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Tectonic escape of a crustal fragment during the closure of the Rheic Ocean:

U–Pb detrital zircon data from the Late Palaeozoic Pulo do Lobo and South Portuguese zones, southern Iberia

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Abstract: The Pulo do Lobo Zone, which crops out immediately north of the allochthonous South Portuguese Zone in southern Iberia, is classically interpreted as a polydeformed accretionary complex developed along the southern margin of the Gondwanan parautochthon (Ossa–Morena Zone), during the late Palaeozoic closure of the Rheic Ocean. This closure was a major event during the amalgamation of Pangaea. U–Pb laser ablation inductively coupled mass spectrometry dating of detrital zircons from late Palaeozoic DevonoCarboniferous clastic units in the South Portuguese Zone and Pulo do Lobo Zone yield contrasting age populations and attest to the exotic nature of both zones. Detrital zircons from the South Portuguese Zone display populations typical of detritus derived from either Gondwana (Ossa–Morena Zone), or periGondwanan terranes. In contrast, rocks from the Pulo do Lobo Zone contain populations consistent with derivation from Baltica, Laurentia or recycled early Silurian deposits along the Laurentian margin. An example of one such deposit is the Southern Uplands terrane of the British Caledonides. Taken together, these data can be reconciled by a model involving tectonic transport of a crustal fragment that was laterally equivalent to the Southern Uplands terrane between the allochthonous South Portuguese Zone and Gondwana as a result of an early Devonian collision between an Iberian indenter with Laurussia.

Supplementary material: U–Pb data tables, concordia diagrams, methods and representative back-scattered electron images are available at http://www.geolsoc.org.uk/SUP18441.

The geology of the middle to late Palaeozoic era was dominated by the amalgamation of the supercontinent Pangaea, which produced orogens in eastern North America and Western Europe that lay within Pangaea’s interior (Cawood & Buchan 2007; Murphy & Nance 2008). The Appalachian–Caledonide–Variscan orogens were produced by (1) the Ordovician–Silurian accretion of peri-Gondwanan terranes (e.g. Ganderia, Avalonia, Meguma) to Laurentia, which resulted in closure of the Iapetus Ocean, followed by (2) the Carboniferous closure of the Rheic Palaeotethys oceans and ensuing terminal collision between Gondwana and Laurussia (e.g. van Staal et al. 1998, 2009; Stampfli & Borel 2002; Fig. 1a). The former continuity of these belts was sundered in the early Mesozoic by the opening of the Atlantic Ocean. As a result, many of the suture zones, particularly those that formed by consumption of the Rheic Ocean during Pangaea amalgamation, were either destroyed or are hidden beneath the Atlantic continental shelves.

In southern Iberia, the Pulo do Lobo Zone has been interpreted as a rare exposure of part of a suture zone that records the final stages of the closure of the Rheic Ocean and the terminal collision between Gondwana and Laurussia (e.g. Eden 1991; One´zime et al. 2003). The Pulo do Lobo Zone is an early to middle Devonian polydeformed tectonic me´lange of oceanic metasediments and olistostromal phacoid quartzites unconformably overlain by a simply deformed Vise´an flysch sequence

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(Eden 1991; Giese et al. 1999; Braid et al. 2010). Together with (1) adjacent portions of the Ossa–Morena Zone to the north, (2) a sequence of dismembered mafic rocks with ophiolitic affinities (Beja Acebuches Ophiolite) and (3) the South Portuguese Zone to the south, these rocks are generally thought to preserve a segment of the Pangaean suture (e.g. Quesada et al. 1994; One´zime et al. 2003; Fig. 1b). In this scenario, the Ossa–Morena Zone, which has Palaeozoic Gondwanan faunal affinities (Robardet 2003), represents the Gondwanan parautochthon and the South Portuguese Zone is underlain by exotic basement of unknown origin (Quesada et al. 1994; One´zime et al. 2003; Pous et al. 2004). Based on palaeogeographical reconstructions (e.g. McKerrow & Scotese 1990; Scotese 2003), it has been suggested that the South Portuguese Zone basement can be correlated with extensions of either Avalonia (e.g. Leistel et al. 1998; Simancas et al. 2005) or the Meguma terrane (e.g. Mart´ınez-Catala´n et al. 1997; de la Rosa et al. 2001). Avalonia and Meguma are among several terranes collectively known as peri-Gondwanan, which originated along the northern Gondwanan margin in the Neoproterozoic but lay along the southern flank of Laurussia by the middle Devonian as a result of the closure of the Iapetus Ocean (van Staal et al. 1998, 2009; Murphy & Nance 2002; Fig. 1a). Despite these correlations there is considerable debate surrounding the late Palaeozoic palaeogeographical history of the South Portuguese Zone and the relationship of the South Portuguese

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| Fig. 1. (a) Schematic late Devonian palaeocontinental reconstruction (modified from Woodcock et al. 2007) assuming a unified Iberia and Armorica with Gondwana. White star shows approximate location of the Southern Uplands terrane of the British Caledonides and black rectangle the approximate location of (b). (b) Variscan tectonic terranes of southern Iberia showing suspect suture zone (Pulo do Lobo Zone) between the South Portuguese Zone (Laurussia?) and the Ossa–Morena Zone (Gondwana) (Pulo do Lobo Zone sample locations are shown in the inset) (adapted from One´zime et al. 2003).  Sample locations: (1) quartzite (sample JB-17) from the Phyllite Quartzite Group, Virgen de la Pen˜a nappe (37836.153’N, 007812.223’W); (2) Ala´jar  Me´lange along Rivera de Santa Ana, phacoid quartzite (sample RSA-01) (37851.429’N, 006842.013’W) and quartzite matrix (sample RSA-02)  (37851.202’N, 006841.817’W); (3) Ala´jar Me´lange phacoid quartzite (sample JB-43) (37853.954’N, 006856.013’W); (4) Ribeira de Limas formation along Rivera de Acebuches (sample AC-03) (37852.049’N, 006849.044’W); (5) Santa Iria Flysch greywacke (sample JAB-08) (37852.310’N, 006851.642’W). |

Zone to Gondwana and peri-Gondwanan terranes, which flanked the Rheic Ocean during its consumption.

To further investigate the processes associated with the formation and evolution of this putative Pangaean suture zone, we sampled the clastic metasedimentary rocks and phacoid quartzites in the Pulo do Lobo Zone and the late Devonian metasedimentary rocks in the South Portuguese Zone and present laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) U– Pb analyses of detrital zircons from these samples. Our data provide new insights into the timing of collision between Gondwana and Laurussia and demonstrate that the Pulo do Lobo Zone me´lange and metasedimentary rocks are not simply derived from the flanking Laurussian or Gondwanan margins. To account for the detrital zircon populations in the Pulo do Lobo Zone we propose derivation from a crustal fragment, which escaped laterally as the result of an early Devonian collision between an Iberian indenter (Gondwana) (Dias & Ribeiro 1995) and Laurussia. Our model not only provides a method for emplacement of the Pulo do Lobo Zone but also potentially explains genetic linkages between enigmatic voluminous magmatism and widespread mineralization in both the Meguma terrane of the Northern Appalachians and the Iberian Pyrite Belt of the South Portuguese Zone not accounted for in other models.

Geology and tectonic framework

# South Portuguese Zone

The oldest exposed units in the South Portuguese Zone are late Devonian continental shelf strata of the Phyllite Quartzite Group. The Phyllite Quartzite Group is composed of siliciclastic prevolcanic rocks deposited in a subtidal environment from fan delta and sand bar systems on a shallow marine continental platform (Moreno & Sa´ez 1990; Oliveira 1990; Moreno et al. 1996). The base of this unit is not exposed and has a minimum thickness of 300–400 m (Soriano & Mart´ı 1999). Its depositional age is constrained by the presence of Fammenian conodonts in limestone lenses interbedded with the clastic strata (Boogaard & Schermerhorn 1980, 1981). The Phyllite Quartzite Group is conformably overlain by the late Famennian–late Vise´an (Oliveira 1990) bimodal volcanic and sedimentary successions of the Volcano-Sedimentary Complex deposited in a transtensional basin (Schermerhorn 1971; Rosa et al. 2008). The VolcanoSedimentary Complex is in turn overlain by a late Vise´an to the Serpukhovian turbiditic flysch group (Schermerhorn 1971; Oliveira 1990; Fig. 1b).

# Pulo do Lobo Zone

The Pulo do Lobo Zone is classically interpreted as an accretionary prism formed during the closure of the Rheic Ocean (e.g. Eden 1991) and is composed of four polydeformed fault-bounded lithotectonic units: (1) the quartz–mica schists and local quartzite me´lange of the Pulo do Lobo formation; (2) a sequence of quartzwackes and phyllites of the Ribeira de Limas formation; (3) hectometre- to metre-scale internally deformed olistostromal quartzites in a polydeformed phyllite–quartzite matrix of the Ala´jar me´lange (Eden 1991); (4) tectonically emplaced mafic blocks in a volcaniclastic matrix (Peramora Me´lange) (Eden 1991). Together these polydeformed units are unconformably overlain by the relatively simply deformed (Giese et al. 1999) greywackes and shales of the Santa Iria Flysch, interpreted to have been deposited during terminal collision between Gondwana and Laurussia (e.g. Braid et al. 2010). Locally, these flysch deposits are crosscut by the c. 330 Ma Gil Ma´rquez pluton, which is part of the voluminous c. 350–300 Ma Sierra Norte Batholith (de la Rosa 1992). The protolith ages of the Pulo do Lobo Zone are constrained by Givetian–Frasnian palynomorphs (Ribeira de Limas formation) and late Devonian–early Carboniferous spores and acritarchs in the flysch deposits (Santa Iria Flysch) (Oliveira et al. 1986; Giese et al. 1988; Lake et al. 1988).

To the north of the Pulo do Lobo Zone, a sequence of dismembered mafic rocks, known as the Beja Acebuches Ophiolite (c. 330–345 Ma) (U–Pb sensitive high-resolution ion microprobe (SHRIMP); Azor et al. 2008), delineates the boundary between the Pulo do Lobo Zone and the Ossa–Morena Zone. The genesis of the Beja Acebuches Ophiolite remains controversial and it is thought to represent either obducted primary Rheic oceanic lithosphere (e.g. Castro et al. 1996) or mafic rocks formed during a transtensional event following the main continent–continent collision (c. 345–390 Ma) (Quesada et al. 1994; Azor et al. 2008; Braid et al. 2010).

# Tectonic evolution

In the late Palaeozoic, regional late Devonian to early Carboniferous south–southeasterly propagating (e.g. Quesada 1998) deformation in the South Portuguese Zone occurred as a result of northward-directed oblique (sinistral) subduction of the Rheic Ocean lithosphere beneath the Ossa–Morena Zone (Gondwana) (Crespo-Blanc & Orozco 1988; Quesada 1998). Subsequently, this subduction would have led to the eventual collision of the continental margin of the South Portuguese Zone (which may have been part of Avalonia or Meguma; e.g. Leistel et al. 1998; de la Rosa et al. 2001), with the Ossa–Morena Zone. In this scenario, oblique sinistral convergence resulted in the development of an accretionary prism (Pulo do Lobo Zone) and is evidenced by widespread c. 355–300 Ma calc-alkaline andesitic magmatic arc in the Ossa–Morena Zone (Ribeiro et al. 1990; Jesus et al. 2007).

The Pulo do Lobo Zone also preserves evidence of this pervasive late Devonian regional sinistral shear, compartmentalized within the Pulo do Lobo formation, the Ribeira de Limas formation and the Ala´jar Me´lange (Braid et al. 2010). Furthermore, the Beja Acebuches Ophiolite is deformed along a sinistral orogen-scale shear zone localized along the boundary with the Pulo do Lobo Zone (South Iberian Shear Zone; Crespo-Blanc & Orozco 1988; Fig. 1b).

Sample selection and methods

To investigate the development of this putative suture zone, six samples were collected for detrital zircons from Devonian to early Carboniferous units of the Pulo do Lobo Zone and South Portuguese Zone (Fig. 1b). We analysed one sample from the late Devonian passive margin quartzites (Phyllite Quartzite Group) from the South Portuguese Zone, to test the provenance of the South Portuguese Zone and its relationship to the Pulo do Lobo Zone; and two samples of phacoid quartzites and one sample of matrix from the me´lange deposits (Ala´jar Me´lange) and one sample of quartzwacke (Ribeira de Limas formation) from the Pulo do Lobo Zone (suture zone). The samples from the Pulo do Lobo Zone test the provenance of the Pulo do Lobo Zone and potential changes in sediment provenance in different lithotectonic units within the suture zone. We also analysed a sample of greywacke from the overlying late Devonian early Carboniferous flysch (Santa Iria Flysch) from the Pulo do Lobo Zone to investigate the potential changes in sediment provenance with proposed changes in tectonic environment.

Approximately 65 zircon grains from each sample were mounted, polished, imaged by electron back-scatter, and analysed for their U and Pb isotopic composition (one analysis per zircon grain) by LA-ICPMS using an Thermo Element 2 high-resolution system coupled to a New Wave Research 213 nm Nd–YAG laser. Detailed description of analytical instrumentation, analytical protocol and methods, data reduction and age calculation at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at the University of British Columbia have been described by Mortensen et al. (1995, 2007). All zircons were analysed using line scans with a laser spot diameter of 20 m. Data were reduced using the program GEMOC Glitter and plots generated using Isoplot/Ex (Ludwig 1999). Age uncertainties are reported at 2 and either the 207Pb/206Pb or the 206Pb/238U age is reported depending on which value gives the lower uncertainty. Of the six samples (c. 65 analyses per sample) only eight analyses revealed .10% discordance and were discarded. Probability distribution plots for all remaining concordant grains are shown in Figure 2.

Results

# South Portuguese Zone

A sample of quartzite (JB-17) was selected from the late Devonian continental shelf deposits (Phyllite Quartzite Group), which are considered the oldest exposed unit in the South Portuguese Zone proper. Of the 60 concordant analyses, only four grains (c. 7%) are Mesoproterozoic. The bulk of the sample (c. 52%) is dominated by Neoproterozoic (c. 0.5–0.7 Ga) zircons, with a strong peak at c. 590 Ma. The remainder of the detritus (c. 35%) is dominated by (c. 1.8–2.3 Ga) Palaeoproterozoic zircons, with only four grains (,7%) yielding Archaean ages (Fig. 2).

# Pulo do Lobo Zone

Both the phacoid quartzites (RSA-01, JAB-43) and quartzite matrix (RSA-02) from the Ala´jar me´lange in the suture zone have similar detrital zircon age distributions, but display a very different distribution from the JB-17 sample from the South Portuguese Zone. For each of the three samples, the largest

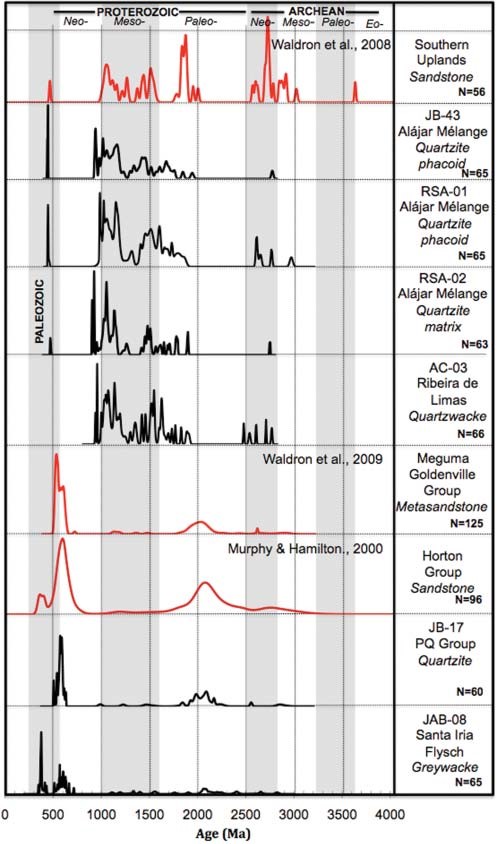


Fig. 2. U–Pb detrital zircon relative probability distribution plots for samples from the Pulo do Lobo Zone (suture) and the South Portuguese Zone (Laurussia?) from this study compared with samples (highlighted in red) from Early Silurian Kirkcolm Formation of the Southern Uplands Terrane of the British Caledonides (after Waldron et al. 2008), the Cambro-

Ordovician Meguma Terrane from the Northern Appalachians (after

Waldron et al. 2009) and the Devono-Carboniferous Horton Group from the St. Mary’s Basin of the Northern Appalachians (after Murphy & Hamilton 2000) (in red). Plots were generated by ISOPLOT (Ludwig 1999).

population is Mesoproterozoic (c. 1.0–1.5 Ga) comprising c. 55–70% of zircons analysed, a significant population (15–25%) is Palaeoproterozoic (c. 1.6–1.9 Ga) but younger on average than the Palaeoproterozoic population in the JB-17 sample from the South Portuguese Zone, and small populations (,10%) of Archaean (c. 2.5–3.0 Ga) and c. 440 Ma early Silurian zircons (,5%) occur (Fig. 2). A concordant grain (JB-43) at 438.7 4.38 Ma provides a maximum depositional age for the phacoid protolith. SEM backscatter images of these c. 440 Ma zircons reveal a zoned, euhedral, multifaceted zircon morphology, whereas older populations are generally well rounded.

The quartzwacke (Ribeira de Limas formation) sample from the Pulo do Lobo Zone (AC-03) lacks c. 440 Ma zircons but otherwise displays a similar detrital zircon age distribution (Fig. 2). The dominant population (c. 55%) is Mesoproterozoic (c. 1.0–1.5 Ga) in age. A second large population (c. 35%) is late Palaeoproterozoic (c. 1.6–1.9 Ga), and one zircon is early Palaeoproterozoic (2447.6 10.2 Ma) in age. The remainder of the detrital zircons are Archaean (c. 10%) in age. The youngest concordant zircon in the sample is 947.6 4.3 Ma.

# Flysch

A sample of greywacke (JAB-08) from the flysch (Santa Iria Flysch), which unconformably overlies the me´lange phacoids and matrix (Ala´jar Me´lange) and quartzwacke (Ribeira de Limas formation) in the Pulo do Lobo Zone, displays the widest range of detrital zircon ages and contains the most Devono-Carboniferous detritus (c. 32%) of all samples, with a strong peak at c. 347 Ma. The sample also displays a variety of Proterozoic populations (c. 30% Neoproterozoic, c. 12% Mesoproterozoic and 21% Palaeoproterozoic) with only minor (,5%) Archaean detritus (Fig. 2). An elongate, multifaceted and zoned concordant grain (Fig. 2) at 347.2 5.5 Ma provides a maximum depositional age.

Tectonic significance

# Origins of the Pulo do Lobo Zone and South Portuguese Zone

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| Fig. 3. Detrital zircon ages from samples from the Ala´jar Me´lange phacoids (RSA-01, JB-43), matrix (RSA-02) and Ribeira de Limas formation quartzwacke (AC-03) and Santa Iria Flysch (JAB-08) of the suture zone and quartzite (JB-17) from the Phyllite Quartzite Group of the South Portuguese Zone. These data are compared with detrital zircon data from the Early Silurian Kirkcolm Formation of the Southern Uplands Terrane of the British  Caledonides (Waldron et al. 2008), Meguma Terrane from the Northern Appalachians (after Waldron et al. 2009) and the Devono-Carboniferous Horton Group from the St. Mary’s Basin of the Northern Appalachians (Murphy & Hamilton 2000). Also shown are tectonothermal events in eastern Laurentia, Baltica, the Amazon craton and the West Africa craton (after Nance et al. 2009). Light red bands denote gaps in zircon populations. |

A comparison between U–Pb detrital zircon ages in the samples and the ages of detrital zircon populations and tectonothermal events in potential source areas are shown in Figure 3. The dominant Neoproterozoic (c. 0.5–0.7 Ga) and Palaeoproterozoic (c. 2.0–2.5 Ga) zircon populations in the continental clastic rocks (Phyllite Quartzite Group) of the South Portuguese Zone are typical of derivation from either West Africa (e.g. Rocci et al. 1991), or the peri-Gondwanan Meguma terrane, which is the only known location in Laurussia with such detrital zircon populations (Krogh & Keppie 1990; Murphy et al. 2004; Waldron et al. 2009; Fig. 3). However, the presence of minor Mesoproterozoic zircons in the Phyllite Quartzite Group sample is not typical of derivation from West Africa but these are present in periGondwanan Avalonia and Meguma (Keppie et al. 1998). In contrast, the dominant Mesoproterozoic (c. 1.0–1.5 Ga) and late Palaeoproterozoic populations (c. 1.6–1.9 Ga) in the phacoid quartzites and matrix (Ala´jar me´lange) and from the quartzwacke (Ribeira de Limas formation) in the Pulo do Lobo Zone are typical of both Laurentia and Baltica (Laurussia) (e.g. Cawood et al. 2007). The Pulo do Lobo Zone samples also lack Neoproterozoic and early Palaeoproterozoic zircon populations, which are typically abundant in Neoproterozoic to Devonian units derived from Gondwana (e.g. Ferna´ndez-Sua´rez et al. 2002a,b; Mart´ınezCatala´n et al. 2004; Gutie´rrez-Alonso et al. 2008; Lo´pezGuijarro et al. 2007) and from peri-Gondwanan terranes (i.e. Meguma, Avalonia; e.g. Murphy & Hamilton 2000; Murphy et al. 2004; Fyffe et al. 2009) but typically absent in clastic rocks derived from both Laurentia and Baltica (Fig. 3). Consequently, the age distributions of these samples suggest that the detritus in the Pulo do Lobo Zone was not derived from Gondwana (Ossa– Morena Zone), nor from the sources of the late Devonian clastic rocks (Phyllite Quartzite Group) of the South Portuguese Zone or peri-Gondwanan terranes that flanked the margin of Laurentia and Baltica in the Devono-Carboniferous.

Taken together these interpretations suggest that the quartzite phacoids and matrix (Ala´jar me´lange) and metasediments (Ribeira de Limas formation) of the Pulo do Lobo Zone were derived from either Baltica or Laurentia. The presence of euhedral, multifaceted c. 440 Ma zircons in the me´lange phacoids (RSA-01 and JB-43) suggests a local early Silurian volcanic source. Volcanism of this age is rare in Gondwana but common along eastern Laurentia (e.g. Midland valley terrane; Grahame et al. 2008). As this volcanism is generally associated with the closure of the Iapetus Ocean, the presence of these euhedral c. 440 Ma zircons is indicative of a source proximal to the Iapetan suture zone located between eastern Laurentia and peri-Gondwanan terranes (Fig. 3). Thus the Pulo do Lobo Zone sediments were not only derived from Laurentia and/or Baltica but also probably derived from early Silurian rocks associated with the closure of the Iapetus, along the eastern margin of

Laurentia.

An example of one such potential source is the early Silurian Southern Uplands terrane of the British Caledonides (Fig. 1a), which borders the Midland Valley terrane to the south. The Southern Uplands terrane is interpreted as a quartzite-dominated accretionary prism (McKerrow et al. 1977) that developed along the eastern margin of Laurentia during the closure of the Iapetus Ocean. A comparison of the Pulo do Lobo Zone detrital zircon data with the detrital zircon ages obtained from quartzite units in the Southern Uplands terrane (Waldron et al. 2008) reveals striking similarities (Figs 2 and 3). Most notably, similar to the detritus in the Pulo do Lobo Zone, detritus from the Southern Uplands terrane contains abundant Mesoproterozoic and late Palaeoproterozoic zircons as well as c. 440 Ma Palaeozoic zircons. Furthermore, the Southern Uplands terrane also lacks early Palaeoproterozoic and significant Neoproterozoic zircons. As the Southern Uplands terrane has potential lateral equivalents in Newfoundland (Waldron et al. 2008) this connection refers not only to the Southern Uplands terrane sensu stricto but also coeval units developed along the Laurentian margin during similar processes, which have been identified in Scotland, Ireland and Atlantic Canada (Waldron et al. 2008).

To a first order, the data suggest that during at least the early to middle Devonian the South Portuguese Zone was outboard of the Gondwanan margin (Ossa–Morena Zone). This interpretation is consistent with late Palaeozoic calc-alkaline andesitic arc magmatism present in the Ossa–Morena Zone (Jesus et al. 2007), which suggests subduction of oceanic lithosphere beneath the Ossa–Morena Zone margin. Therefore the South Portuguese Zone basement is either a rifted Silurian West African ribbon continent that derived late Devonian passive margin clastic rocks from itself or peri-Gondwanan Meguma basement with Phyllite Quartzite Group clastic rocks sourced from the Meguma Group, which is dominated by c. 0.6–2.1 Ga detritus (Krogh & Keppie 1990; Waldron et al. 2009). However, the Phyllite Quartzite Group (JB-17) contains a paucity of Mesoproterozoic zircons (Fig. 3), the lack of which is generally considered a fingerprint of West African provenance (e.g. Linnemann & Romer 2002). In addition, in view of the fact that (1) palaeogeographical reconstructions propose that the Meguma terrane was immediately outboard of the southern Iberia margin during the early Devonian (e.g. Mart´ınez-Catala´n et al. 1997; One´zime et al. 2003; Simancas et al. 2003) and that (2) West Africa lacks Silurian– early Devonian rift to passive margin deposits that would reflect a separation of the South Portuguese Zone along the periphery of West Africa, we support the former scenario, in which the South Portuguese Zone basement is part of the peri-Gondwanan Meguma terrane.

# Timing of Ossa–Morena Zone and South Portuguese Zone collision

The detrital zircon signature of the flysch (Santa Iria Flysch) in the Pulo do Lobo Zone displays a broad range of Neoproterozoic to Palaeoproterozoic zircons consistent with derivation from sources located in Gondwana, peri-Gondwanan terranes and Laurussia (Fig. 3). These data imply that by the Vise´an, detritus was being shed to the Pulo do Lobo Zone from itself and from both Gondwana (Ossa–Morena Zone) and the South Portuguese Zone (Meguma?). Therefore, juxtaposition of the South Portuguese Zone and Ossa–Morena Zone occurred between c. 347.2 Ma and c. 330 Ma as constrained by the maximum age for deposition of the Santa Iria Flysch and the age of the crosscutting Gil Ma´rquez Pluton. These data suggest that if the ophiolites (Beja Acebuches Ophiolite) formed during c. 330– 345 Ma (Azor et al. 2008) then they are probably related to a transtensional bend along the sinistral South Iberian Shear Zone. In this case, later transpressional deformation recorded along the South Iberian Shear Zone (e.g. Crespo-Blanc & Orozco 1988) was probably a result of continued transpression during continent–continent collision, and was isolated from the simply deformed Vise´an Santa Iria Flysch (Braid et al. 2010). However, our data do suggest that, despite the possibility that the Beja Acebuches Ophiolite may not be primary Rheic oceanic lithosphere as was already suggested by Quesada et al. (1994), the South Portuguese Zone did not contribute detritus to the suture zone until the Vise´an, and therefore support an exotic South Portuguese Zone palaeogeographical history with respect to Gondwana (Ossa–Morena Zone).

# Synthesis and evolutionary model

Taken together, the detrital zircon data from the Pulo do Lobo Zone and the South Portuguese Zone indicate that (1) the polydeformed Ala´jar me´lange and metasediments of the Pulo do Lobo Zone can all be assigned to the same tectonic environment (similar source), (2) the Pulo do Lobo Zone polydeformed sediments were not derived from the Ossa–Morena Zone or from the South Portuguese Zone during Devonian subduction of an oceanic basin beneath the Ossa–Morena Zone, (3) a source for the Pulo do Lobo Zone polydeformed deposits similar to the Southern Uplands Terrane of the British Caledonides is required, (4) the South Portuguese Zone is probably exotic with respect to both the Pulo do Lobo Zone and the Ossa–Morena Zone and contains late Devonian continental clastic rocks (Phyllite Quartzite Group) similar to the Devonian detritus from the Meguma terrane of the Northern Appalachians and (5) the South Portuguese Zone accreted to the Pulo do Lobo Zone and the Ossa– Morena Zone by c. 347 Ma, the age of the youngest concordant detrital zircon in the Pulo do Lobo Zone flysch (Santa Iria Flysch), which contains mixed zircon populations derived from all three crustal fragments .

Interpretation of a source equivalent to the Southern Uplands terrane for the Pulo do Lobo Zone requires either a substantial across-strike fluvial transport during the Devonian from a source NW of the peri-Gondwanan terranes (Avalonia, Meguma) or a tectonic transport of a crustal fragment along strike of the Southern Uplands to a location between the South Portuguese Zone and the Ossa–Morena Zone. In our view, the latter scenario is favoured by (1) presence of c. 440 Ma grains with a euhedral morphology, consistent with a short-lived sedimentary history, in both the quartzite phacoids and quartzite matrix, (2) the absence of peri-Gondwanan detritus in the Pulo do Lobo Zone samples that would be expected in a fluvial system extending from the Laurentian margin to a Devonian basin outboard of Gondwana and (3) our interpretation that both the polydeformed olistostromal phacoid quartzites (samples RSA-01 and JB-43) of the Ala´jar me´lange as well as the quartzite matrix (sample RSA-02) were derived from the same source. These factors favour a proximal source for the Pulo do Lobo Zone deposits over a distal fluvial derivation of zircon grains. This interpretation requires that the quartzite phacoids and matrix (Ala´jar me´lange) and metasediments (Ribeira de Limas formation) were all derived locally and not the result of distal fluvial systems where the phacoids would be expected to yield different zircon populations from the matrix. Taken together, these data and interpretations suggest that the deposition of the Pulo do Lobo Zone units requires not only a source along the early Silurian Laurentian margin (Southern Uplands terrane?) but also the subsequent spatial juxtaposition of this source with the Ossa–Morena Zone, prior to c. 347 Ma (i.e. a relative displacement of many hundreds of kilometres).

A model that satisfies these requirements should also be consistent with late Palaeozoic continental reconstructions. Although most late Palaeozoic reconstructions agree on the general relative positions of Gondwana and Laurussia during the closure of the Rheic Ocean, the relative positions of Iberia and Gondwana are debated. There are essentially two versions, which may affect the details of models concerning Iberian late Palaeozoic geological evolution: either Iberia was part of autochthonous Gondwana throughout the Palaeozoic (e.g. McKerrow & Scotese 1990; Robardet 2002, 2003; Scotese 2003; Mart´ınez-Catala´n et al. 2004) or Iberia was part of the Armorican Composite Terrane, which separated from Gondwana during the Silurian and collided with Laurussia prior to its terminal collision with Gondwana (e.g. Van der Voo 1979, 1982; Stampfli & Borel 2002). The latter reconstruction is largely based on palaeomagnetic evidence and the interpretations of the age of magnetization of units in the Iberian autochthon remain controversial (e.g. Perroud et al. 1991). On the other hand, faunal, lithological and palaeoclimatic indicators are in general agreement and indicate that the southern European regions (e.g. Ossa–Morena Zone) remained connected with Gondwana throughout the late Palaeozoic (e.g. Robardet 2002, 2003). Furthermore, the Ossa–Morena Zone records an early Ordovician to late Palaeozoic passive margin (Robardet & Gutie´rrez Marco 2004), which lacks Silurian rift to drift deposits predicted by an early Palaeozoic separation of an Armorican Composite Terrane from Gondwana. Therefore in terms of understanding the enigmatic and contrasting Devono-Carboniferous evolution of the Pulo do Lobo Zone, South Portuguese Zone and Ossa–Morena Zone we adopt a reconstruction with a unified Iberia and Gondwana. Although this choice may affect the details of our model, it does not affect the basic processes involved.

Reconstructions that unify Gondwana and Iberia also indicate Iberia as a promontory of Gondwana, with a re-entrant between this promontory and North Africa (e.g. McKerrow & Scotese 1990; Scotese 2003; Woodcock et al. 2007). This promontory probably experienced post-orogenic oroclinal bending to form the Ibero-Armorican Arc (e.g. Weil et al. 2010); however, we adopt the view that the continental margin was probably nonlinear prior to the Variscan orogeny (e.g. Matte 1986, 1991; Woodcock et al. 2007).

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| Fig. 4. Tectonic model showing juxtaposition of the Iapetan suture and a Southern Uplands equivalent crustal block with the Ossa–Morena Zone assuming juxtaposition of the Ossa–Morena Zone with West Africa (e.g. Robardet 2003) and the Bay of Biscay closed (e.g. Ries 1978). SUT, Southern Uplands terrane. (a) Late Silurian closure of the Rheic Ocean; (b) early Devonian collision of the Iberian promontory with the British Caledonides; (c) late Devonian–early Carboniferous escape of a crustal fragment toward a Gondwana re-entrant with associated local extension and deposition of the Pulo do Lobo Zone; (d) Vise´an juxtaposition of the South Portuguese Zone, Pulo do Lobo Zone and Ossa–Morena Zone and deposition of the Santa Iria flysch. |

Using this general reconstruction, we propose that early Devonian oblique collision between an Iberian indenter and Laurussia and the existence of a small remnant ocean basin (reentrant) between southern Iberia, North Africa and the northern Appalachians resulted in tectonic escape of a crustal fragment correlative with the Southern Uplands of the British Caledonides across the remnant ocean. This escape was accommodated by development of a new subduction zone beneath the Ossa– Morena Zone (Fig. 4b). A collision originating at c. 390–400 Ma between a late Palaeozoic Iberian indenter and Britain and Ireland (Woodcock et al. 2007; Fig. 4b) is supported by (1) early Devonian Acadian shortening in central Britain, (2) coeval

dextral early Devonian deformation along the Bristol Fault zone in SE England, (3) opposing sinistral deformation in the Southern Uplands of Scotland (Phillips et al. 1995) and the South Iberian Shear Zone (Crespo-Blanc & Orozco 1988) and other major lineaments (Quesada 1991) in southern Iberia (Fig. 4), and (4) onset of deformation and flysch deposition in Iberia (Quesada et al. 1991; Gonza´lez Clavijo 1996).

In this model, northwesterly subduction beneath Laurussia in the Late Silurian was disrupted by collision with the Iberian promontory of Gondwana such that oblique subduction with a sinistral component commenced beneath the Ossa–Morena Zone. This subduction was accompanied by the generation of the sinistral South Iberian Shear Zone (Crespo-Blanc & Orozco 1988) and a tectonic free face (e.g. Mann 1997) along the reentrant between Iberia and North Africa (Fig. 4b and c). This situation is analogous to the generation of microplates and tectonic escape of crustal blocks away from a continental indenter in modern Mediterranean (e.g. Dhont et al. 2006) and Himalayan (e.g. Tapponnier & Molnar 1976; Kapp & Guynn

2004) collisional zones.

During the stages of tectonic escape, late Devonian passive margin deposits (Phyllite Quartzite Group), probably sourced from the Meguma terrane, were deposited on South Portuguese Zone basement, which was part of the escaping block. As these are passive margin deposits they are probably only indicative of a local passive margin setting in basins within the escaping block. Following deposition of these continental clastic rocks, late Devonian–early Carboniferous extension occurred within the South Portuguese Zone, typical of internal deformation in escaping blocks (e.g. Mann 1997; see also the model by Castroviejo et al. 2010, for the particular case of the South Portuguese Zone and how this transtensional event facilitated ascent and eruption of the bimodal volcanism in the Iberian Pyrite Belt). This model is consistent with (1) documented dextral movement in the Meguma terrane relative to Avalonia in the northern Appalachians (Keppie & Dallmeyer 1987), (2) the late Devonian–early Carboniferous transtension required for bimodal volcanism (c. 355–330 Ma) of the Iberian Pyrite Belt (e.g. Quesada 1998; Solomon & Quesada 2003; Castroviejo et al. 2010) in the South Portuguese Zone, and (3) extension-related voluminous magmatic episodes evident in the Meguma terrane in Maritime Canada (c. 380–300 Ma) and the South Portuguese Zone (Sierra Norte Batholith, c. 350–300 Ma). Although these connections are independent of the derivation of the Pulo do Lobo Zone they further support both a detrital zircon genetic linkage between the South Portuguese Zone and the Meguma terrane and a Devono-Carboniferous tectonic escape mechanism as the probable mode of transport for part of the Laurentian– Iapetan suture (Southern Uplands?) toward the Ossa–Morena Zone.

The eventual juxtaposition of rocks from the Southern Uplands equivalent terrane with a Rheic subduction zone beneath the Ossa–Morena Zone (Fig. 4c) led to cannibalization and deposition of metasediments (Pulo do Lobo Zone) from this terrane and spatial juxtaposition of the South Portuguese Zone, Pulo do Lobo Zone and Ossa–Morena Zone. In this case, the internal fabric evident in the cannibalized phacoid quartzites of the Pulo do Lobo Zone (Ala´jar me´lange) (Braid et al. 2010) potentially preserves a record of the closure of the Iapetus, whereas deformation in the quartzite matrix and the quartzwacke (Ribeira de Limas formation) records subduction of the Rheic-related ocean basin and terminal collision between the Ossa–Morena Zone and the South Portuguese Zone.

The data presented here suggest that both the Pulo do Lobo Zone and the South Portuguese Zone terranes should be regarded as exotic to the Gondwanan parautochthon (Ossa–Morena Zone), and that terminal collision between the Ossa–Morena Zone and South Portuguese Zone occurred between c. 347 and c. 330 Ma. The Pulo do Lobo Zone records the juxtaposition of an exotic crustal fragment with southern Iberia and occurred as a result of tectonic escape along orogen-scale shear zones (e.g. South Iberian Shear Zone, and probably others), which spanned the Iapetan suture.

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