon ages, and yielded three age clusters of 2.5–2.4 Ga, 2.1–1.9 Ga and 610–480 Ma (Fernández-Suárez *et al*. 2003). They record the major events in the African section of northern Gondwana, where no Mesoproterozoic events have been identified.

The ophiolitic units have yielded a wide range of ages. The youngest of them have been dated by U–Pb on zircons at 405–395 Ma in the Morais and Órdenes complexes, and are interpreted as suprasubduction-zone or arc-related ophiolites formed during the closure of the Rheic Ocean (Díaz García *et al*. 1999; Pin *et al*. 2002, 2006; Sánchez Martínez *et al*. 2007). Older mafic ensembles, dated at 447 ± 24 Ma in the Morais complex and 497 Ma in the Órdenes complex, are interpreted as mid-ocean ridge or suprasubduction-zone ophiolites, but formed during the opening of the same ocean (Pin *et al*. 2006; Arenas *et al*. 2007). An even older mafic unit in the Cabo Ortegal complex has yielded zircons clustering around 1159 ± 39 Ma, and has been interpreted as a pre-Rodinian ophiolite (Sánchez Martínez *et al*. 2006). It is worth noting that these are so far the only Mesoproterozoic zircons dated in the exotic terranes of NW Iberia.

In the basal units, granitic and peralkaline orthogneisses have yielded Rb–Sr whole-rock (Van Calsteren *et al*. 1979; García Garzón *et al*. 1981) and U–Pb zircon (Santos Zalduegui *et al*. 1995) ages of 480–460 Ma, the latter with an inherited component of 1.8 Ga. This magmatism reflects Ordovician rifting (Ribeiro & Floor 1987; Pin *et al*. 1992), and is coeval with that found in the autochthon. The absence of ophiolites between the basal units and the autochthon indicates that both formed part of the same continental realm, the northern platform of Gondwana. The rift-related Ordovician magmatism in both supports this interpretation.

The exotic terranes are separated from the Iberian autochthon by a 3–7 km thick imbricate thrust sheet known as the parautochthon (Ribeiro *et al*. 1990) or Schistose Domain (Farias *et al*. 1987). The parautochthon consists of Ordovician, Silurian and Devonian sedimentary sequences and volcanic rocks, and younger synorogenic flysch deposits (Pereira *et al*. 1999; González Clavijo & Martínez Catalán 2002; Valverde-Vaquero *et al*. 2005; Piçarra *et al*. 2006*a*, *b*).

Some discussion has arisen on the appropriateness of using the

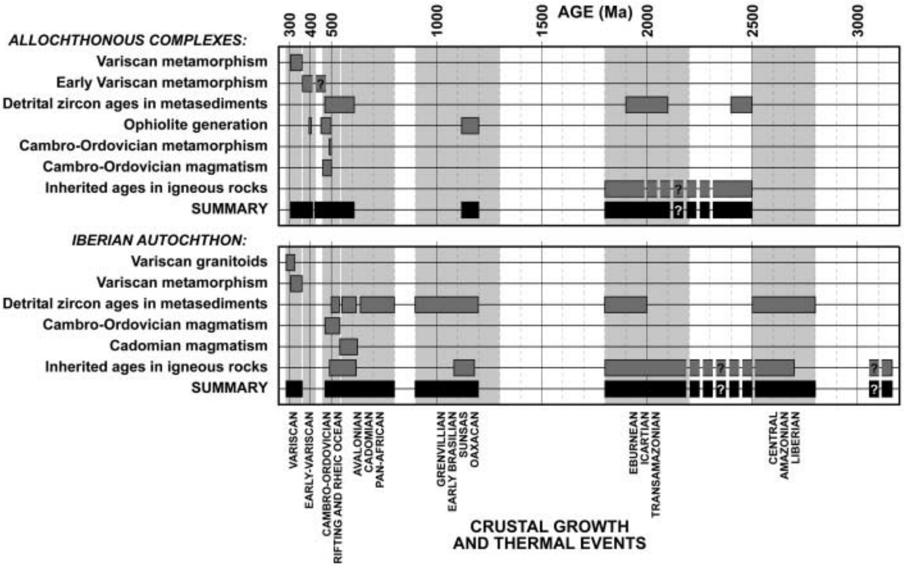

Fig. 2. Diagram summarizing the main populations of isotopic ages found in the allochthonous complexes and the NW Iberian autochthon. The ages have been obtained on many kinds of rocks and represent past igneous and metamorphic events. A summary of crustal growth and thermal events is included to facilitate comparison with the age clusters yielded by zircons in the synorogenic samples studied.

term parautochthon, because Ordovician volcanic rocks have been demonstrated to lie on top of Silurian metasediments (Valverde-Vaquero *et al*. 2005), indicating a truly allochthonous character. From a palaeogeographical point of view, however, the complete Silurian–Lower Devonian sequence of the Schistose Domain is of a relatively small thickness and commonly includes lydites (carbonaceous cherts) and limestone in the upper part. These characteristics are similar to those of the successions in the surrounding Iberian autochthon (Sarmiento *et al*. 1999; Gutiérrez-Marco *et al*. 2001), although different from the rest of the western Iberian autochthon (Piçarra *et al*. 2006*a*), which supports the parautochthonous nature of at least a part of the Schistose Domain.

Stratigraphic and faunal similarities between the Schistose Domain and the neighbouring Iberian autochthon, and the common presence of Ordovician volcanic rocks, point to a correlation of the Schistose Domain with the Palaeozoic autochthonous sequences (Farias *et al*. 1987; Valverde-Vaquero *et al*. 2005; Piçarra *et al*. 2006*a*). These facts and the absence of ophiolites inside or at the contact with the autochthon suggest that the parautochthon represents a relatively distal part of the Gondwanan continental margin, tectonically emplaced over the autochthon.

In Portugal, Rodrigues *et al*. (2003, 2006) have recently distinguished an upper parautochthon, structurally characterized by recumbent folds, and a lower parautochthon, where imbrication dominates the structure. The imbricate fan of the latter and its relationships with the autochthon are well preserved in the Alcañices synform, and are shown in Figure 3. It should be noted that the structural column is schematic, and many more imbricate units actually occur, as seen in the cross-sections. For more detailed information about the stratigraphy and structure of the Alcañices synform, the reader is referred to González Clavijo (1997), Meireles (2000*a*, *b*), González Clavijo & Martínez Catalán (2002) and Rodrigues *et al*. (2006).

Variscan evolution

A discussion on the orogenic evolution of NW Iberia has been given by Martínez Catalán *et al*. (2007). A clear diachronism of the deformation was demonstrated by Dallmeyer *et al*. (1997) and confirmed by later age data, with the oldest deformation events identified in the highest exotic terranes, and a progression occurring towards the lower ones and then to the autochthon, where deformation is older in the hinterland, to the west or SW, and younger towards the foreland, to the east or NE. Devonian deformation and metamorphism of the allochthonous units, which represent terranes with varying grades of exotism, are clearly linked to convergence related to closure of the Rheic Ocean, and associated to subductive and accretionary processes (Martínez Catalán *et al*. 1996, 1997). Devonian orogenic activity is commonly referred to as early Variscan, by contrast with the Variscan deformation spanning most of the Carboniferous and that is related to the Laurussia–Gondwana collision.

The earlier events occurred in the upper exotic terranes, which accreted to Laurussia possibly during the closure of the Iapetus or Tornquist ocean. They mark the widest extent of the Rheic Ocean and the start of its consumption. A Silurian or Early Devonian age for this accretion (prior to 410 Ma) has been proposed on the basis of ^{40}Ar/^{39}Ar and U–Pb dating of high-pressure granulite- and amphibolite-facies metamorphic fabrics (Fernández-Suárez *et al*. 2007; Gómez Barreiro *et al*. 2007). Furthermore, abundant U–Pb ages between 405 and 390 Ma (Fig. 2) have been obtained on zircons, monazites, titanites and rutile in high-pressure granulites of the upper allochthonous units (Schäfer *et al*. 1993; Santos Zalduegui *et al*. 1996; Ordóñez Casado *et al*. 2001; Fernández-Suárez *et al*. 2002*a*; Roger & Matte 2005). This Early Devonian metamorphic event was followed by a subsequent retrograde amphibolite-facies metamorphism at 390–380 Ma in the upper units (Dallmeyer *et al*. 1991, 1997; Valverde Vaquero & Fernández 1996). A similar but prograde metamorphism affected the ophiolitic units during the same interval, 390–380 Ma (Dallmeyer *et al*. 1991, 1997), closely following oceanic crust generation. This age is that of the foliation related to ophiolite imbrication, and represents a stage of the closure of the Rheic Ocean (Díaz García *et al*. 1999; Sánchez Martínez *et al*. 2007).

The basal allochthonous units represent the external edge of the continental margin that underwent subduction followed by thrusting and exhumation during the Variscan collision (Gil Ibarguchi & Ortega Gironés 1985; Arenas *et al*. 1995; Martínez Catalán *et al*. 1996, 1997; Rubio Pascual *et al*. 2002). Subduction may have started at 380 Ma and ended at *c*. 365 Ma (Van Calsteren *et al*. 1979; Santos Zalduegui *et al*. 1995; Rodríguez *et al*. 2003).

The age of Variscan deformation was established by Dallmeyer *et al*. (1997) with several ^{40}Ar/^{39}Ar whole-rock and muscovite analyses of low-grade regional cleavages and thrust-related phyllonites in the autochthon of NW Iberia. The first cleavage (S_1), associated with recumbent folding (D_1), was dated between 359 and 336 Ma, whereas subsequent thrusting (D_2) yielded ages between 343 and 321 Ma (Fig. 2), with the ages younging eastwards in both cases. The exotic terranes were thrust onto the parautochthon after 346 Ma, the age of high-temperature metamorphism predating thrusting (Abati & Dunning 2002), and probably around 340 Ma, the ^{40}Ar/^{39}Ar age of the regional cleavage according to Dallmeyer *et al*. (1997). Afterwards, the parautochthon was emplaced on top of the NW Iberian autochthon carrying the exotic terranes piggyback, and then thrusting propagated into the autochthon.

Finally, gravitational collapse of the thickened crust led to extension with development of extensional detachments and gneiss domes, although a late episode of upright folding (D_3) with linked crenulation cleavage (S_3) took place associated with large strike-slip shear zones (Iglesias Ponce de León & Choukroune 1980). The age of this event has been established between 315 and 305 Ma (Capdevila & Vialette 1970; Ries 1979; Regêncio Macedo 1988; Valle Aguado *et al*. 2005).

Variscan granitoids are abundant in NW Iberia (Fig. 1), and result from melting of the continental crust thickened during the Variscan orogeny. Capdevila (1969), Capdevila & Floor (1970), and Capdevila *et al*. (1973) established the main types, which include a syntectonic biotite- (and hornblende-) rich metaluminous type, formed by melting of the lower crust with variable mantle participation, a more abundant two-mica, peraluminous type, also syntectonic and derived from melting of mid-crustal metasediments rich in hydrous phases, and a wide group of post-tectonic granitoids with compositions similar to those of the syntectonic groups. Early metaluminous granodioritic to tonalitic intrusions were emplaced at *c*. 325 Ma, syntectonic peraluminous leucogranites crystallized between 315 and 310 Ma, and post-tectonic monzogranites and granodiorites intruded between 295 and 285 Ma (Fernández-Suárez *et al*. 2000*a*).

The synorogenic San Clodio, San Vitero and Gimonde formations

Synorogenic sedimentary rocks are well preserved in the two external zones of the Iberian Massif, the South Portuguese and

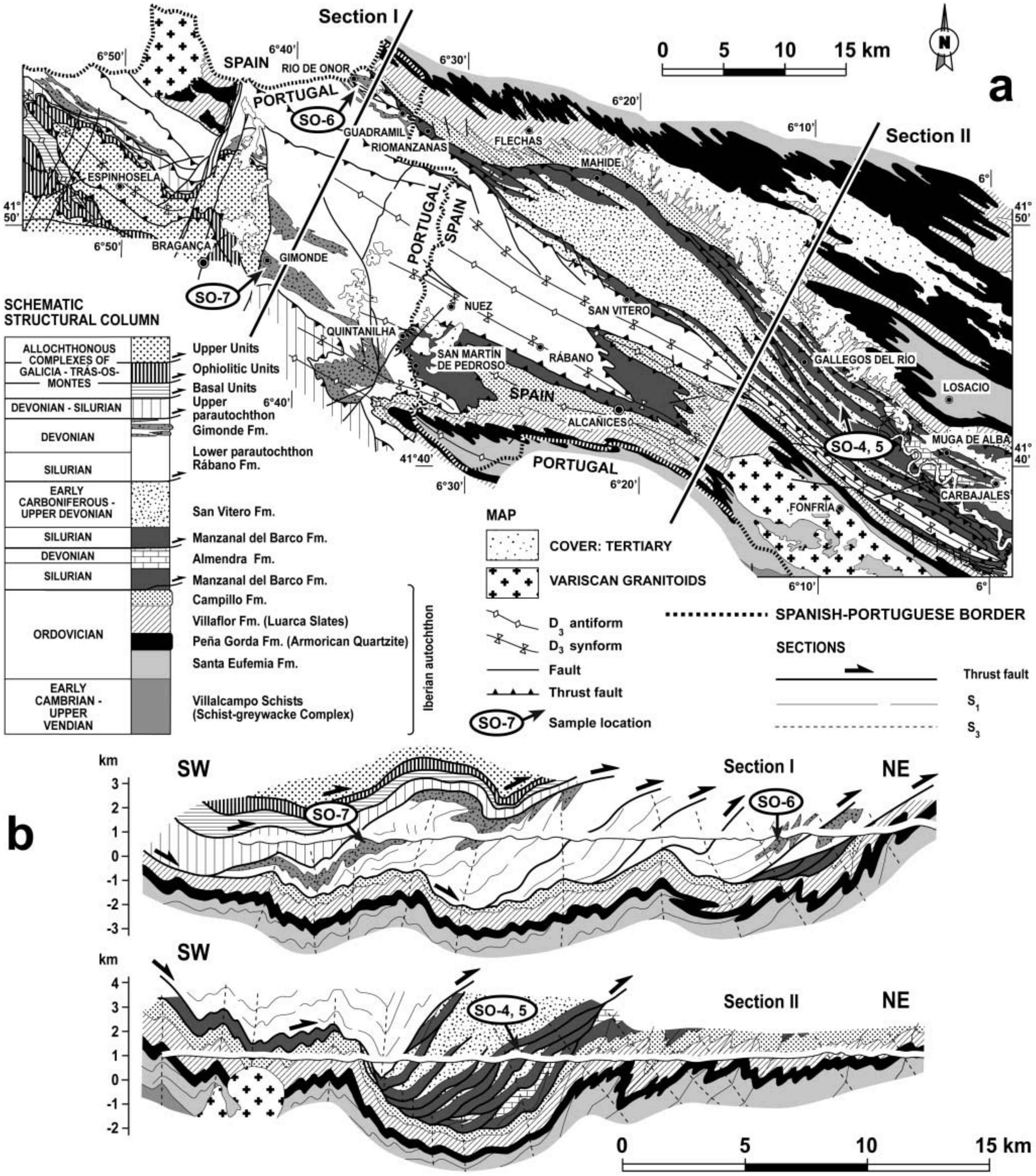

Fig. 3. (**a**) Geological map of the Alcañices synform showing the sampling localities. The structural column is simplified and shows the main units of the allochthonous and parautochthonous ensembles; however, many more imbricates exist, as shown in the cross-sections. (**b**) Geological sections. Thin, long lines represent axial surfaces of D_1 recumbent folds and associated cleavage S_1; short dashed lines depict the attitude of S_3 crenulation cleavage and D_3 folds. It should be noted that D_1 folds are cut by thrusts (D_2) and both are overprinted by later upright folds (D_3). Sampling localities have been projected into the closest section to show their structural position.

Cantabrian Zones, with ages ranging from Late Viséan to Early Westphalian in the former (Oliveira 1990) and Namurian to Westphalian in the latter (Marcos & Pulgar 1982; Pérez-Estaún *et al*. 1988). In the internal zones, synorogenic deposits are much less abundant, probably because of larger amounts of erosion, but occur in the core of late Variscan synforms, two of them in NW Iberia (the Sil and Alcañices synforms). These deposits have been interpreted as Variscan synorogenic flysch related to the central European Culm facies (Antona & Martínez Catalán 1990).

The San Clodio Fm. crops out along the NW–SE-striking Sil synform (Fig. 1), and consists of synorogenic turbidites made up of pelites and greywackes, minor carbonaceous cherts at the base, thin coal veins, poorly preserved plant debris, and pebbles of quartzite, slate, gneiss and granite (Riemer 1966; Matte 1968; Pérez-Estaún 1974). It was deposited at the front of the allochthonous thrust complex formed by the exotic terranes and the parautochthon, according to Martínez Catalán *et al*. (2004), who dated detrital zircons in two samples of the formation (samples SO-1 and SO-2, Fig. 1). The analyses yielded four zircon age populations: Archaean (2.9–2.5 Ga), Palaeoproterozoic (2.3–1.8 Ga), Neoproterozoic–Ordovician (660–470 Ma), and latest Silurian–Carboniferous (417–324 Ma). Furthermore, they helped to establish a maximum depositional age for the formation of 324 ± 7 Ma, at the Early–Middle Carboniferous limit, interpreted as closely reflecting the time of sedimentation. Zircon age populations pointed to the exotic terranes preserved in the allochthonous complexes of NW Iberia as the source area, confirming the close link between their emplacement and synorogenic sedimentation, as suggested by González Clavijo & Martínez Catalán (2002).

The San Clodio Fm. is the more external synorogenic deposit preserved in the hinterland of the NW Iberian basement. More internal synorogenic deposits occur to the NE of the Portuguese allochthonous complexes of Bragança and Morais, namely the San Vitero and Gimonde formations, which after deposition were involved in the thrust tectonics related to the emplacement of the complexes and were preserved in the core of the Alcañices synform (Fig. 3).

The San Vitero Fm. (Martínez García 1972) occurs along the northern flank of the Alcañices synform, forming an imbricate fan between the lower parautochthon and the Iberian autochthon. It consists of terrigenous turbidites, including microconglomerates with metamorphic pebbles, and also plant debris. Alternations of thin carbonaceous cherts are common near the base. The thickness of this formation is difficult to evaluate because of pervasive imbrication but several hundred metres is a reasonable estimate. The contact with the underlying Manzanal del Barco Fm., of Silurian age, is a disconformity: the beds are regionally parallel to each other, but in detail, there is an erosive surface at the base of the first turbiditic cycle (González Clavijo & Martínez Catalán 2002). The age of the formation is uncertain, because no fossils (other than unclassifiable plant debris) have been found.

The Gimonde Fm. (Pereira *et al*. 1999) forms part of the lower parautochthon, and consists of alternations of slates and fine-grained greywackes, which locally pass into microconglomerates and conglomerates containing pebbles of meso- and catazonal gneisses and basic rocks derived from the allochthonous complexes, as well as low-grade metasandstones, metacherts, metatuffs, phyllites and quartzites (Ribeiro & Ribeiro 1974; Meireles 2000*a*). The formation crops out mainly at the northern and southern limits of the lower parautochthon, although minor exposures can be found between them, and is clearly dismembered and repeated by the thrust tectonics affecting the area (Meireles 2000*a*, *b*). Its age was established as Late Devonian by Teixeira & Pais (1973) using plant debris and, according to palynological data by Pereira *et al*. (1999), the formation is older (Givetian–Frasnian) in the south, around Gimonde, and younger (Frasnian) to the north, in the area of Rio de Onor.

Sample description

Two samples (SO-4 and SO-5) were collected in the San Vitero Fm., 390 m apart from each other within the same thrust sheet, and two more in the Gimonde Fm., one to the north, close to Rio de Onor (SO-6), and a second sample in the south, close to Gimonde (SO-7; Fig. 3). The four samples are low-grade (chlorite zone) metagreywackes, one of them conglomeratic, consisting of monomineralic and lithic fragments and a fine-grained matrix, and are characterized by a spaced cleavage formed essentially by pressure-solution. Monomineralic grains include quartz, feldspar (both plagioclase and K-feldspar), detrital muscovite and chloritized biotite, and opaque minerals. The lithic fragments vary from one sample to other, but always include polycrystalline quartz aggregates. Other common types are metasandstones, carbonaceous metacherts, phyllites and schists; that is, fragments with a previous deformational and metamorphic history, apparently always of greenschist facies.

SO-4 is a metaconglomerate from the San Vitero Fm. consisting of grain-supported angular to rounded pebbles, equigranular to elongate, up to 15 mm long, and little deformed. The matrix is sandy and pelitic, formed by very fine-grained clayey or micaceous material and grains of quartz and plagioclase. Metamorphic pebbles include quartzitic schists, with a tectonic fabric marked by micas (muscovite, chloritized biotite and chlorite), whose attitude varies from one pebble to another. The quartz in the pebbles shows undulose extinction, recovery, recrystallization with serrate grain boundaries, and lamellae of the deformation and Boehm types, most of them indicating low-temperature deformation. Pebbles of slate are also common, with a very fine slaty cleavage, which in this case is subparallel to that of other similar pebbles and also to the weak tectonic cleavage affecting the whole rock. These seem to represent intrabasinal detritus without a previous, inherited tectonic fabric.

SO-5 is a metagreywacke from the San Vitero Fm. formed by angular to rounded grains, equigranular to elongate, up to 1.5 mm long, within a fine-grained matrix. Monomineralic grains are common, and include all deformation microstructures described in the previous sample. Lithic fragments are also abundant, and include metasandstones, quartz schists, metacherts, slates and carbonaceous slates. Many of them show an inherited tectonic fabric previous to that affecting the rock, which has a spaced, anastomosing cleavage, irregular in detail, that suggests formation by pressure solution.

SO-6 is a metagreywacke from the Gimonde Fm., similar to SO-5 but with smaller fragments (up to 0.7 mm), and a comparable spaced cleavage. However, the proportion of monomineralic grains is higher, and large mica grains, mostly muscovite, are characteristic. The quartz is often strain-free, and plagioclase is more abundant. The lithic fragments are scarce and include cherts, metasandstones and schists.

SO-7 is also a metagreywacke from the Gimonde Fm., differing from the previous sample in being poorer in lithic fragments and more intensely deformed. The fabric is a closely spaced pressure-solution cleavage marked by insoluble material. The quartz fragments are angular and very elongated parallel to the cleavage, and show evidence of pressure solution at their margins, but little internal deformation. Plagioclase is common, as well as muscovite and chloritized biotite, but lithic fragments are very scarce, and mostly consist of polycrystalline quartz. Phyllites or schists with inherited fabrics have not been found.

Analytical methods: U–Pb zircon dating

Mineral separation was carried out at the Universidad Complutense (Madrid) following conventional techniques. Zircon grains were mounted in epoxy discs and polished. Back-scattered electron images (BSE) were obtained for all grains selected for LA-ICP-MS analysis to ensure ablation of homogeneous zircon domains. Procedures for zircon separation, mounting and cleaning were similar to those described by Martínez Catalán *et al.* (2004).

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 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 on-line software package GLITTER (www.mq.edu.au/GEMOC; 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.

We have employed the common-Pb correction procedure of Andersen (2002) and the analyses presented here have been corrected assuming recent lead loss with a common lead composition corresponding to present-day average orogenic lead as 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 analytical error in ^{206}Pb/^{238}U and ^{207}Pb/^{235}U, or that have less than 0.2% common lead. Concordia diagrams and probability density distribution plots were generated using the Isoplot software, version 3.0 (Ludwig 2003).

Sixty analyses were performed on single grains from each of the four samples. The results are shown as concordia diagrams (Fig. 4) and relative probability plots (Fig. 5). A table of LA-ICP-MS U–Pb results is available online at http://www.geolsoc.org.uk/SUP18305.

Although the analytical methods and BSE imaging ensure ablation of homogeneous zircon domains, only analyses that are concordant at the 2σ confidence level have been considered for Neoproterozoic and Palaeozoic populations, on which the subsequent discussion mainly focuses. In the case of pre-Neoproterozoic zircons some slightly discordant analyses have been considered (see Fig. 4 and the Supplementary Publication).

The ages reported in the probability plots of Figure 5 are the concordia ages and errors as defined by Ludwig (1998) for concordant analyses and the ^{207}Pb/^{206}Pb ages and 2σ errors for the few slightly discordant pre-Neoproterozoic analyses.

Results and interpretation

The two samples analysed in the San Vitero Fm. (SO-4 and SO-5; Figs 4 and 5) yielded similar populations and have been plotted together in the concordia diagrams. A total of 117 zircons fulfilled the concordance criteria, of which 15 are Archaean (3.5–2.5 Ga), 28 Palaeoproterozoic (2.5–1.8 Ga), eight Mesoproterozoic (1.5–1.0 Ga), 46 Neoproterozoic (850–540 Ma), 17 Cambro-Ordovician (540–455 Ma), one is early Variscan (380 Ma) and two are Variscan (360–355 Ma).

The first important conclusion concerns the age of the formation, which had not been dated palaeontologically. The presence of two concordant Variscan zircons with ages of 355 ± 8 and 360 ± 6 Ma in sample SO-5 indicates a maximum depositional age around the Devonian–Carboniferous boundary. The second is the confirmation of its synorogenic character, as it includes Variscan zircons and was deformed during the Variscan cycle, demonstrated by its low-grade cleavage, and its involvement in the Variscan thrust tectonics.

The San Vitero Fm. includes all significant age clusters present in both the Iberian autochthon and the allochthonous complexes (Fig. 2), which obviously does not help to discriminate between them as the possible source. However, the relative abundance of Mesoproterozoic zircons, scarce in the exotic terranes, and the wide interval covered by the Neoproterozoic population, similar to that of the autochthon, together with the presence of an early Variscan zircon, which can only derive from the allochthon, supports a mixed provenance.

Sample SO-6, from the Gimonde Fm. in the north (Figs 3–5), has yielded 58 concordant zircons, of which one is Archaean (2.7 Ga), five are Palaeoproterozoic (2.3–2 Ga), one is Mesoproterozoic (1.7 Ga), eight are Neoproterozoic (640–547 Ma), 32 Cambro-Ordovician (524–457 Ma) and 11 early Variscan (430–380 Ma).

The youngest zircon has an age of 378 ± 6 Ma, indicating a Late Devonian (Frasnian) maximum depositional age according to Gradstein *et al.* (2004). This is also the depositional age as deduced from palynomorphs by Pereira *et al.* (1999), consistent with the conclusion that when synorogenic deposits have a representative population of synorogenic zircons, the age of deposition matches closely that of the youngest zircon (Martínez Catalán *et al.* 2004). In this case, the sediments seem to derive from the exotic terranes, because of the absence of Grenvillian zircons and the importance of the early Variscan synorogenic population, as early Variscan metamorphism occurs only in the allochthonous complexes.

Sample SO-7, from the southern outcrops of the Gimonde Fm. (Figs 3–5) has yielded a unique three-age population spectrum. Of the 60 analysed zircons, nine are Archaean (3.4–2.6 Ga), 28 Palaeoproterozoic to early Mesoproterozoic (2.4–1.6 Ga) and 23

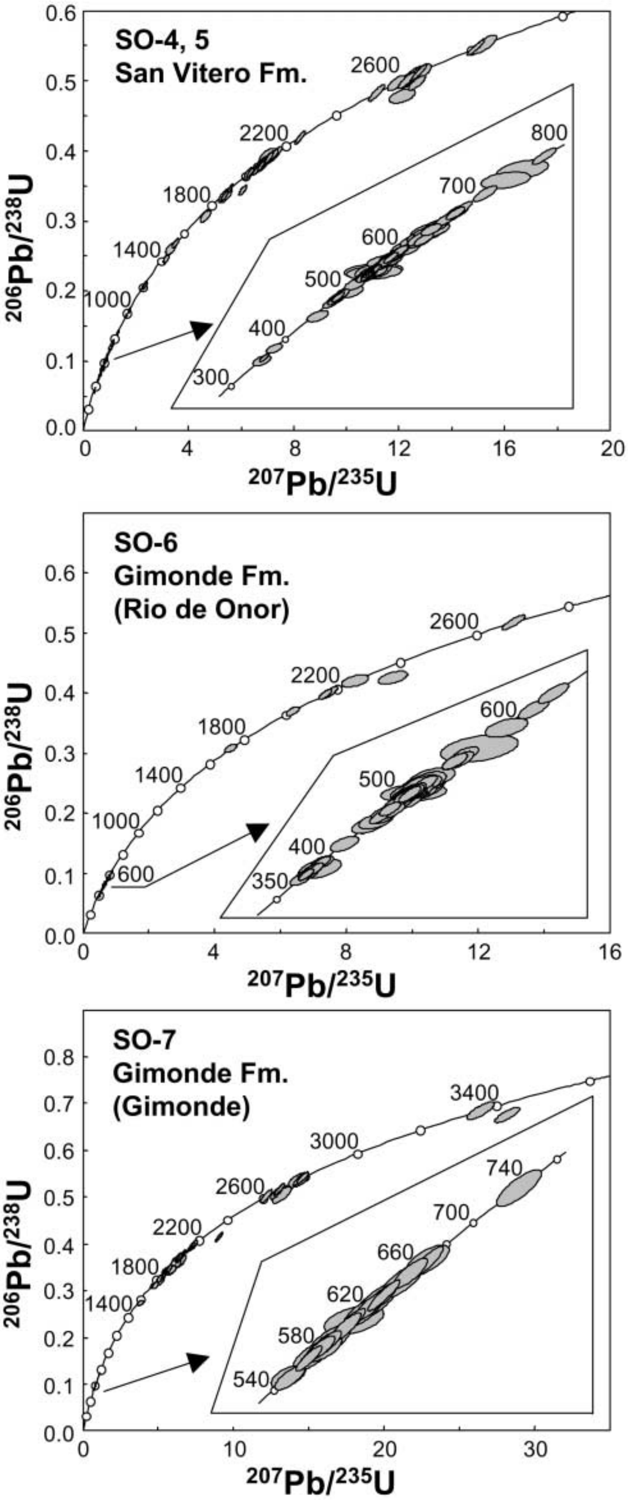

Fig. 4. Concordia plots of U–Pb analytical data from the synorogenic San Vitero and Gimonde formations. Ellipses represent 2σ uncertainties. Insets show the Neoproterozoic and Palaeozoic zircon populations.

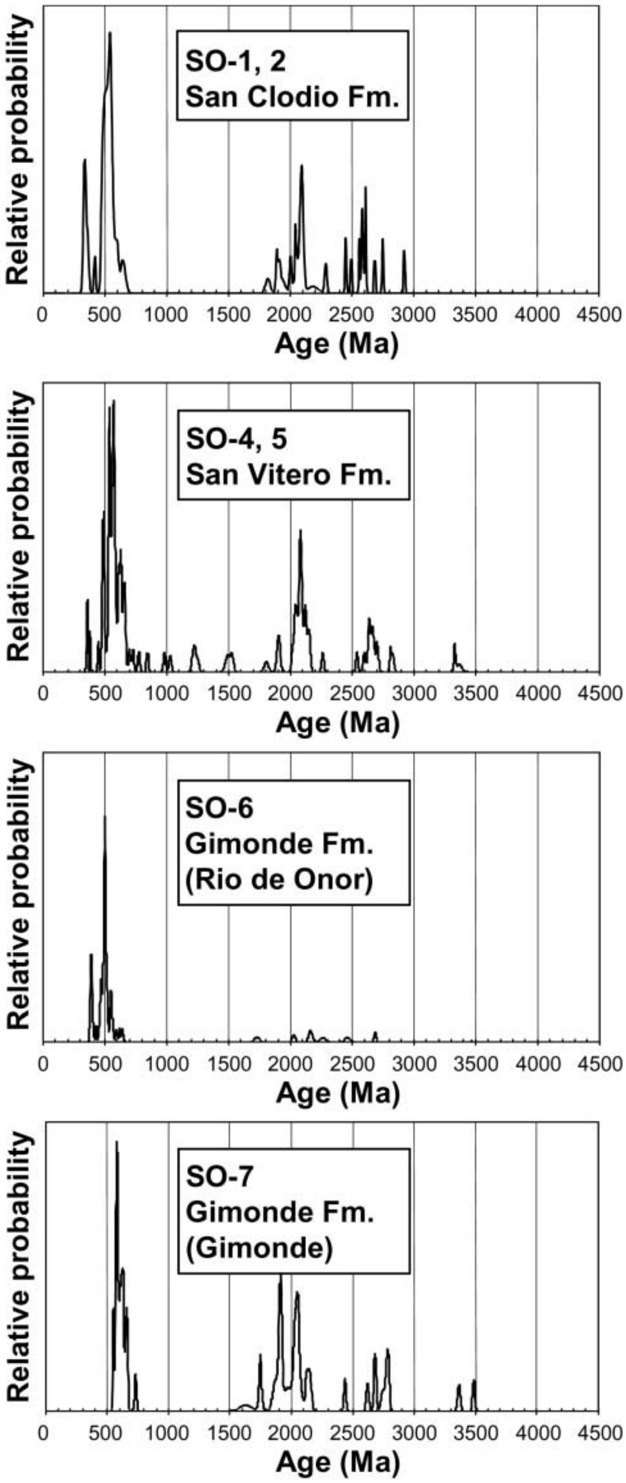

Fig. 5. Cumulative probability plots of U–Pb ages from San Clodio, San Vitero and Gimonde formations. Data from San Clodio Fm. are after Martínez Catalán *et al*. (2004).

Neoproterozoic (735–555 Ma). Neither Grenvillian nor Palaeozoic zircons have been dated.

The lack of early Variscan and Variscan zircons cast doubts on the synorogenic nature of this sample, which lacks the typical low-grade metamorphic pebbles of the other three samples analysed. Furthermore, the palaeontological age of the same rocks was reported as Givetian–Frasnian by Pereira *et al*. (1999), although that age was based on very poorly preserved spores. If this sample is older than SO-6, it could well represent a preorogenic deposit.

The absence of a Cambro-Ordovician population in sample SO-7 points to the same conclusion, because in our study of the zircon age distribution of Palaeozoic, preorogenic quartzites in NW Iberia (Martínez Catalán *et al*. 2004), we found that such a population was very scarce (two ages in 102 zircons) in three samples of Late Ordovician, Early Silurian and Early Devonian quartzite. The same is true for the Early Ordovician Armorican Quartzite, analysed by Fernández-Suárez *et al*. (2002*c*). Conversely, the other synorogenic samples have always provided a good Cambro-Ordovician population (Figs 4 and 5). In general terms, the scarcity of recycled Cambro-Ordovician zircons (representing granitoids and coeval volcanic rocks) suggests little reworking of older deposits, and points to preorogenic rather than synorogenic sedimentation. This could also explain the fact that sample SO-7 is more intensely deformed.

If sample SO-7 is preorogenic, it would be the first low-grade preorogenic metasediment in the parautochthon to have been analysed for detrital zircons. The absence of a Grenvillian age population would cast doubt on its interpretation as simply representing more external domains of the Gondwana margin than that underlying the NW Iberian autochthon (Farias *et al*. 1987). If confirmed with further analyses, this might indicate that the derivation of the parautochthon differs from that of the underlying NW Iberian autochthon, implying a tectonic transport larger than previously assumed.

Geological implications of detrital zircon ages in synorogenic deposits

To extract the maximum information on the zircon age population of synorogenic deposits of NW Iberia, we must consider the results from the San Clodio Fm. (Martínez Catalán *et al*. 2004) in addition to those presented here. For that reason, the relative probability plot for samples SO-1 and SO-2 has been included in Figure 5. The San Clodio Fm. is the more external synorogenic deposit in the hinterland of NW Iberia, and its maximum depositional age, based on its youngest zircon (324 ± 7 Ma), is at the Early–Middle Carboniferous boundary (Serpukhovian–Bashkirian). The apparent absence of younger zircons in an area of active tectonism and abundant syntectonic magmatism, ranging between 325 and 310 Ma (Fernández-Suárez *et al*. 2000*a*), suggests that the actual age of sedimentation is Namurian.

In the San Vitero Fm., the youngest zircon (355 ± 8 Ma) suggests a depositional age older than for the San Clodio Fm., although the scarce Variscan zircons found in the two samples of this formation make this claim speculative. The Gimonde Fm. in Rio de Onor is clearly older than both the San Clodio and San Vitero formations, as suggested by its youngest zircon (378 ± 6 Ma) and in agreement with palynomorph dating (Pereira *et al*. 1999).

As the San Clodio Fm. occurs in a more external part of the Variscan belt than the San Vitero Fm. (closer to the core of the Ibero-Armorican arc; see Fig. 1), and the Gimonde Fm. occurs in an even more internal part, these ages establish a clear diachronism in the sedimentation of the synorogenic deposits, younging towards the external zones. When comparing these ages with the known Variscan deformation ages, it is evident that migration in the sedimentation coincides in time with migration of deformation in the internal domains of NW Iberia (Dallmeyer *et al*. 1997; Martínez Catalán *et al*. 2007). Our new data confirm that the depocentres of synorogenic sedimentation migrated during the emplacement of the exotic terranes currently exposed in the allochthonous complexes, as suggested by González Clavijo & Martínez Catalán (2002) and Martínez Catalán *et al*. (2004).

Concerning the provenance of the different zircon populations, the only possible source of early Variscan (420–360 Ma) zircons was the advancing wedge of exotic terranes, the only place where early Variscan deformation occurred. The maximum preserved thickness of the allochthonous wedge approaches 20 km in the Órdenes Complex, including the parautochthon (Martínez Catalán *et al*. 2002), but taking into account that erosion has occurred since its emplacement, the allochthonous sheet should have been more than 20 km thick.

However, the Iberian autochthon may also have contributed variable amounts of detritus, and this contribution may also be linked to the emplacement of the allochthonous terranes. Flexure of the underlying lithosphere during thrusting might have created a forebulge ahead of the successive depocentres, high enough to be reached by erosion. For the San Clodio and Gimonde formations, or at least for the samples analysed, the lack of a Grenvillian population, a feature of all preorogenic deposits of the autochthon, points to the exotic terranes as the dominant source of sediments.

Conversely, the San Vitero sample seems to have received a larger amount of autochthonous detritus, as suggested by its low abundance of Variscan and early Variscan zircons and the relative importance of its Grenvillian population. It is worth noting that the San Vitero Fm. overlies Silurian carbonaceous slates and cherts, and the erosion involved in the disconformity separating the two is responsible for the lack of Devonian sediments. González Clavijo & Martínez Catalán (2002) suggested that erosion was due to a forebulge created at some early stage of thrusting of the exotic terranes, whereas the deposit of San Vitero Fm. reflected subsequent filling of the foreland basin created in front of the advancing allochthon. The zircon content of San Vitero samples is in agreement with the existence of emerged bulges acting as sources of synorogenic sediments.

Conclusions

Variscan and early Variscan detrital zircon ages of three synorogenic greywackes corresponding to two different imbricates, used in conjunction with published results for two samples of a third synorogenic unit, demonstrate the migrating character of synorogenic sedimentation in NW Iberia, and suggest a close relationship between migration of depocentres towards the foreland and the advance of a large wedge of exotic terranes. The whole spectrum of zircon age populations yielded by these samples establishes the exotic terranes as an important, perhaps the main source of detrital material for the studied deposits. However, at least in one of the samples, the Iberian autochthon also seems to have contributed.

One of the samples analysed lacks Variscan and early Variscan detrital zircons; this feature, together with the absence of low-grade metamorphic pebbles and of a Cambro-Ordovician zircon age population, casts doubt on its synorogenic character. If this sample is representative of the preorogenic sediments in the parautochthon, it might indicate that the derivation of this tectonic unit differs from that of the underlying NW Iberian autochthon.

This work forms part of the research carried out in the project CGL2004-04306-C02-01/BTE of the Dirección General de Investigación, of the Spanish Ministerio de Educación y Ciencia. It is also a contribution to the Project IGCP 497: The Rheic Ocean: Its Origin, Evolution and

Correlatives. Brendan Murphy and Craig Storey are kindly acknowledged for their constuctive and detailed reviews.

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