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Special Issue Contribution: ANALYSIS OF SEDIMENT PROPERTIES AND PROVENANCE

The transition from Pangea amalgamation to fragmentation: Constraints from detrital zircon geochronology on West Iberia paleogeography and sediment sources

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ABSTRACT

Detrital zircon U-Pb geochronology data from late Carboniferous to Triassic clastic sedimentary rocks in SW Iberia were used to investigate the regional paleogeography during the transition from Pangea amalgamation to break-up. The major U-Pb zircon age peaks are middle Devonian to Carboniferous (~390–300 Ma), Cambrian-Ordovician (~530–440 Ma), Cryogenian-Ediacaran (~750–540 Ma), Stenian-Tonian (~1.2–0.9 Ga) and Paleoproterozoic (~2.3–1.8 Ga). Rapid exhumation of Variscan crystalline rocks at the contact between the South Portuguese zone and Ossa Morena Zone, explains the abundance of late Paleozoic ages in the upper Carboniferous-lower Permian continental successions. The U-Pb zircon data constrain the maximum depositional age of the Santa Susana Basin to c. 304 Ma and the Viar Basin to c. 297 Ma. The Triassic sequences, despite being c. 100 Ma younger than the Variscan tectonothermal events, contain low proportions of late Paleozoic zircon. The major peaks in all zircon spectra closely resemble those found in the adjacent basement rocks, indicating small source areas, mainly located near the rift shoulders. Longer travelled fluvial systems are postulated for the eastern portions of the Algarve Basin, which was closer to the westward advancing Tethys Ocean than the rift basins of West Iberia. Sequences that contain significant proportions of ~1.2–0.9 Ga zircon are probably recycled from post-collisional Carboniferous-Permian continental deposits that were more extensive than those found today.

1. Introduction

The time period between the Carboniferous and Triassic was a period of profound changes on Iberia that marked the transition from continental amalgamation to Pangea fragmentation. The closure of the Rheic Ocean and a series of orogenies were responsible for a mountain range hundreds of kilometres wide, which extended along much of the margins of northern Gondwana and southern Laurussia (e.g., Simancas et al., 2005; Martínez Catalán et al., 2007; Ribeiro et al., 2007). In Iberia, deformation associated with Pangea assembly was also responsible for the development of prominent orocline(s), which may have played an important role in the development of regional topographical relief following Pangea amalgamation, although the timing and mode of formation of these oroclines remains debated (see discussion in Weil et al., 2013; Pastor-Galán et al., 2015, 2016; Dias et al., 2016). At the time of Pangea fragmentation Iberia was close to both North Africa and North America (Fig. 1). Late Permian rifting led to the Iberian Basin on the eastern margin of the Iberian microplate (Arche and López-Gómez, 1996), while along western Iberia it just took place during the Triassic (e.g., Pinheiro et al., 1996; Leleu et al., 2016).

Detrital zircon geochronology has been extensively applied to the study of the provenance of Paleozoic and Precambrian sedimentary sequences on Iberia, and has helped constrain the potential contribution of these successions to Mesozoic and Cenozoic sedimentary sequences (e.g., Díez Fernández et al., 2010; Esteban et al., 2011; Pereira et al., 2012a, 2012b; Talavera et al., 2012; Pastor-Galán et al., 2013; Fernández-Suárez et al., 2014; Shaw et al., 2014; da Silva et al., 2015; Rodrigues et al., 2015). The detrital record of syn- to post-collisional basins has provided important information on the exhumation history and the sedimentary transport systems during orogenesis (Dinis et al., 2012; Pastor-Galán et al., 2013). This method has also been applied to the

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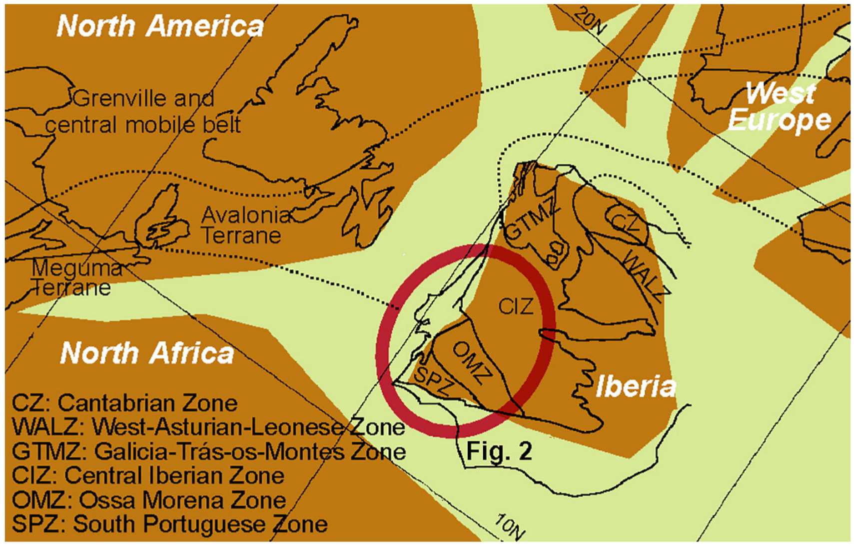

Fig. 1. Location of Iberia between today's major continental masses at the transition from Pangea amalgamation to break-up. Distribution of continental blocks based on Stampfli and Kozur (2006), Golonka (2007) and Sibuet et al. (2012).

central and western Iberian basins associated with Pangea break-up, which show clear provenance changes attributed to changes in the paleoflow and the scale of the sedimentary transport systems during both rifting development and the subsequent transition to a passive margin (Sánchez Martínez et al., 2012; Dinis et al., 2016; Pereira et al., 2016, 2017).

In this study we present new U-Pb detrital zircon age data from a set of sedimentary basins on Western and Southern Iberia that formed during the transition from the final stages of Pangea amalgamation (Pennsylvanian) to early fragmentation (Permian-Triassic) (Table 1). These new geochronology results are coupled with recently published data for the Triassic sequences of the Lusitanian (Pereira et al., 2016), Alentejo and Algarve basins (Pereira et al., 2017), and the Pennsylvanian of the Buçaco Basin (Dinis et al., 2012) of western and southern Iberia (Fig. 2). These datasets help constrain the regional paleogeography and the tectonic changes that occurred during this period on Iberia and the neighbouring northern Atlantic and western Mediterranean regions. Particular emphasis is given to (1) constraints on the timing of deposition of the studied continental successions, (2) regional differences in relief, denudation and sediment generation rates, (3) the relative contributions of sediments derived from Gondwana and Laurussia, and (4) the configuration and geometry of the main sediment dispersal pathways.

2. Geological setting

2.1. Tectonic framework

The late Paleozoic closure of the Rheic Ocean followed by the continental collision between Gondwana and Laurussia were responsible for the development of the Variscan-Alleghanian orogenic belt. Continental collision started at approximately 365 Ma (Dallmeyer et al., 1997; Ribeiro et al., 2007), causing significant crustal shortening and the emplacement of voluminous igneous rocks (Fernández-Suárez et al., 2000; Jesus et al., 2007; Martínez Catalán et al., 2007). The basement of the South Portuguese Zone (SPZ) of the Variscan Iberian Massif is likely associated with one of the continental blocks that docked with Laurentia (i.e., Meguma or Avalonia) prior to Pangea amalgamation (e.g., Oliveira and Quesada, 1998; de la Rosa et al., 2002; von Raumer et al., 2003; Ribeiro et al., 2007; Braid et al., 2011). Hence, the contact zone between the Ossa Morena Zone (OMZ), a peri-Gondwana geotectonic unit, and the SPZ may be underlying a suture recording the final stages of the closure of the Rheic Ocean (Quesada et al., 1994; Matte, 2001). Deformation continued throughout the Carboniferous, and comprised both compressive and extensional phases that varied spatially within the Variscan Belt (e.g., Arenas and Martínez Catalán, 2003; García-Navarro and Fernández, 2004; Martínez Catalán et al., 2009).

Table 1
Summary of the zircon age results obtained in each basin.

Sampled units			Summary of zircon age results						
Age	Basin (sampled Fm./unit)	Sample	N	Main groups of ages (Ga)					Youngest age (Ma)
				V-pV	C-Ord	PA-Cd	Grenv.	Ebur.	
Triassic	Lusitanian B. (Conraria Fm)	McVg	70 (65)		0.52–0.43 ($n = 24$)	0.60–0.55 ($n = 17$)			244 ± 3.3
		CO	108 (96)	0.36–0.29 ($n = 17$)		0.79–0.56 ($n = 48$)	1.07–0.86 ($n = 12$)		293 ± 4.9
		SO	100 (89)	2.17–1.87 ($n = 15$)		0.69–0.56 ($n = 26$)	1.09–0.88 ($n = 19$)		275 ± 4.4
	Alentejo B. (SC1)	STC3	101 (97)	0.35–0.33 ($n = 5$)		0.68–0.61 ($n = 46$)		2.30–1.95 ($n = 19$)	296 ± 7.6
	Algarve (AB1)	TL1	60 (58)	0.35–0.33 ($n = 4$)		0.64–0.51 ($n = 33$)			326 ± 7.3
		CM2	88 (86)	0.36–0.31 ($n = 13$)		0.65–0.48 ($n = 28$)	1.13–0.96 ($n = 11$)	1.78–1.55 ($n = 9$)	278 ± 8.3
Permian	Viar B. (RLB)	V152	94 (81)	0.35–0.34 ($n = 9$) 0.31–0.29 ($n = 6$)		0.67–0.54 ($n = 33$)		2.17–1.94 ($n = 17$)	293 ± 5.0
		V153	118 (110)	0.39–0.30 ($n = 53$)		0.66–0.55 ($n = 19$)		2.14–1.76 ($n = 19$)	296 ± 9.4
		V154	103 (93)	0.35–0.30 ($n = 10$)		0.69–0.54 ($n = 49$)		2.16–2.03 ($n = 13$)	302 ± 2.5
Pennsylvanian	St. Susana B. (Upper Unit)	StSz4	105 (89)	0.39–0.30 ($n = 36$)		0.70–0.54 ($n = 23$)		2.11–2.02 ($n = 7$) 1.92–1.79 ($n = 6$)	324 ± 4.0
		StSz2	88 (88)	0.39–0.32 ($n = 45$)		0.65–0.59 ($n = 13$)		2.00–1.92 ($n = 21$)	324 ± 3.2

V-pV: Variscan and post-Variscan. C-Ord: Cambrian-Ordovician. PA-Cd: Pan-African or Cadomian. Grenv: Grenvillian. Ebur: Eburnean. RLB: red layers deposits with basaltic sills. N: number of ages; number of concordant ages between brackets.

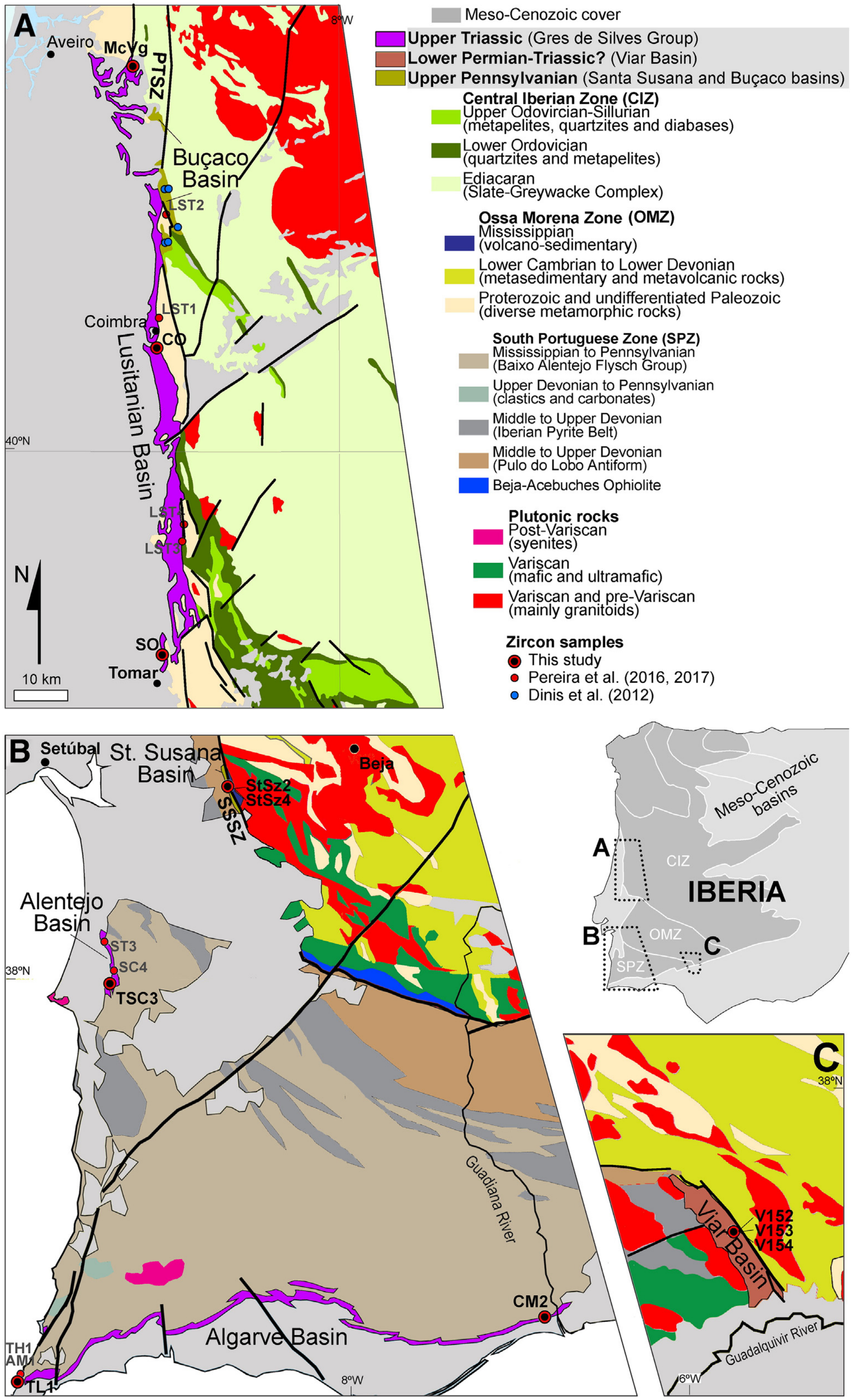

Fig. 2. Geological sketch maps of the SW border of the Iberian Massif with late Carboniferous to Triassic basins. (A) Buçaco Basin and Triassic of the Lusitanian Basin. (B) Santa Susana Basin and Triassic of the Alentejo and Algarve basins. (C) Viar Basin. Locations of the samples used in this study are also indicated. PTSZ: Porto-Tomar Shear Zone; SSSZ: Santa Susana Shear Zone.

Several authors have suggested that after the main phase of Variscan deformation, there was a period of delamination and crustal collapse with an associated increased heat flow responsible for renewed igneous activity in central and NW Iberia (c. 310–290 Ma), which was probably promoted by orocline bending (Gutiérrez-Alonso et al., 2008, 2011, 2012; Weil et al., 2010, 2013; Pastor-Galán et al., 2013). The nature of the regional stress field and tectonic regime during these late phases of Variscan deformation are not universally accepted, however recent models that have suggested a regional compression direction either orogen-parallel or slightly oblique have gained acceptance (Martínez Catalán, 2011; Weil et al., 2013; Edel et al., 2015).

It is widely regarded that the Porto-Tomar Shear Zone and the Santa Susana Shear Zone (Fig. 2) played an important role in accommodating the oblique convergence between Laurussia and Gondwana (Ribeiro et al., 1990; Dias and Ribeiro, 1993; Shelley and Bossière, 2000; Simancas et al., 2005; Martínez Catalán et al., 2007; Ribeiro et al., 2007). Other authors, however, consider that these shear zones represent large strike-slip faults that crosscut the original boundaries between the Variscan geotectonic zones (Martínez Catalán, 2011; Ballèvre et al., 2014; Martínez Catalán et al., 2014; Gutiérrez-Alonso et al., 2015). Regardless of their specific roles during Variscan and post-Variscan deformation, they have a dextral sense of movement and are associated with the formation of the Pennsylvanian Buçaco (along the Porto-Tomar Shear Zone; Flores et al., 2010) and Santa Susana (along the Santa Susana Shear Zone; Machado et al., 2012) pull-apart basins (Fig. 2). These basins are located on the boundaries between some of the major geotectonic units of the Iberian Variscan Massif (Wagner, 2004): the Santa Susana Basin lies between the OMZ and the SPZ, and the Buçaco Basin between the Central Iberian Zone (CIZ) and the OMZ (Fig. 2A and B). The early Permian NW-SE orientated Viar Basin is bounded on its NE flank by structures that also define the SPZ-OMZ boundary (Fig. 2C).

Subsequent rifting started during the Early Permian in eastern and central Iberia, and is recorded by the sedimentary basins of the Pyrenees-Cantabrian and Iberian ranges (Sopeña et al., 1988; Arche and López-Gómez, 1996; López-Gómez et al., 2002). Rifting probably developed later in West Iberia, where, the oldest sedimentary unit associated with break-up is the Triassic Silves Group of the Lusitanian, Alentejo and Algarve basins (Palain, 1976; Pinheiro et al., 1996; Soares et al., 2012; Leleu et al., 2016). Permian rift basins formed following the collapse of the thickened Variscan orogen, and were controlled by the reactivation of earlier Variscan structures (Simancas et al., 1983; García-Navarro and Sierra, 1998; Arche and López-Gómez, 1996). It has been proposed that basin formation was influenced by broadly E-W dextral shear zones that run north and south of Iberia (Arche and López-Gómez, 1996; Ribeiro et al., 2007; Soares et al., 2012).

In Western Iberia, Pangea fragmentation during the Triassic was associated with the formation of N-S trending basins (e.g. the Lusitanian and Alentejo basins along with others located offshore), whereas the Algarve Basin is usually considered to have resulted from left-lateral motion between Africa and Iberia (Ziegler, 1988; Terrinha et al., 2002; Leleu et al., 2016). The majority of the structures that controlled Triassic rifting were also inherited from the Variscan and pre-Variscan deformation (Pinheiro et al., 1996; Soares et al., 2012; Leleu et al., 2016). The Porto-Tomar Shear Zone, which underlies the eastern border of the Lusitanian Basin in the north (Fig. 2A) is thought to have acted as an antithetic Riedel conjugate shear to the dextral megashear zone between the southern Appalachians and the Urals (Arthaud and Matte, 1977), and may have exhibited a component of sinistral strike-slip movement during the early Mesozoic (Soares et al., 2012).

2.2. Stratigraphy of the studied successions

2.2.1. Pennsylvanian of the Santa Susana Basin

The Santa Susana Basin infill (c. 200 m thick) includes a basal unit composed of conglomerates and sandstones and an upper unit with sandstones, shales and coal seams (Fig. 3A). These strata were deposited in fluvial environments and, during later infilling stages, in spatially restricted lacustrine settings (Gonçalves and Carvalhosa, 1984; Andrade et al., 1995; Machado et al., 2012). It is assumed that the clastic succession is associated with lateral supply from the basin edges and south-directed sedimentary transport, although a substantial part of the basin fill can be linked to the Late Devonian to Mississippian Beja Massif of the OMZ (Oliveira et al., 1991; Ribeiro et al., 2010). Fossil plants collected in the Santa Susana Basin point to a Pennsylvanian age (latest Westphalian D or earliest Cantabrian; Sousa and Wagner, 1983; Wagner and Sousa, 1983). This age is confirmed by the palynomorph assemblages, which place the upper part of the basin infill within the Kasimovian (Machado et al., 2012).

2.2.2. Permian of the Viar Basin

The Viar Basin (Fig. 2C) is comprised of non-marine Lower Permian red beds that lie unconformably on SPZ rocks and were subsequently overthrusted by the OMZ (Sierra et al., 2009), being probably capped by clastic Triassic strata (Wagner and Mayoral, 2007). Although there is no uniform consensus on the basin structure and the volcano-sedimentary stratigraphy (see Wagner and Mayoral, 2007; Sierra et al., 2009), the succession appears folded in an asymmetrical syncline with an inverted NE limb. The sedimentary succession of the Viar Basin (up to c. 300 m thick) comprises red conglomerates, sandstones and mudstones intercalated with minor limestone, and mafic and felsic volcanic rocks (Fig. 3B). Sedimentation started with fluvial conglomerates and sandstones passed through a phase strongly influenced by volcanic activity that included the volcano-sedimentary Los Canchales Formation (Sierra et al., 2009) and culminated with a thick red bed succession deposited mostly in lacustrine environments (Wagner and Mayoral, 2007) or meandering systems with restricted swamp areas (Sierra et al., 2009). The location of the main volcanic vents is difficult to ascertain, possibly as a result of later compressive deformation (García-Navarro and Fernández, 2004; Sierra et al., 2009). Plant macrofossils indicate a Cisuralian age (Wagner and Mayoral, 2007).

2.2.3. Triassic of South-West Iberian margin

On the Portuguese mainland the Upper Triassic Silves Group (Palain, 1976) comprises red bed sequences at the base of the Mesozoic fill of the Lusitanian, Alentejo and Algarve basins (Fig. 2A, B). The Triassic successions consist mostly of red sandstones and conglomerates, which are sometimes very coarse-grained and rich in lithic fragments, interbedded with variegated mudstones, dolostones and marls that become more frequent towards the top of the succession (Fig. 3C–E). The Silves Group in the Lusitanian Basin defines a continuous belt of outcrops to the west of the Porto-Tomar Shear Zone (c. 117 km long; 350 m thick) that rests with an angular unconformity on basement rocks of the CIZ and OMZ (Fig. 2A). Sedimentological studies on the Silves Group point to alluvial fans and braided river systems interrupted only by a brief marine incursion near the top of the unit (Palain, 1970, 1976; Soares et al., 2012). The Silves Group is traditionally separated into three fining and thinning upwards megasequences (A, B and C) bounded by unconformities (Palain, 1970, 1976). This widely used lithostratigraphic framework was recently challenged by Soares et al. (2012), who argued for a redefinition of the Silves Group into four formations, which are in ascending order: i) the Conraria Formation, composed mostly of alluvial conglomerates and sandstones that pass upwards into salt marsh and floodplain mudstones; ii) the Penela Formation, dominated by coarse-grained alluvial deposits; iii) the Castelo Viegas Formation, with coarse- and fine-grained beds deposited in a littoral plain; and iv) Pereiros Formation, composed of sandstones, marls, mudstones and dolostone deposited in a coastal setting. The fossil assemblages in the Silves Group of the Lusitanian Basin suggest a Late Triassic age (Carnian; Adloff et al., 1974).

Both the Algarve and Alentejo basins (Figs. 2B and 3) unconformably overlie folded and faulted basement rocks of the SPZ. The Algarve Basin strikes E-W and crops out for approximately 136 km; the Alentejo Basin is oriented N-S and is presently limited to a belt approximately 18 km along strike (Fig. 2B). Sedimentation in these two basins also initiated with Triassic continental deposits of the Silves Group (up to c. 400 m thick in the Algarve Basin and 180 m thick in the Alentejo Basin), which typically comprises: i) a lower unit, termed AB1 in the Algarve Basin and SC1 in the Alentejo Basin, mostly composed of sandstones and conglomerates and deposited in alluvial fan to braided fluvial

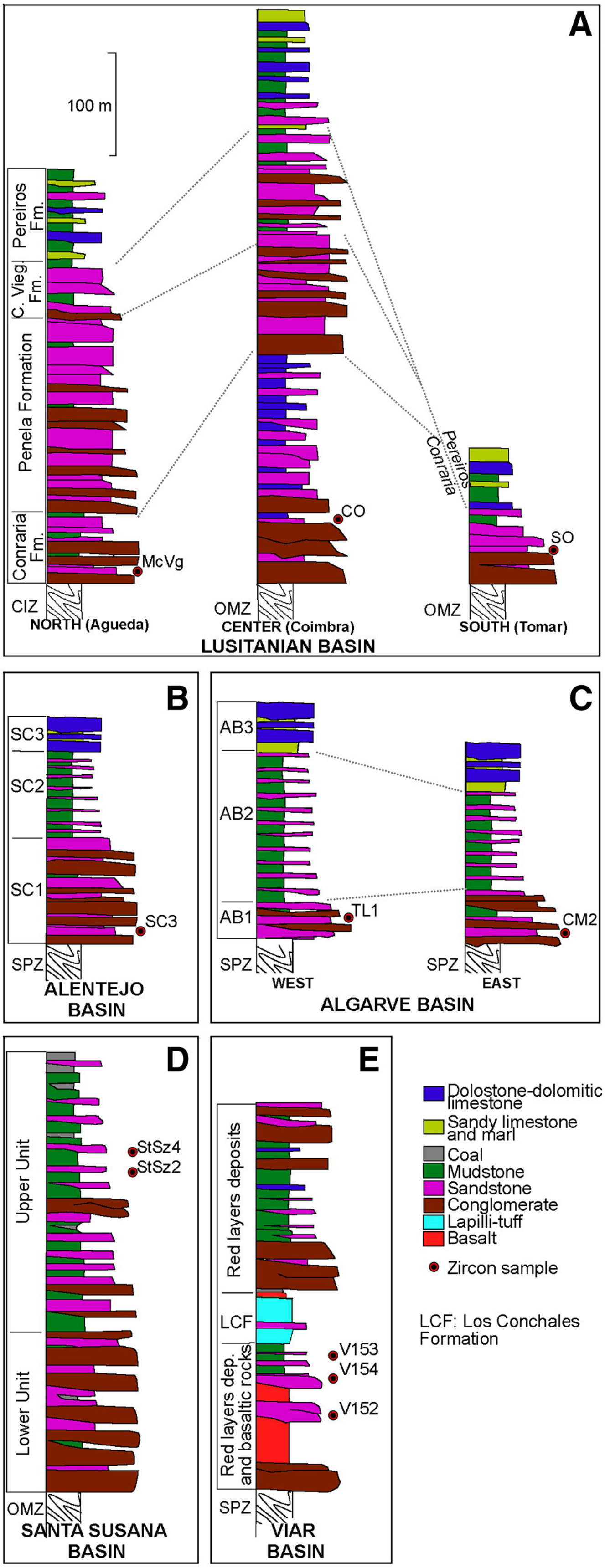

Fig. 3. Simplified stratigraphic sequences sampled in this research. (A) Triassic of the Lusitanian Basin based on Palain (1976) and Soares et al. (2012); (B) Triassic of Alentejo and (C) Algarve basins based on Palain (1976); (D) Pennsylvanian of Santa Susana Basin based on Andrade et al. (1995); (E) Permian of Viar Basin based on Sierra et al. (2009); LCF: Los Conchales Formation.

environments; ii) an upper unit, termed AB2 in the Algarve Basin and SC2 in the Alentejo Basin, consisting of variegated mudstones interbedded with siltstones and dolomites, associated with lower energy fluvial-lacustrine settings and likely influenced by marine incursions (Palain, 1976). A Late Triassic age has been proposed on the basis of faunal and floral associations found in unit AB2 (Palain, 1976; Manuppella, 1992).

3. Materials and methods

3.1. Sampled sedimentary rocks

Eleven samples from Pennsylvanian to Triassic continental basins of West and South Iberia were selected for this study (Fig. 3; Table 1). Two Pennsylvanian samples were collected from the upper part of the Santa Susana Basin. Three Permian samples from the Viar Basin were collected from the red layer deposits with basaltic sills. The Triassic samples came from the basal units of the Silves Group (Conraria Formation in the Lusitanian Basin, AB1 and SC1 in Algarve and Alentejo basins), and comprise three samples from the Lusitanian Basin, one sample from the Alentejo Basin and two samples from the Algarve Basin. Pb detrital zircon data in this research complement and are discussed together with previously published detrital zircon data from coeval units, namely those reported for the Upper Pennsylvanian of the Buçaco Basin (Dinis et al., 2012) and the Triassic of the Lusitanian Basin (Pereira et al., 2016) and the Alentejo and Algarve basins (Pereira et al., 2017). Sample selection was undertaken so as to give a regional perspective on the paleogeographic conditions during the transition from Pangea amalgamation to fragmentation, encompassing: 1) the late Carboniferous and early Permian episodes of deformation associated with N-S and WNW-ESE shear zones and 2) the subsequent Triassic rifting in West and South Iberia.

All samples were collected from moderately to poorly-sorted coarse-grained sandstones to conglomerates. Their petrographic composition was determined by the Gazzi-Dickinson method (Ingersoll et al., 1984). Santa Susana and Viar basins samples are characterized by a predominance of lithic fragments over quartz, with very minor amounts of feldspar (Fig. 4D). Detrital white mica flakes, likely sourced from medium-grade metamorphic rocks, are also common. Most lithic fragments are comprised of quartzite, metapelite or schist, with minor amounts of acid and basic porphyritic rocks. Quartz clasts are usually very angular to sub-angular, and polycrystalline quartz is abundant, particularly in the Santa Susana Basin. Triassic rocks contain higher amounts of quartz, usually sub-angular to sub-rounded, with subordinate lithic fragments (mostly quartzite and metapelites) and feldspar (Fig. 4D). Orthoclase, microcline and plagioclase were identified in the Triassic rocks, with K-feldspar prevalent. An opaque Fe-cement coats most clasts in both late Paleozoic and Triassic continental units, although secondary carbonate or silica cements are also common.

3.2. Analytical procedures

Zircon grains were separated at the Earth Sciences Department of University of Coimbra using conventional techniques. Samples were crushed down to 0.5 mm and the fraction finer than 0.045 mm was removed through wet sieving. Heavy liquids and a Frantz isodynamic magnetic separator were used to obtain the non-magnetic heavy mineral concentrate.

The zircon grains selected for dating were hand-picked and mounted in epoxy resin discs. The growth textures were previously examined with scanning electron microscopes equipped with secondary-electron and cathodoluminescence. U-Pb isotopic compositions determined by laser-ablation inductively coupled plasma mass spectrometry (LA-ICPMS) are provided in Supplementary Material 1. Most samples were analysed at the Department of Geology, Trinity College Dublin, using a Photon Machines Analyte Exite 193 nm ArF Excimer laser-ablation system coupled to a Thermo Scientific iCAP Qc. Samples McVg and StSz2 were analysed at the Geochronological Research Center of the University of São Paulo, using a Thermo Neptune multicollector ICPMS, coupled to an excimer ArF laser ablation system. Detailed analytical procedures are described in Supplementary File 1.

Analytical data are presented in Supplementary File 2. When the ratios between the $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ ages were within a 10% cut-off the results were considered concordant. Because $^{207}Pb/^{206}Pb$ ages are less reliable for younger zircons, the adopted age was calculated from the $^{206}Pb/^{238}U$ ratio for zircons younger than 1000 Ma, and from the $^{207}Pb/^{206}Pb$ ratio for older zircons. Isoplot 3.72 (Ludwig, 2003) and Density Plotter (Vermeesch, 2012) were used to create the concordia diagrams and the combined Kernel density estimates and histogram plots respectively. Only concordant data were included in the frequency diagrams. The Ogg et al. (2016) timescale was used in the accompanying data description.

4. Results

4.1. Carboniferous of the Santa Susana Basin

Samples StSz2 and StSz4 yield similar age spectra (Table 1 and Fig. 5). The zircon ages are mainly Devonian-Carboniferous in age (41–51%), with maxima frequency peaks of c. 342–330 Ma. The second most abundant populations are Paleoproterozoic (23–30%) and Ediacaran-Cryogenian (16–23%). Very minor Stenian-Tonian and Archean peaks are also present.

4.2. Permian of the Viar Basin

Two different age signatures were recognised in the samples from the Viar Basin (Table 1 and Fig. 5). Sample V153 yields mainly Devonian to earliest Permian zircons (48%). Cryogenan-Ediacaran (21%) and Paleoproterozoic (19%) zircons are also common. Samples V152 and V154 are dominated by Cryogenian-Ediacaran zircon (44–58%), yielding a maximum frequency peak at c. 640–585 Ma. The next most common age populations are Paleoproterozoic (17–29%) and Carboniferous-Permian (11–19%). Two distinct peaks of c. 350 Ma and 300 Ma are recognised in V152. Samples V152 and V154 also comprise a few Devonian, Stenian-Tonian and Archean grains.

4.3. Triassic of the Lusitanian Basin

The northern sample of the Lusitanian Basin (McVg) yielded the youngest age measured in this study (244 ± 3 Ma), which was determined on a small zircon grain (~40 μm) with oscillatory zoning. The majority of the concordant ages in the McVg sample are either Cryogenian-Ediacaran (41%), with a maximum peak at c. 570 Ma, or Cambrian-Ordovician (35%), with a maximum peak at c. 470 Ma (Fig. 6). Two secondary age populations are recognised in the Mesoproterozoic to early Neoproterozoic age and the Paleoproterozoic age. Triassic (244 Ma), Permian (298 Ma), Carboniferous (339 and 319 Ma), Devonian (385 and 379 Ma) and Silurian (four ages, but only one concordant result of 434 Ma) zircons also occur.

The detrital spectra obtained for sample CO is dominated by Cryogenian to Ediacaran zircons (50%), yielding a maximum peak at c. 605 Ma. Secondary age populations of Late Devonian to Early Permian (18%) and Stenian-Tonian (13%) are also present. A few grains yield Cambrian-Early Silurian, Paleoproterozoic and Archean ages.

The sample from the southern Lusitanian Basin yields a detrital zircon spectrum dominated by Stenian to Ediacaran ages (60%), with peak maxima at c. 615 Ma and c. 980 Ma. A few Early Cryogenian ages (six grains ranging from 829 to 729 Ma) occur between these two larger peaks. Sample SO also yields abundant

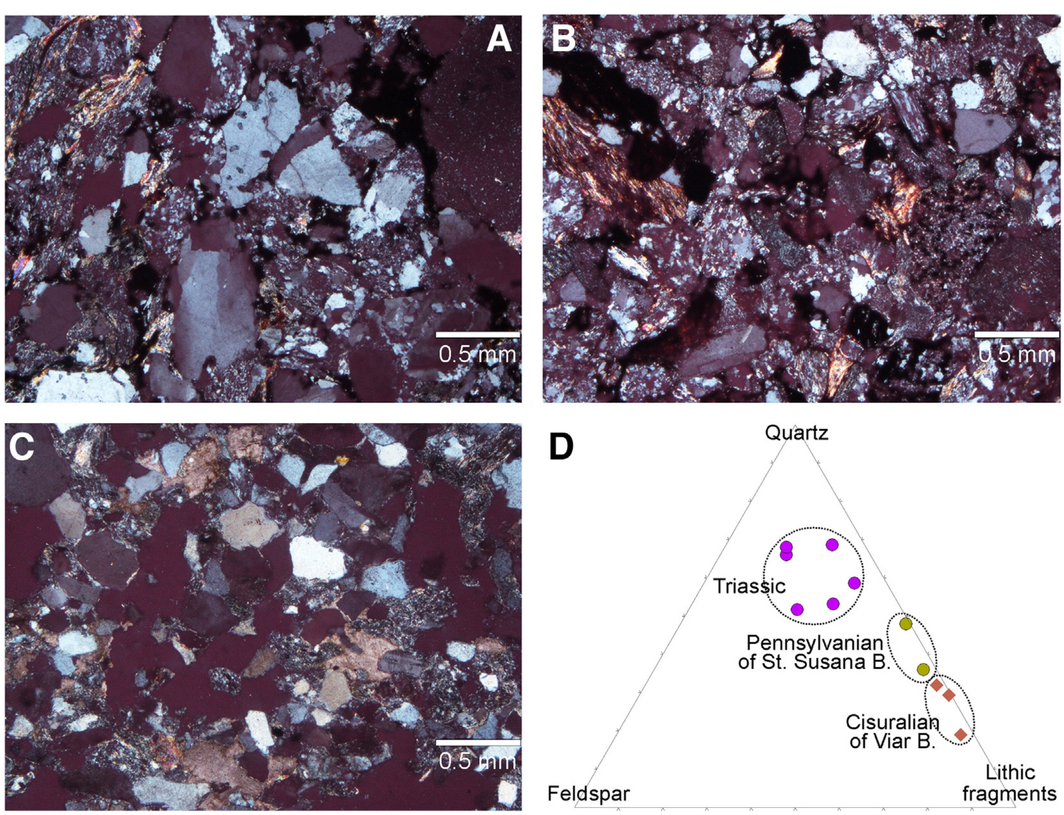

Fig. 4. Thin-section photos of sandstones sampled in the Santa Susana Basin (A), Viar Basin (B) and Lusitanian Basin (C), and clast composition of late Paleozoic-Triassic continental deposits (D).

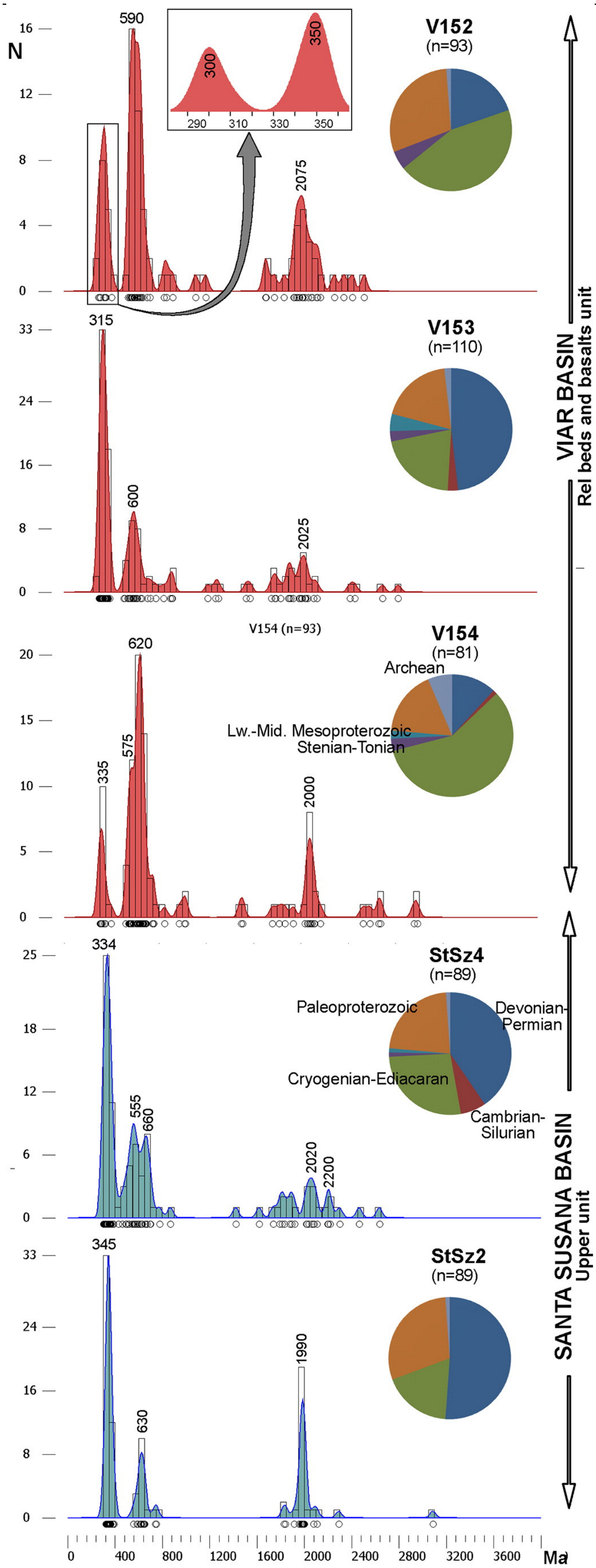

Fig. 5. Combined histograms and Kernel density plots of detrital zircon ages for the late Paleozoic Santa Susana and Viar basin. Bandwidth of 20 Ma and bins of 50 Ma.

Paleoproterozoic zircons (21%) and a few Carboniferous-Permian, Cambrian-Silurian and Archean ages.

4.4. Triassic of the Alentejo Basin

Only one sample (TSC3) from the Alentejo Basin was selected for geochronology analysis (Table 1 and Fig. 7). Cryogenian to Ediacaran grains predominate in this sample (56%; maximum frequency peak at c. 627 Ma). Subsidiary populations include Paleoproterozoic (24%) and Devonian-Permian (10%) peaks. The sample yields minor amounts of Stenian-Tonian zircon.

4.5. Triassic of the Algarve Basin

The western (TL1) and eastern (CM2) samples collected from the Algarve Basin exhibit different age signatures (Table 1; Fig. 7). Most zircon grains in sample TL1 are Cryogenian to Cambrian in age (66%, with a maximum peak at c. 600 Ma). This sample also yields a few Stenian-Tonian, Ordovician-Silurian and Carboniferous ages. Zircon grains older than 1.2 Ga are uncommon.

The sample from the eastern Algarve Basin (CM2) contains similar proportions of Cryogenian-Early Cambrian grains (25%; maximum peak at c. 570 Ma), and Devonian-Permian grains (21%; maximum peak at c. 331 Ma). Sample CM2 also yields a few zircon ages between these two clusters (14%, ranging from 532 to 410 Ma) and a discernible Stenian-Tonian population (14%). The wide time interval spanning from the Neoarchean to the middle Mesoproterozoic (2.6–1.3 Ga) represents 24% of the age spectrum.

5. Discussion

5.1. Main zircon forming events and sources

Combining all age data into one dataset allows the main zircon forming events to be distinguished based on the most prominent frequency peaks (Fig. 8). The youngest peak at c. 335 Ma corresponds with abundant collisional magmatism on Iberia, which started at c. 350 Ma and persisted for almost the entire Carboniferous (Dias et al., 1998; Fernández-Suárez et al., 2000; Jesus et al., 2007). Late Carboniferous to Early Permian zircon ages (c. 300–290 Ma) are also reported in the CIZ and are probably linked with the buckling of the Cantabrian Orocline (Gutiérrez-Alonso et al., 2004; Gutiérrez-Alonso et al., 2011; Pastor-Galán et al., 2013). These ages are present in the dataset, including in the basins along the contact OMZ-SPZ, where distinctive peaks can be identified (Fig. 5).

A Cambro-Ordovician population is clearly seen in some samples from the Lusitanian Basin (Fig. 9) and was also identified in the Pennsylvanian of the Buçaco Basin (Dinis et al., 2012). It may be related to crystalline rocks that presently crop out in several locations of western and central Iberia (Valverde-Vaquero and Dunning, 2000; Valverde-Vaquero et al., 2005; Bea et al., 2007; Castiñeiras et al., 2008; Chichorro et al., 2008; Solá et al., 2008; Antunes et al., 2009; Díez Montes et al., 2010; Liesa et al., 2011; Rubio Ordóñez et al., 2012). The main peak at c. 470 Ma approximately coincides with the end of the tectonic activity in the Ollo de Sapo Domain in the northern CIZ and Galicia Trás-os-Montes Zone (Montero et al., 2009; Talavera et al., 2013) and the phase of felsic volcanism reported in the Galicia-Trás-os-Montes Zone (Valverde-Vaquero et al., 2005). Abundant Cambro-Ordovician detrital zircons with approximately the same age range and peaks were found in one sample of the Ordovician Armorican quartzites (Shaw et al., 2014) and in Paleozoic meta-sedimentary rocks that lithologically resemble the Precambrian-Cambrian Schist-Greywacke Complex (Talavera et al., 2012). Older Cambrian zircon may be linked to the rift-related magmatism reported in the OMZ (Oliveira et al., 1991; Solá et al., 2008; Chichorro et al., 2008).

The Cryogenian to Ediacaran population (peaks at c. 625 and 580 Ma) corresponds with the Pan-African and Cadomian orogenies, which overlap temporally in northern Gondwana regions (Murphy and Nance, 1991; Nance and Murphy, 1994; Linnemann et al., 2008). The zircon ages that can be attributed to these orogenic events are almost ubiquitous in Ediacaran and Paleozoic metasedimentary successions of the Iberian Massif. Stenian-Tonian ages are very likely associated with the Grenvillian events (Fig. 9). Zircon of Grenvillian age is scarce in the basement rocks that crop out in the vicinity of the studied basins, namely in the OMZ (Linnemann et al., 2008; Fernández-Suárez et al., 2014), in the Schist-Greywacke Complex (Pereira et al., 2012a; Talavera et al., 2012; Fernández-Suárez et al., 2014) and in the Ordovician “Armorican Quarztites” (Pereira et al., 2012a; Shaw et al., 2014), but is common in several Paleozoic units from NW Iberia (Fernández-Suárez et al., 2002; Martínez Catalán et al., 2004; Pastor-Galán et al., 2013; Shaw et al., 2014). The abundant Paleoproterozoic zircon and the occasional Archean zircons are most likely inherited from older Paleozoic to Precambrian Iberian metasedimentary successions that yield peaks of similar ages (Talavera et al., 2012; Pastor-Galán et al., 2013; Shaw et al., 2014; Rodrigues et al., 2015; Pérez-Cáceres et al., 2017).

5.2. Constraints on the time of formation of the late-collision and early fragmentation basins

The detrital zircon data help to constrain the maximum depositional age of the Santa Susana and Viar continental basins (Fig. 10).

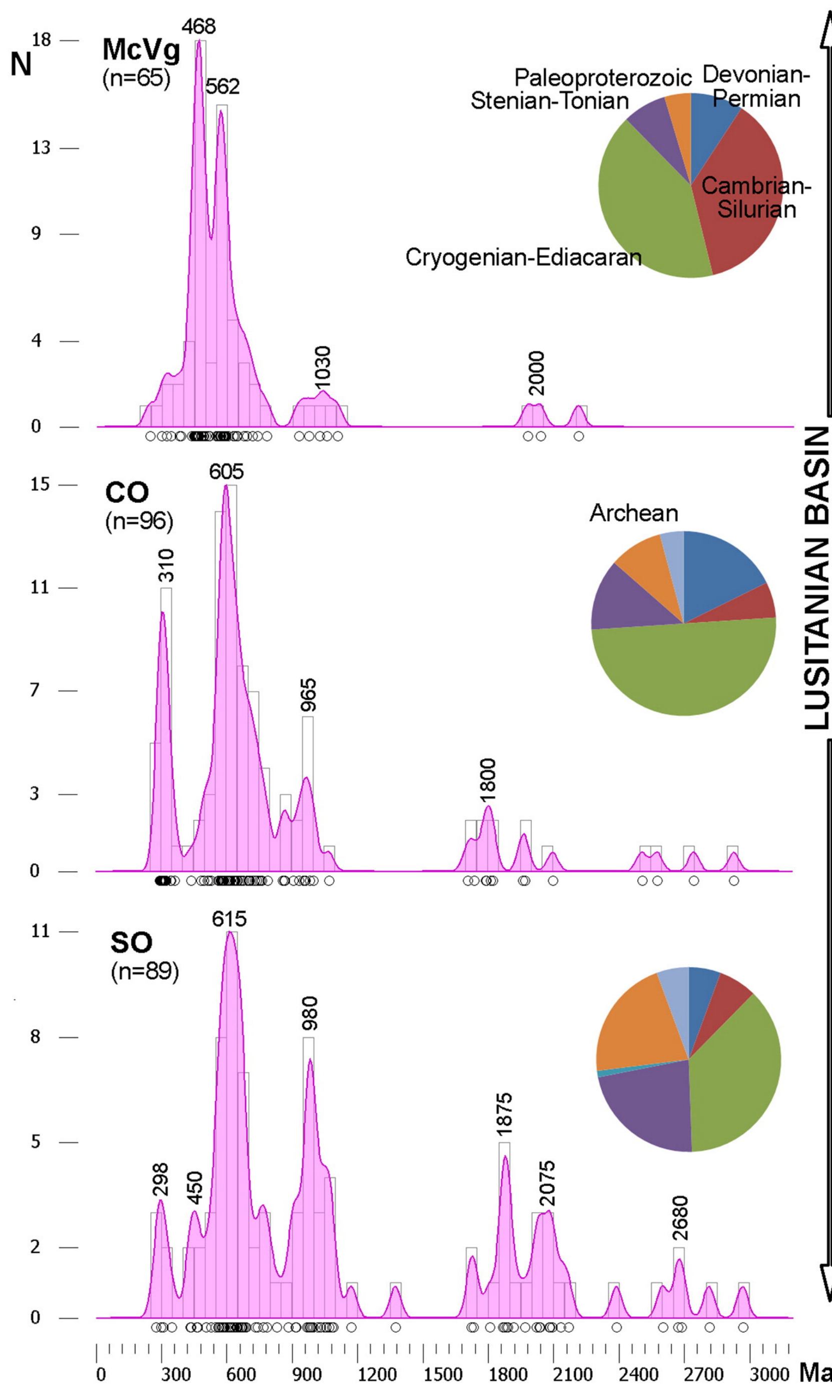

Fig. 6. Combined histograms and Kernel density plots of detrital zircon ages for the Triassic Silves Group of the Lusitanian Basin. Bandwidth of 20 Ma and bins of 50 Ma.

Fossil plant assemblages in the Santa Susana Basin (Sousa and Wagner, 1983; Wagner and Sousa, 1983) and the miospore assemblages (Machado et al., 2012) place most of the SSB infill within the Kasimovian stage, possibly extending down into the Moscovian (Machado et al., 2012; Lopes et al., 2014). The three youngest zircons measured in samples from the Santa Susana Basin (305–303 Ma in sample StSz4) yield a concordia age of 303.9 ± 2.2 Ma (Fig. 9), which precludes the possibility of the upper part of the succession being Moscovian in age. The Viar Basin infill is considered to be Lower Permian (mid-Autunian and lower Rotliegend) on the basis of floral assemblages (Wagner and Mayoral, 2007). The samples from the Viar Basin yielded three Permian zircon grains (c. 298–294 Ma) that yield a concordia age of 296.7 ± 3 Ma (Fig. 10), corresponding to the early Cisuralian (Asselian).

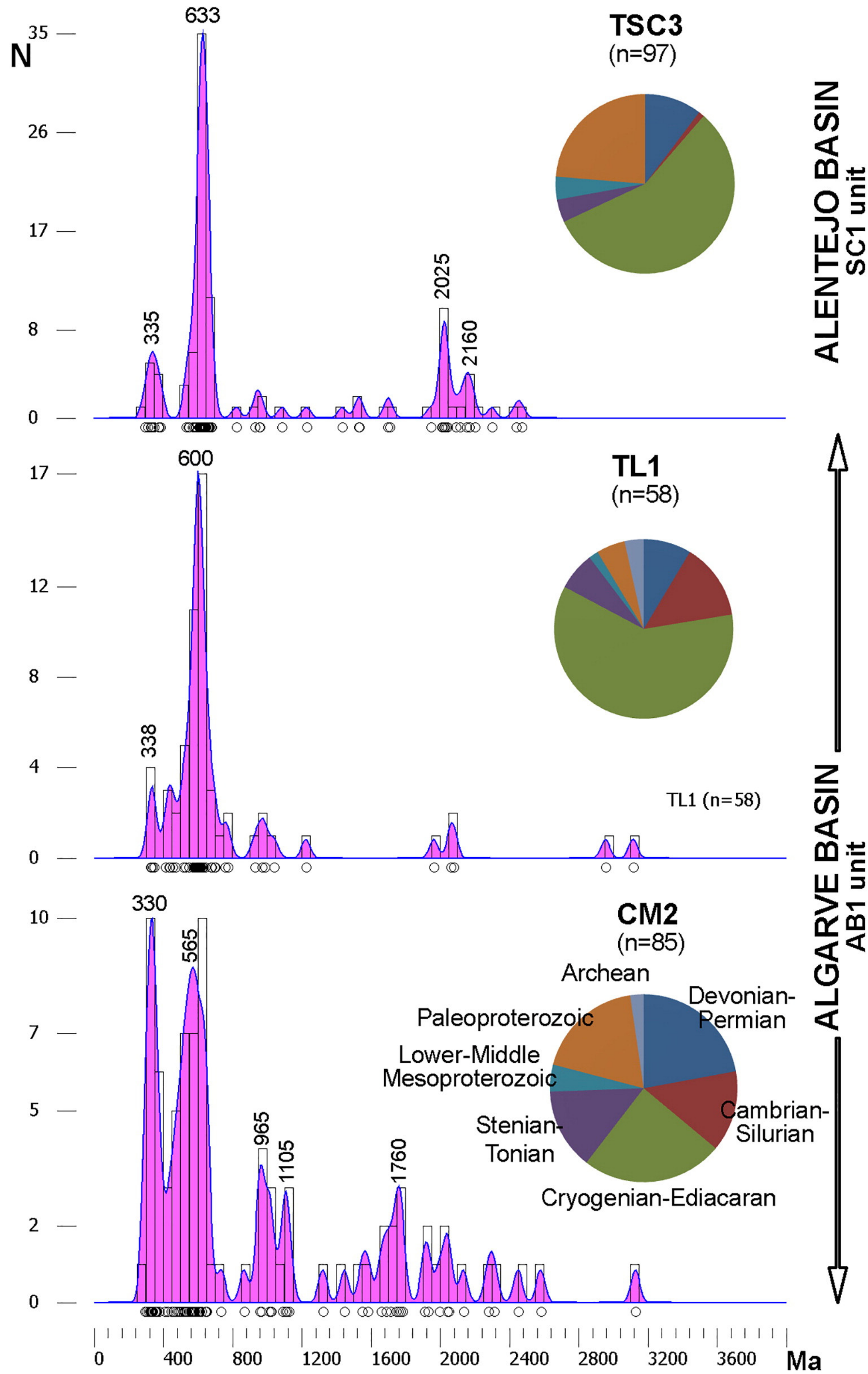

Fig. 7. Combined histograms and Kernel density plots of detrital zircon ages for the Triassic Silves Group of the Alentejo and Algarve basins. Bandwidth of 20 Ma and bins of 50 Ma.

Although sedimentary successions formed in extensional settings are less likely to include zircon grains of syn-depositional age compared to those formed in convergent and collisional settings (cf Cawood et al., 2012), the detrital age signatures of the Triassic strata can still shed some light on the timing of rifting in the West Iberian margin. The lower part of the Silves Group in the Lusitanian, Alentejo and Algarve basins is fossil-poor. However, floral assemblages in the upper part of Conraria Formation in the Lusitanian Basin assign this unit to the Carnian (Adloff et al., 1974), which is consistent with brachiopod fauna collected in the Algarve Basin (Palain, 1976). The studied set of samples provided a Triassic grain (244 ± 3 Ma) in the Lusitanian Basin, which is the youngest zircon found so far in the Silves Group. The youngest zircon ages analysed in the Alentejo Basin and the Algarve Basin are substantially older than the estimated depositional age for the base of the Silves Group. One grain dated at c. 278 Ma coincides with the older limit of a minor population assumed to predate Pangea rifting (Pereira et al., 2014), and two grains at c. 296–293 Ma are approximately contemporaneous with the youngest zircons measured in the Viar Basin.

5.3. Paleogeography of the source areas

5.3.1. Late Carboniferous-Permian (late amalgamation)

Extensive Carboniferous-Permian clastic deposits have been documented on the Laurussian continent, in particular on the Grenville, Avalonia and Meguma terranes (e.g., Lowe et al., 2011; Piper et al., 2012; Morton et al., 2015) and several remnants have been found on the NW Iberia margin (e.g., Capdevila and Mougenot, 1988). Previous authors have proposed that these continental deposits were much more extensive at the time of Pangea break-up than today (Corrales, 1971; Piper et al., 2012; Dinis et al., 2016). Scattered Upper Pennsylvanian (Gzhelian) outcrops are presently found in West Iberia in association with major faults and in the axial zones of Variscan synclines (Sousa and Wagner, 1983; Domingos et al., 1983; Wagner and Álvarez-Vázquez, 2010) and aligned with the Cantabrian Orocline in the Cantabrian and West Asturian-Leonese zones of North Iberia (Colmenero et al., 2008; Wagner and Álvarez-Vázquez, 2010; Pastor-Galán et al., 2011). It is probable that the Pennsylvanian outliers constitute the lower portions of originally thicker Carboniferous-Permian sequences that extend behind the limits of the so-called "Stephanian basins" recognised today (Fig. 11A).

Late Paleozoic zircon ages are predominant in most of the upper Carboniferous-lower Permian sedimentary rocks of South Iberia, reflecting exhumation of Variscan and post-Variscan crystalline rocks in their source areas. The presence of zircon grains with approximately the same crystallization age as their host sedimentary units indicates either fast exhumation of plutonic rocks, or the erosion of hypabyssal or extrusive volcanic rocks. Hypabyssal and pyroclastic calc-alkaline rocks associated with post-collisional, transtensional to extensional tectonics have been identified in several parts of central and southern Iberia (Ferreira and Macedo, 1977; Lago et al., 2004, 2005) and some of these magmatic units are coeval with the volcanoclastic deposits of the Viar Basin. The volcanic-related rocks of Viar show a wide compositional range including felsic material (Wagner and Mayoral, 2007; Sierra et al., 2009) which can account for part of the younger zircon population. Hypabyssal or extrusive volcanic rocks are probably also the source of the younger zircons found in the Santa Susana Basin. Indeed, dykes and sills cut the lower conglomeratic unit of the Santa Susana basin but also closely resemble one of the common clast types found in the succession (Machado et al., 2012). In contrast, Variscan ages in the Buçaco Basin are very rare, and the youngest zircon is approximately 25 Ma older than the depositional age (Dinis et al., 2012). The scarcity of Variscan zircon may indicate that the regional sedimentary transport systems were unable to deliver these grains due to proximal supply or insufficient denudation. In the vicinity of the Buçaco Basin, the Variscan tectonic shortening likely resulted in thickened crust with substantially less magmatic contribution than at the contact OMZ-SPZ.

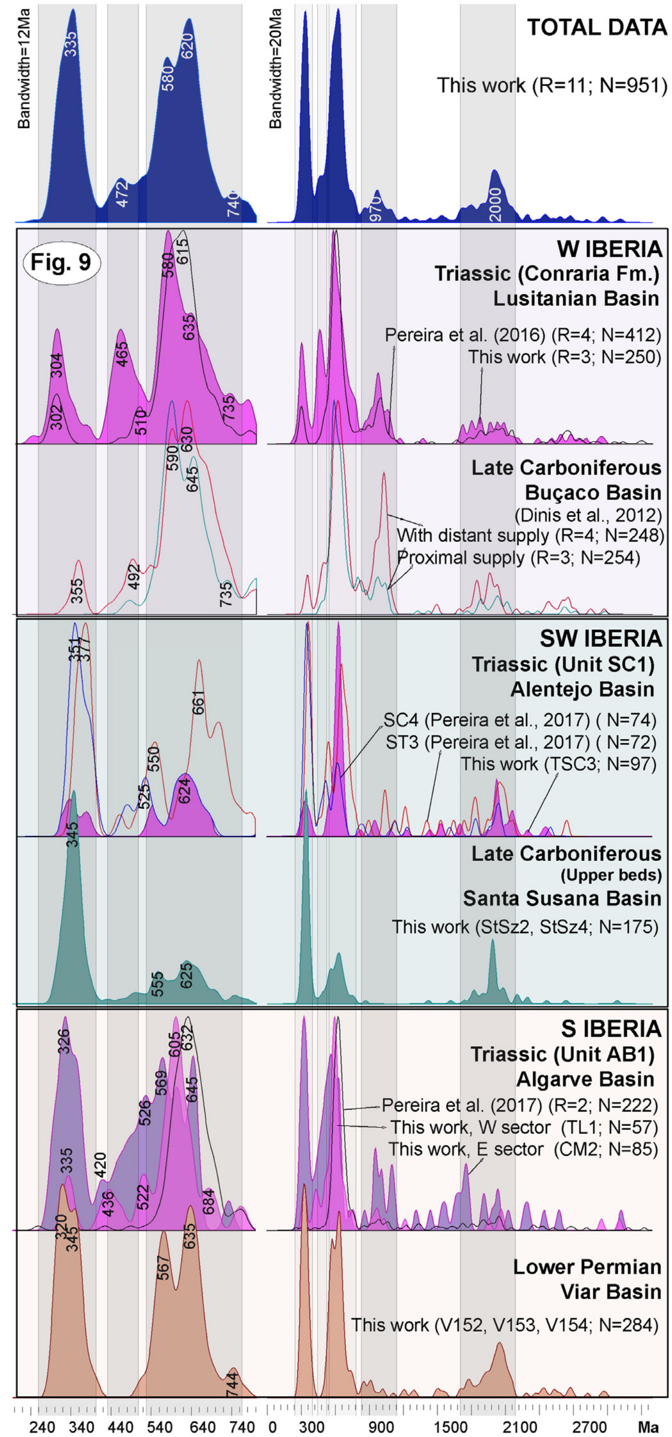

Fig. 8. Zircon U-Pb age data for the Upper Carboniferous, Permian and Triassic continental deposits of SW Iberia. N: number of concordant age results. Vertical grey bands mark the major zircon forming events. The orientation of the Alentejo Basin almost orthogonal to the basement strike accounts for the variability in its detrital age signature.

Mesoproterozoic zircon populations, despite being well represented in several geological units that presently outcrop in the Pulo do Lobo Antiform (Braid et al., 2011; Pérez-Cáceres et al., 2017), near the contact with the OMZ (Fig. 2B), are uncommon in the Late Paleozoic Santa Susana Basin and Viar basins of SW Iberia, ruling out the possibility of major zircon derived from the SPZ. During most of the Carboniferous, the OMZ was likely elevated relative to the SPZ, and the flysch basins of the SPZ (<340 Ma) were mainly sourced by the OMZ (Rosas et al., 2008; Jorge et al., 2013). Early Permian tectonic uplift of the OMZ was

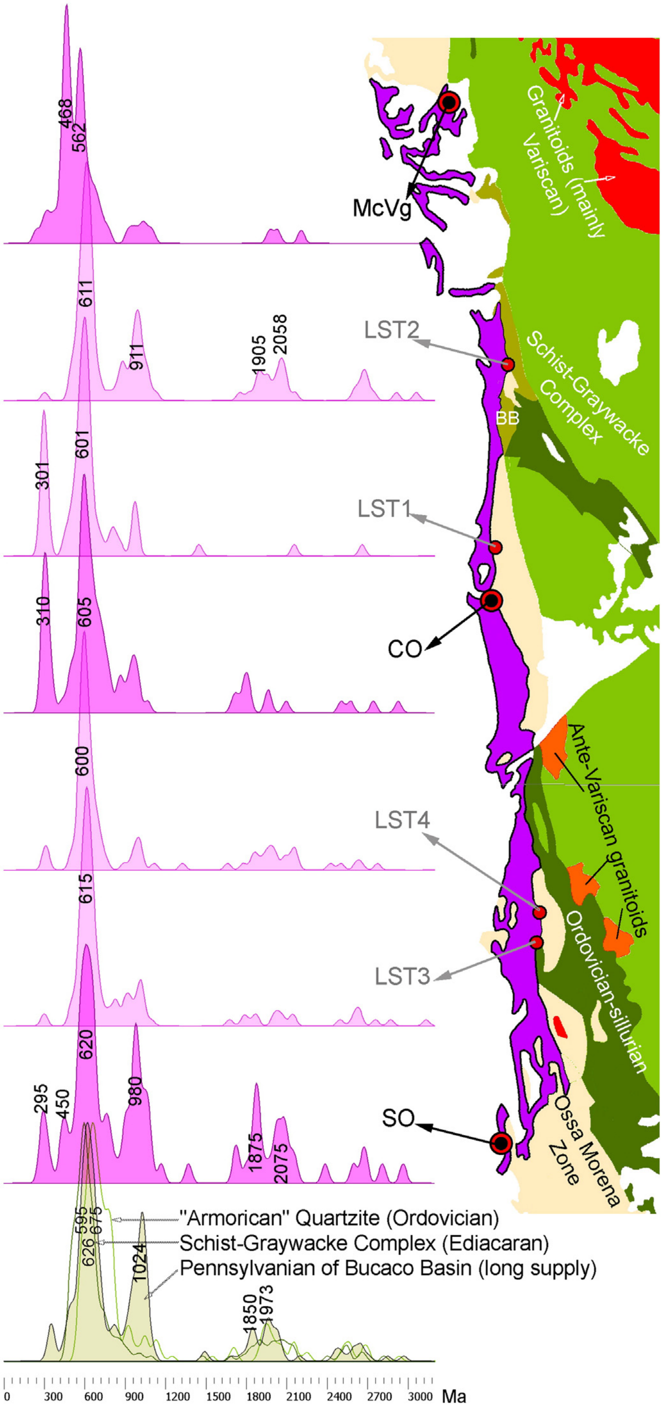

Fig. 9. Compilation of all zircon U-Pb age data available for the Triassic sedimentary units of the Lusitanian Basin. LST1, LST2, LST3 and LST4 from Pereira et al. (2016). BB: Buçaco Basin. Kernel bandwidth of 25 Ma. Zircon age data for the Buçaco Basin from Dinis et al. (2012) and for the "Armorican Quartzites" and the Schist-Greywacke Complex from Pereira et al. (2012a).

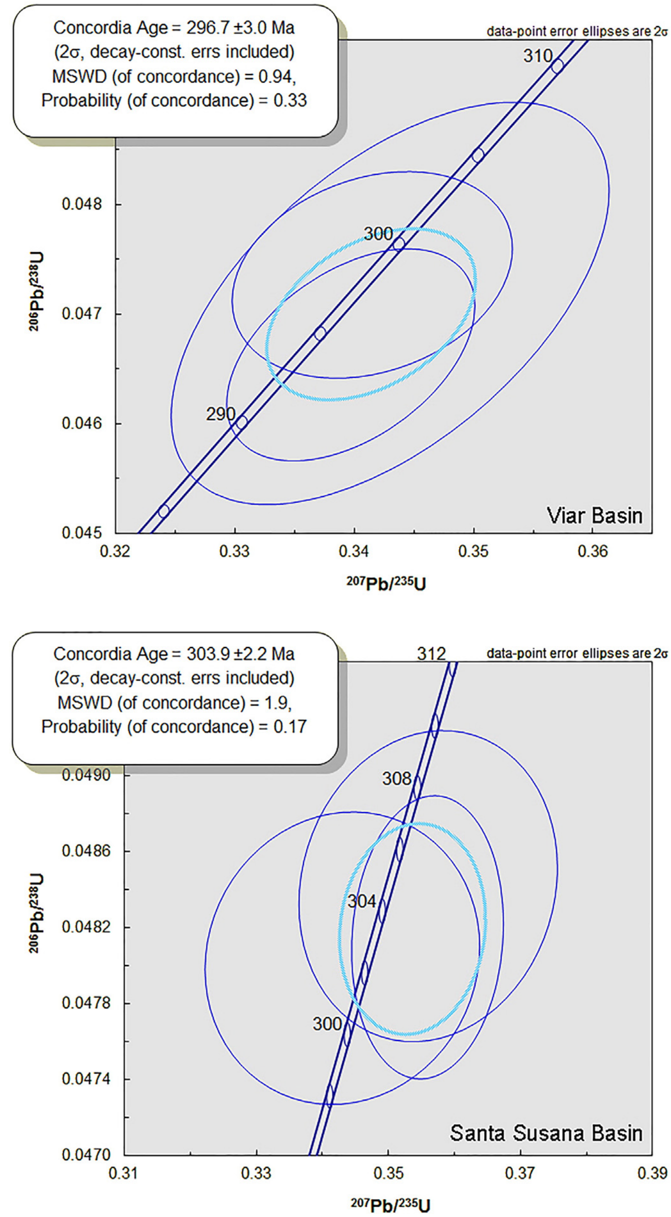

Fig. 10. Concordia diagrams for the Santa Susana and Viar basins indicating their maximum depositional ages.

also postulated for the Viar region (García-Navarro and Fernández, 2004; Sierra et al., 2009). The model of lithospheric delamination promoted by the buckling of the Cantabrian Orocline suggests that the outer arc of that orocline, which includes the CIZ (Gutiérrez-Alonso et al., 2011), should have been strongly uplifted during the late Carboniferous to early Permian times (Weil et al., 2013).

The detrital zircon data from the Santa Susana and Viar basins, which indicate comparable maximum depositional ages and a prevailing source from the uplifted OMZ, can be taken as an evidence of similar genetic processes along the SPZ-OMZ contact during the final episodes of Pangea amalgamation. Dextral strike slip movement acting along N-S to NW-SE bounding structures is recognised in both the Santa Susana and Viar basins, although on the basis of structural data, it was proposed that the Viar Basin is associated with a younger extensional stage linked with the emplacement of basaltic sills and NW-SE trending dykes (García-Navarro and Fernández, 2004; Sierra et al., 2009). We also assume that the sediment transport systems of the Buçaco and Santa Susana basins were influenced by the basin-bounding dextral shear zones (Fig. 11A). A large south-directed axial drainage system controlled by the Porto-Tomar Shear Zone may be responsible for the occasional abundance of the 1.2–0.9 Ga detrital zircon in the Buçaco Basin (Dinis et al., 2012).

Taking into account the distribution of the upper Pennsylvanian to Lower Permian basins in Iberia and neighbouring continental blocks, and the source areas as indicated by the detrital zircon age spectra, the formation of the basins appears strongly affected by major dextral transcurrent movement between Gondwana and Laurussia and the uplift of the OMZ relative to the SPZ and, probably, of the CIZ relative to the OMZ (Fig. 11A). The zircon age data indicate that tectonothermal events were particularly active at the OMZ-SPZ boundary during the late Carboniferous to early Permian. At this time, the region was affected by the northward subduction of the western portion of the Paleotethys Ocean (Cocks and Torsvik, 2006; Stampfli and Kozur, 2006; Pereira et al., 2014). The absence of zircon grains coeval with the deposition in the Buçaco Basin, in contrast to the Santa Susana and Viar basins, may be partially due to the greater distance of the Buçaco Basin from this former subduction zone (Fig. 11A).

5.3.2. Triassic (early fragmentation)

The sedimentology of the Triassic deposits, namely the paleocurrent dispersion and the predominance of poorly sorted, coarse-grained and compositionally immature sedimentary rocks (Palain, 1970, 1976; Soares et al., 2012), suggests that the source areas should be in the vicinity of the rift basins. A proximal provenance is also supported by several features of the age spectra (Fig. 8), such as: (1) the abundance of Cryogenian to Ediacaran zircon ages, which are very abundant in basement metapelites (Pereira et al., 2012a, 2012b; Braid et al., 2011; Talavera et al., 2012; Shaw et al., 2014; Pérez-Cáceres et al., 2017); (2) the coincidence of the Paleozoic zircon population with magmatic events in the surrounding areas (Fernández-Suárez et al., 2000; Jesus et al., 2007; Azor et al., 2008; Rosa et al., 2009) and the detrital record of the upper Paleozoic basement rocks (Braid et al., 2011; Dinis et al., 2012; Pereira et al., 2012b; Pérez-Cáceres et al., 2017).

All samples from the Lusitanian Basin (including the four samples of Pereira et al., 2016; Fig. 9) contain minor proportions of Late Paleozoic zircon (5–18%), suggesting that the drainage areas were small and almost entirely situated on the rift shoulders where Variscan crystalline rocks were absent (Fig. 11B). A Triassic zircon (244 ± 3 Ma) identified in the northern sample (McVg), which exhibits oscillatory zoning and a relatively high Th/U ratio (0.93) must be derived from a magmatic source. It may be linked with the local exhumation of igneous rocks coeval with early rifting metamorphic units reported for the western Iberian margin (Gardien and Paquette, 2004). This northernmost sample within the Lusitanian Basin is also characterized by the presence of exceptionally high proportions of Cambro-Ordovician zircons (35% of all grains, ranging from 517 to 445 Ma). A discrete Ordovician peak (c. 450 Ma) is also observed in the southern sample from the Lusitanian Basin (SO). Taking into account that the basement rocks found today in the surrounding areas yield limited amounts of Cambro-Ordovician zircons (Talavera et al., 2012; Pereira et al., 2012a; Shaw et al., 2014) and the majority of these zircon grains do not display morphological features indicative of polycyclic origin, a proximal first cycle source should be considered. This sediment source unit has not yet been identified.

The Triassic rocks of the Lusitanian Basin comprise minor proportions of Late Silurian-Early Devonian zircons, which are likely associated with the accretion of Avalonia and Meguma with Laurussia (van Staal et al., 2009; Murphy et al., 2011) and could reveal a provenance from the Iberian conjugate margin. “Exotic” source units can be invoked for the southernmost sample from the Lusitanian Basin. This sample yields a significant amount of 1.2–0.9 Ga zircon (Figs. 8 and 9), which has been used as evidence for sediment delivery systems in the Iberian Basin that were several hundreds of km long, extending as far as the Avalonia Terrane (Sánchez Martínez et al., 2012). However, this scenario cannot apply to the basins of the Atlantic margin, where the Triassic deposits appear to be very locally fed. Lacking other primary or secondary sources, the upper Carboniferous-lower Permian continental deposits may be responsible for contributing recycled ~1.2–0.9 Ga zircon grains into the Triassic of the Lusitanian Basin (Fig. 9). The abundance of rounded/sub-rounded quartz in these sequences (Fig. 4) when the sedimentological features suggest a very proximal source area supports the possibility of recycling processes.

Substantially larger drainage areas extending further inland in Iberia can be postulated only for the western sector of the Algarve Basin (Fig. 11B) explain the abundance of pre-Variscan Paleozoic (c. 450–370 Ma) and Paleoproterozoic to Mesoproterozoic (c. 1600–1200 Ma) zircon in sample CM2. These ages are only well represented in the northern realms of the SPZ (~60 km to the north of CM2 sampling site), namely in the Peramora-Alájar Mélange Quartzite and Ribeira de Limas Formation (Braid et al., 2011) and in the Horta da Torre Formation (Pérez-Cáceres et al., 2017), and are considered evidence for an “exotic” Avalonia-source. More extensive fluvial systems in this sector are compatible with an earlier rifting episode reflecting the westward advancing Tethys Ocean into South Iberia (Ziegler, 1988; Arche and López-Gómez, 1996).

6. Conclusions

U-Pb detrital zircon data from clastic rocks of SW Iberia imply that during the late Carboniferous and early Permian, the OMZ was uplifted relative to the SPZ. Hence, continental basins that formed at the suture between these two Variscan tectonic units were mainly sourced from the core of the Iberian Massif (i.e. from the north). U-Pb detrital zircon age data also constrain the maximum depositional age for the Santa Susana Basin at c. 304 Ma and the Viar Basin at c. 297 Ma, and these U-Pb ages are likely only marginally older than the true depositional age of these basins. The Upper Pennsylvanian to Lower Permian basins (Santa Susana, Buçaco and Viar) appear genetically linked to the late phases of Pangea amalgamation when major dextral shear movement in N-S structures (current coordinates), contemporaneously with the final stages of the development of the Cantabrian Orocline formation, affected Iberia. It is proposed that the absence of late Pennsylvanian zircon grains in the Buçaco Basin, in contrast to the Santa Susana and Viar basins, is due to a combination of factors including the local Variscan basement geology and the greater distance to an inferred Paleotethys subduction zone in SE Iberia.

Most of the Triassic sediments yield detrital zircon age spectra characterized by a predominance of c. 800–540 Ma ages and/or Variscan to post-Variscan ages, for which potential local sources (to the east for the Lusitanian and Alentejo basins, and to the north for the Algarve Basin) can be postulated, indicating small supply systems. Abundant Cambro-Ordovician zircon in the northern part of the Lusitanian Basin has no obvious source. This population and the youngest zircon measured in this study (244 ± 3 Ma) are likely associated with the exhumation of igneous rocks along the Porto-Tomar Shear Zone. In addition, upper Carboniferous–Lower Permian continental deposits probably constituted secondary sources of recycled zircons into the Triassic basins, accounting for the local abundance of Grenville-age zircon (1.2–0.9 Ga) in the Lusitanian Basin. Zircon recycled from late Paleozoic rocks of the SPZ with Laurussia-affinity (c. 1.6–1.2 and 0.45–0.37 Ga) suggests relatively larger drainage areas (>50–100 km in length) in the eastern part of the Algarve Basin. Longer fluvial systems are explained by the closer proximity of the Algarve Basin to the westward advancing Tethys Ocean than the rift basins formed on the Iberia western margin.

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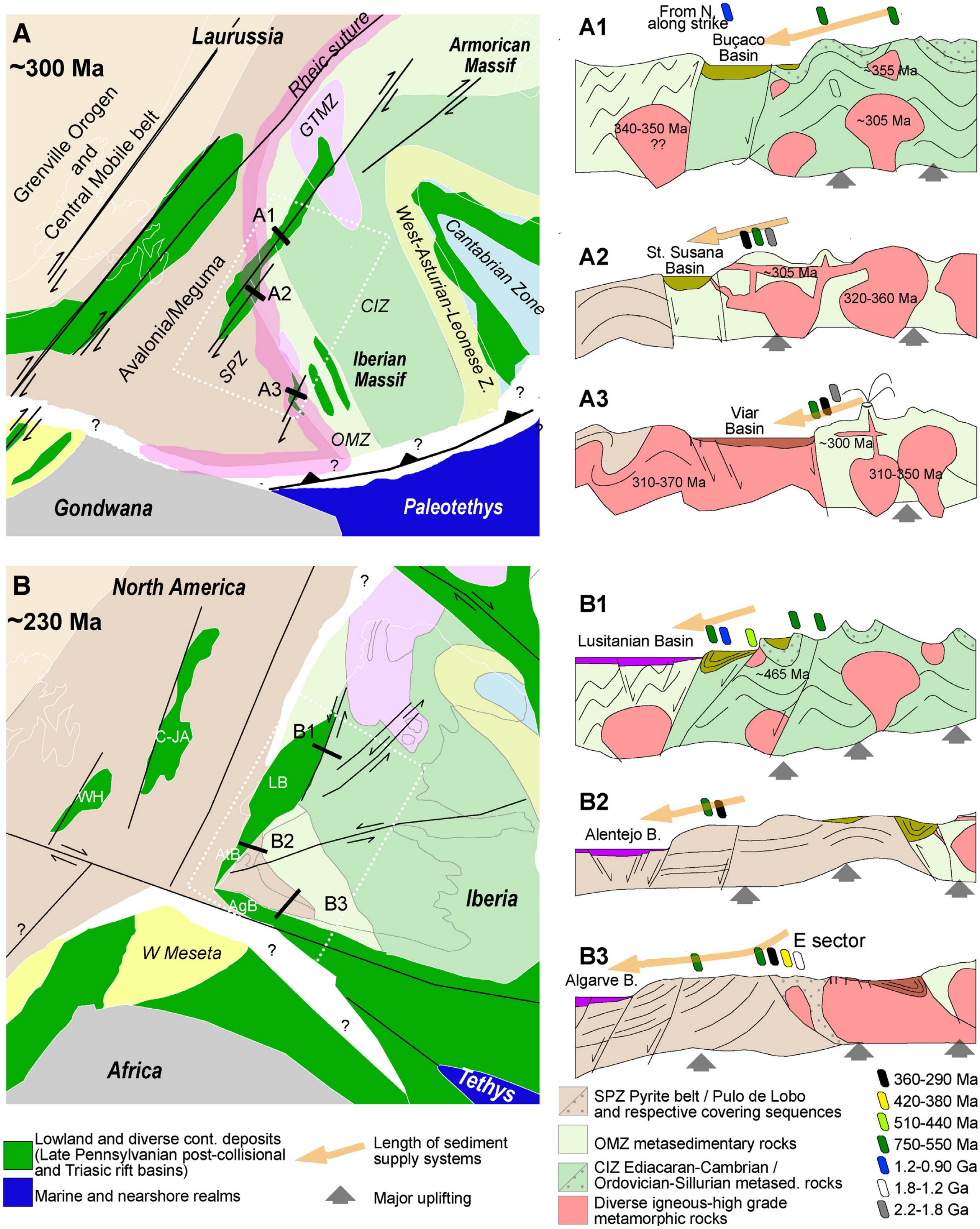

Fig. 11. Tentative model for the distribution of zircon source units and sediment delivery paths at the western and SW borders of the Iberian microplate during late amalgamation (A) and early Pangea break up (B). Schematic cross-sections (A1–A3 and B1–B3) not to scale. Note that the regional relief and the formation of the depositional basins during the two periods are controlled by almost the same structural directions. Regional paleogeography based on Stampfli and Kozur (2006), Sibuet et al. (2012) and Leleu et al. (2016). Basins in West Iberia and its conjugate margin: WH: Whale and Horseshoe; C-JA: Carson and Jeanne d'Arc; LB: Lusitanian; AtB: Alentejo; AgB: Algarve; GTMZ: Galicia-Trás-os-Montes Zone. White dotted lines indicate the approximate limits of the study area.

and suggestions made by Daniel Pastor-Galán, Heinrich Bahlburg and a third anonymous reviewer.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.sedgeo.2017.09.015.

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