
Cadomian/Pan-African consolidation of the Iberian Massif assessed by its detrital and inherited zircon populations: is the ~610Ma age peak a persistent Cadomian magmatic inheritance or the key to unravel its Pan-African basement?

Martim Chichorro¹ Ana Rita Solá² Telmo M. Bento dos Santos^{3,4} João Lains Amaral^{2,3} Lourenço Crispim³

¹GeoBioTec, Departamento de Ciências da Terra, FCT, Universidade Nova de Lisboa
2829-516 Caparica, Portugal. E-mail: ma.chichorro@fct.unl.pt

²Laboratório Nacional de Energia e Geologia (LNEG)
Ap. 7586, Alfragide, 2610-999 Amadora, Portugal

³Universidade de Lisboa, Faculdade de Ciências, Instituto Dom Luiz
1749-016, Lisboa, Portugal

⁴DG-FCUL - Departamento de Geologia, Faculdade de Ciências da Universidade de Lisboa
Ed. C6, Piso 4, Campo Grande, 1749-016 Lisboa, Portugal

| A B S T R A C T |

This work assessed the age distribution of Cadomian/Pan-African orogenic events (550-590 and 605-790Ma, respectively) in several zones of Iberian Massif by means of detrital and inherited zircon analysis compilation. Detrital zircon age spectra show that throughout the late Neoproterozoic-to-Early Ordovician era (~120Ma sedimentary record), the main systematic peak occurs at ~610Ma, followed by peaks at typical Cadomian ages (~590-550Ma). Inherited zircons incorporated in Cambrian-to-Lower Ordovician igneous rocks show typical Cadomian ages (~590-550Ma) but, once again, a remarkably consistent Pan-African ~610Ma peak occurs.

In accordance with compiled zircon data and taking into account the evidence of North African peri-cratonic inliers, Ediacaran (~610Ma) zircons incorporated in Paleozoic magmas provide indirect evidence of Pan-African magmatism, suggesting that these magmas and synorogenic sediments are likely to constitute the cryptic stratigraphic infrastructure of most of the Iberian Massif. The main source of ~610Ma inherited zircons may be the lateral chrono-equivalents of the Saghro and Bou Salda-M' Gouna Groups (Anti-Atlas, Morocco) and/or coeval igneous rocks from West African Craton or Trans-Sahara Belt, emplaced at a stratigraphic level below the late-Ediacaran sediments of the Ossa Morena Zone and the Central Iberian Zone.

Assuming that the Iberian crust is a fragment of the Pan-African orogen, a relative paleoposition situated between the West African Craton and the Trans-Saharan Belt during the Late Neoproterozoic is proposed. The closed-system behaviour of Stenian-Tonian detrital zircon ages in the Trans-Sahara Belt suggests that this mega-cordillera acted as a barrier, in paleogeographic terms, separating the Sahara Metacraton from Iberia. In Iberia, the opening of the system to Stenian-Tonian detrital zircons during the Ordovician indicates that, at that time, the Trans-Saharan Belt had already become a vast peneplain, which favoured a large drainage system with a long-distance transport mechanism that fed the passive continental margins.

KEYWORDS | Pan-African. Cadomian. Inherited zircon. Peri-Gondwanan. Iberian Massif.

INTRODUCTION

The rearrangement of Gondwana's northwestern marginal block (Fig. 1), where the paleoposition of Iberia and other segments of the Western European Variscan belt is assumed to be (Linnemann *et al.*, 2008; Nance *et al.*, 2008), is due to global tectonic events associated with both the Pan-African orogenic cycle and the peri-Gondwanan Cadomian Orogeny.

The Pan-African Orogeny includes all the orogens which developed following the final Grenvillian thermotectonic events up until the creation of Gondwana. It was a global, long-term orogenic cycle (1,000-550Ma) and one of the most important periods of crustal maturation in Earth's history, including the diachronic opening and closing of large ocean realms and the accretion and collision of buoyant crustal blocks (Abdelsalam *et al.*, 2002; Bento dos Santos *et al.*, 2015; Collins and Pisarevsky, 2005; Ennih and Liégeois, 2008; Hefferan *et al.*, 2014; Kroner and Stern, 2004; Murphy *et al.*, 2013; Rino *et al.*, 2008).

The final consolidation of Gondwana also included the peripheral Cadomian-Avalonian orogenic events (590-550Ma), affecting the north-western Gondwana marginal block (Fig. 1). (Linnemann *et al.*, 2008; Nance *et al.*, 2008).

The Trans-Saharan Belt (TSB) (Cahen *et al.*, 1984) is a Pan-African Gondwanan interior orogen associated with the development of a collisional belt between two major continental land masses, the West African Craton (WAC) and the Sahara Metacraton (SMC), and the progressive thermal heating caused by crustal thickening with abundant post-collisional to syn-orogenic magmatism and high-grade metamorphism (whose peak was attained during the thermal climax), whereas the Cadomian orogenic setting is well constrained as being a peripheral magmatic arc developed in the northern region of the Gondwana supercontinent (Alvaro *et al.*, 2014; Boullier, 1991; Ferré *et al.*, 2002; Murphy and Nance, 1991). Neoproterozoic crustal accretion has been documented around the western, northern and eastern boundaries of the West African Craton (Ennih and Liégeois, 2001) and the Anti-Atlas

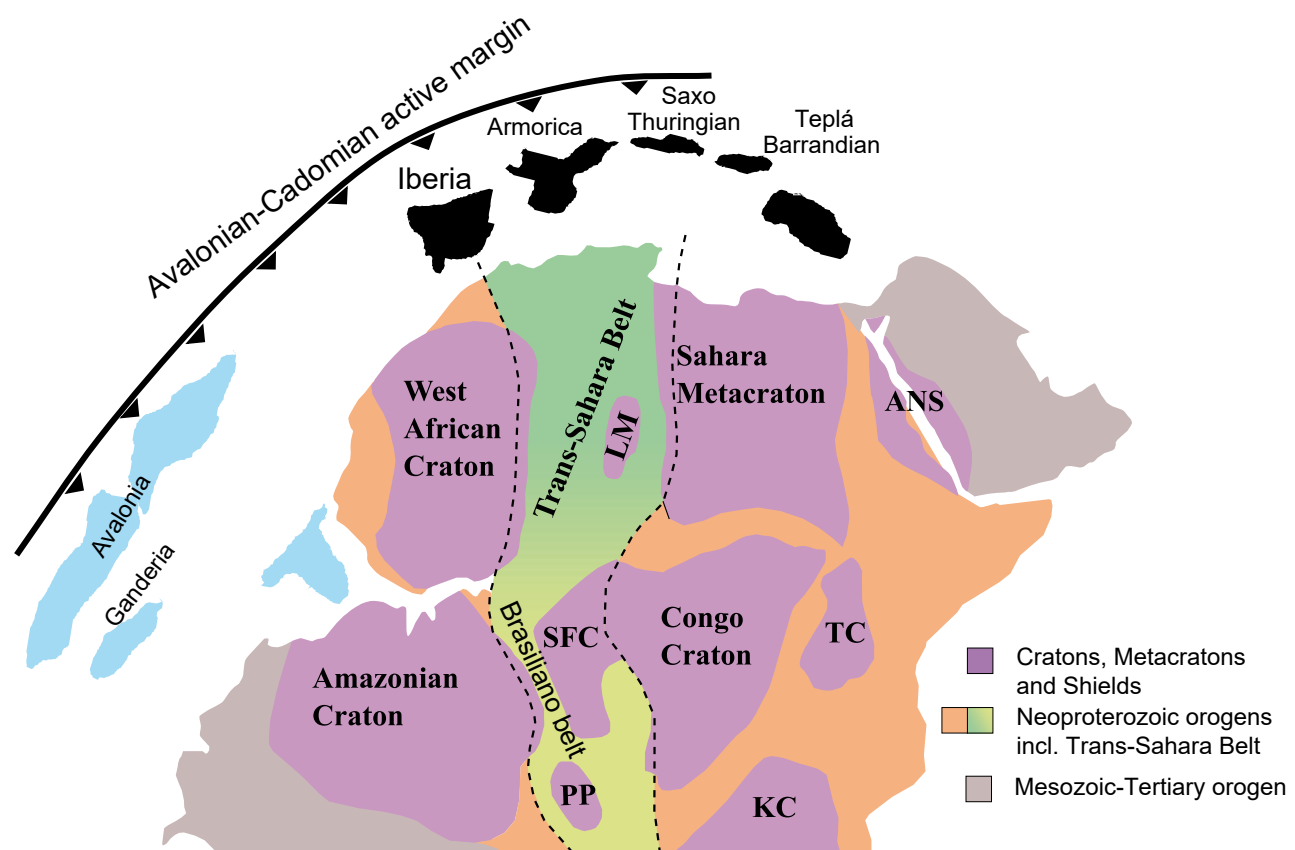


FIGURE 1. Reconstruction of Gondwana at the end of the Neoproterozoic. Proposed simplified scheme for the relative location of the West-Central European (Iberia, North Armorican, Saxo-Thuringian Zone and Teplá-Barrandian Cadomian Belt) and Northern African (Anti-Atlas, High-Atlas and Western Meseta) peri-Gondwana correlatives within the Avalonian-Cadomian active margin during Ediacaran-Early Cambrian times c.570-520Ma (adapted from Cambeses *et al.*, 2017; Ennih and Liégeois, 2001; Linnemann *et al.*, 2004; Murphy *et al.*, 2006; Nance *et al.*, 2002; Pereira *et al.*, 2008, 2012a, b). Amazonian Craton (AM); West African Craton (WAC); Trans-Sahara Belt (TSB); Sahara Metacraton (SMC); Arabian-Nubian Shield (ANS); LATEA Metacraton (LM); São Francisco Craton (SFC); Paranapanema Plate (PP); Congo Craton (CC); Tanzania Craton (TC); Kalahari Craton (KC).

(AA) in southern Morocco is a key area to understand such Neoproterozoic geotectonic events (Abati *et al.*, 2010; Alvaro *et al.*, 2014; Errami *et al.*, 2020; Liégeois *et al.*, 2006).

Most attempts to constrain time frames for each Neoproterozoic magmatic event associated with the consolidation of the Iberian crust constitute difficult and subjective undertakings, especially covering the late Cryogenian-to-early Ediacaran timeframe, during which the Cadomian and Pan-African events overlapped, in terms of both time and space. This is why most Cryogenian-Ediacaran zircon-forming events expressed in age probability distributions are generally interpreted as reflecting the existence of a long-lived magmatic arc which developed along the North-Gondwana margin (Avalonian-Cadomian belt and Pan-African belt) (Pereira *et al.*, 2012a, b; and references therein). However, recent studies have suggested that the two events occurred separately. The magmatic activity associated with the Cadomian arc started at c. 590Ma and lasted until c. 550Ma (Linnemann *et al.*, 2008, 2014, 2018), whereas in internal domains of North Africa (for example, the Anti-Atlas domain in Morocco and the TSB), two main Pan-African stages of magmatic activity are assumed to have occurred (Black *et al.*, 1994; Gasquet *et al.*, 2005; Linnemann *et al.*, 2004): the first of these was ocean opening followed by subduction-related arc magmatism (790-690Ma); the second was ocean closure followed by continent-continent collision (690-605Ma), with major peaks at 660 and 615Ma (Black *et al.*, 1994; Gasquet *et al.*, 2005; Linnemann *et al.*, 2004).

Most paleogeographic reconstructions are based on the “main peak” paradigm, while the analysis of frequency and density distributions of detrital (and inherited) U-Pb zircon age data generating curves group the main peaks in well-defined time intervals of magmatic production. Detrital zircon age distributions provide a window on the ages of exposed crystalline and sedimentary rocks and also reflect the proximal-to-distal erosional, recycling, and depositional systems associated with main source areas (Nelson, 2001).

The aim of this study is to describe how the Cadomian/Pan-African orogenic events impacted on the Neoproterozoic units of the Iberian Massif and how the Cadomian-Pan-African signature persists in the subsequent Rift-to-Drift cycle based on compiled and new zircon age distributions (Table 1). An approach to determining the nature of Cadomian/Pan-African events in the Iberian Massif is presented in this study and discussed with reference to: i) detrital zircon analysis of Neoproterozoic sediments (Pan-African-Cadomian cycle); ii) detrital zircon analysis of Lower Paleozoic sediments (Rift-to-Drift cycle) and iii) inherited zircon ages in Cambrian-to-Lower Ordovician igneous rocks (Rift-to-Drift cycle). In

the present study, only inherited/xenocrystic pre-magmatic zircons (Bea *et al.*, 2007) were taken into account. All ages within the analytical uncertainty of the crystallization age of the igneous protolith were excluded.

In addition, for the purpose of comparison and in order to help track the position of Iberian terranes in peri-Gondwana margin paleogeography, several composite probability and histogram plots of U-Pb detrital, igneous, and metamorphic zircon ages from north-western Gondwana (the SMC, the TSB and the AA realm) were also produced based on indications in the literature (Abati *et al.*, 2010; Altumi *et al.*, 2013; Avigad *et al.*, 2012; Cambeses *et al.*, 2017; Errami *et al.*, 2020; Karaoui *et al.*, 2015; Linnemann *et al.*, 2008; Meinhold *et al.*, 2011, 2013; Wang *et al.*, 2020; Žák *et al.*, 2021).

Finally, we attempt to correlate the major U-Pb age peaks in Iberia with the main ages of igneous rocks representative of the Cadomian and Pan-African orogens in northern Africa, with the inclusion of Mesoproterozoic orogenic belts and the Paleoproterozoic-to-Archaean cratonic areas emplaced within the internal sectors of Gondwana (Fig. 1). The state of the art relative to the position of Peri-Gondwana terranes in North Gondwana (see, for example, Avigad *et al.*, 2012; Cambeses *et al.*, 2017; Pereira *et al.*, 2008, 2012a, b; Shaw *et al.*, 2014) are then examined using paleogeographic reconstructions (Fig. 1).

THE PRE-VARISCAN IBERIAN MASSIF

Two cycles prior to the Variscan Orogeny were decisive for the development of the Iberian Massif: the first was the creation of the Gondwana supercontinent and its erosional dismantling through Neoproterozoic Cadomian/Pan-African Orogeny; the second was subsequent Lower Paleozoic rifting and Rift-to-Drift crustal evolution from Cambrian to Lower Devonian times (Chichorro *et al.*, 2008; Linnemann *et al.*, 2008; Nance *et al.*, 2010; Sánchez-García *et al.*, 2003, 2019).

The pre-Mesozoic basement of the Iberian Massif (Fig. 2) comprises zones with distinct tectono-stratigraphic and magmatic features and such differentiation is largely reminiscent of these two cycles (Eguiluz *et al.*, 2000; Oliveira *et al.*, 1991; Quesada, 1991; Ribeiro *et al.*, 1990a; Sánchez-García *et al.*, 2003). The differences between their Neoproterozoic and Lower Paleozoic sedimentary successions, as well as the representativeness and nature of Ediacaran (Cadomian/Pan-African-related)-to-Cambro-Ordovician (Rift-to-Drift-related) magmatism are critically important for any paleogeographic constraints to be defined. Differences in the nature of sedimentary successions are generally interpreted as reflecting their relative proximity to

TABLE 1. Summary of the zircon data compilation from detrital and inherited zircon

Zircon type	Geodynamic setting	Atributed age	Tectono-Stratigraphic Domain	Geologic unit	Samples	References	
Detrital zircon	Back-Arc or Retro-Arc	Ediacaran	OMZ	Série Negra	BSC-1 (n=6), CSN-26 (n=18), SEC-1 (n=28)	Chichorro, 2006	
					2B-CMR (n=17), 2C-CMR (n=19)	Pereira <i>et al.</i> , 2010	
					ETZ-32 (n=112)	Pereira <i>et al.</i> , 2012b	
					ZD-6, (n=42)	Fernández-Suárez <i>et al.</i> , 2002b	
					PAL-2 (n=7)	Schafer, 1990	
					SNM-1, (n=34)	Linnemann <i>et al.</i> , 2008	
			HOR-5 (n=26)	Ordoñez-Casado, 1998			
			CIZ	Douro-Beiras Supergroup (Beiras Group)	CTT68 (n=69), CTC67 (n=88), CTP62 (n=78)	Talavera <i>et al.</i> , 2012	
					PNC-1 (n=110); PNC-2 (n=101)	Pereira <i>et al.</i> , 2012	
	WALZ-CZ	Allande and Navelgas units (Narcea antiform)	OD-2 (n=215); OD-5& OD-7 (n=406)	Fernández-Suárez <i>et al.</i> , 2014			
	Rift Stage	Lower-Medium Cambrian	OMZ	Lower to Upper Detrital Groups	OGL-1 (n=36)	Linnemann <i>et al.</i> , 2008	
					CTO-33 (n=30), 2A-OGL (n=28)	Pereira <i>et al.</i> , 2011	
					ETZ-30 (n=77)	Pereira <i>et al.</i> , 2012b	
					OSS (n=106), FTQ (n=38)	Chichorro, unpublished data	
		Lower Cambrian	CIZ	Douro-Beiras Supergroup (Douro Group) Monterrubio Fm and Aldeatejada Fm	ZD-1 (n=15), ZD-4 (n=6)	Gutiérrez-Alonso <i>et al.</i> , 2003	
					Douro-Beiras Supergroup (Douro Group) Azorejo-Tamames sandstones	OD-3 (n=142)	Fernández-Suárez <i>et al.</i> , 2014
			WALZ-CZ	Cándana Group arkoses and Cándana-Herrería sandstones	JG-16 (n=15), OD-1 (n=199)	Fernández-Suárez <i>et al.</i> , 2000; 2014	
			Upper Cambrian-Lower Ordovician	CIZ	Sarnelhas arkosic sandstones	PNC-3 (n=120)	Pereira <i>et al.</i> , 2012
	Malpica do Tejo and Villalcampo schists	CTP-64 (n=68), CTS-55 (n=108)			Talavera <i>et al.</i> , 2012		
	GTMZ	Arkoses from the Mora-Saldanha Volcano-Sedimentary Complex		SALD-1 (n=124)	Dias da Silva <i>et al.</i> , 2015		
Basal allochthonous units (Upper sequence)		BA-1 (n=164), BA-9 (n=138), BA-12 (n=165)		Díez-Fernández <i>et al.</i> , 2010			
Drift Stage	Lower Ordovician- Floian	CIZ	Armorican quartzite	QAM-1 (n=34)	Linnemann <i>et al.</i> , 2008		
				PNC-4 (n=57)	Pereira <i>et al.</i> , 2012		
		WALZ-CZ	Barrios Formation	LAZ-5 (n=113), LAZ-26 (n=130), SCS-5 (n=115), GCZ-3 (n=115), WALZ-1 (n=139), WALZ-2 (n=129), CZ-2 (n=113)	Shaw <i>et al.</i> , 2014		
				WALZ-1 (n=139), WALZ-2 (n=129), IBR-2 (n=125), CZ-02 (n=113)	Shaw <i>et al.</i> , 2014		
Xenocrystic/Inherited zircon	Rift Stage	Lower Cambrian	OMZ	Alcaçovas Orthogneiss	ALC+ALC-10 (n=3)	Cordani <i>et al.</i> , 2006; Chichorro <i>et al.</i> , 2008	
				Barquete granite	BQR (n=6)	Pereira <i>et al.</i> , 2011	
				Bodonal-Cala, Pallares granite and other felsic orthogneisses	BOD-2, Arr-1, Pal, Arg-3, Arg-5 (n=9)	Ordoñez-Casado, 1998	
	Rift-to-Drift Stage	Upper Cambrian-Lower Ordovician	CIZ	Urro Formation Carrascal and Portalegre granites	PORT-4, PORT-33, Urro-1, Urro-2 (n=34)	Solá <i>et al.</i> , 2008; Solá, 2007	
					Ollo de Sapo Fm.	IM(x), LA(x) (n=316)	Bea <i>et al.</i> , 2007
					Castilian region	Guadarrama, Tormes, Berzosa (n=284)	Bea <i>et al.</i> , 2006; Talavera <i>et al.</i> , 2013; Villaseca <i>et al.</i> , 2016
			GTMZ	Schistose Domain	CT(x), ER(x), Sisargas (n=142)	Talavera <i>et al.</i> , 2008; Talavera <i>et al.</i> , 2013; Díez-Fernández <i>et al.</i> , 2012; Montero <i>et al.</i> 2009a	
					Malpica-Tuy Complex / Basal Allochthonous Units	MTG(x) (n=67)	Díez-Fernández <i>et al.</i> , 2012

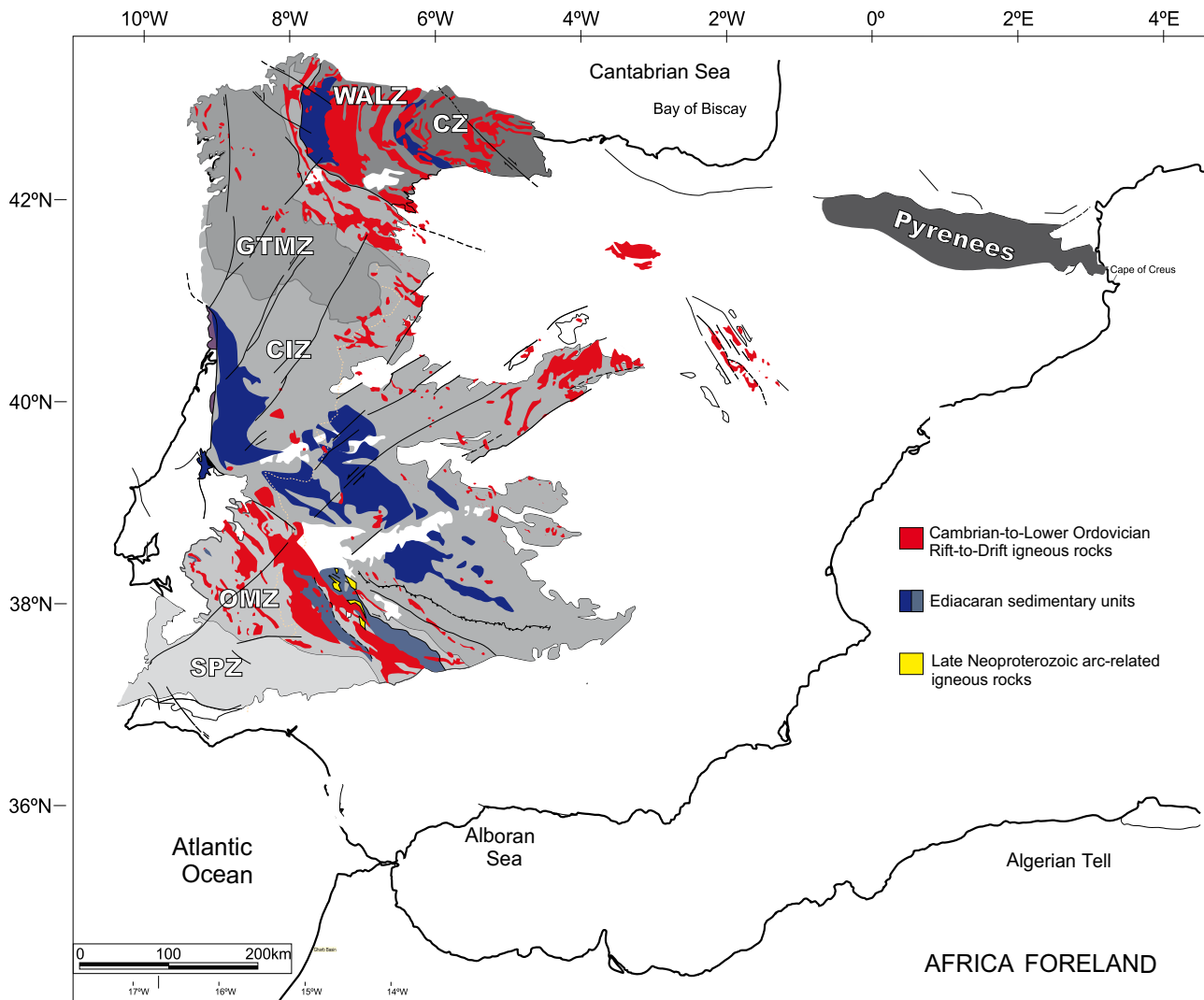


FIGURE 2. Iberian Massif: Zone boundaries modified after [Julivert *et al.* \(1974\)](#), [Quesada \(1991\)](#) and [Martínez-Catalán *et al.* \(2014\)](#). Highlighted in blue: Major Neoproterozoic Sedimentary units; Highlighted in Red: Rift-to-Drift igneous rock related outcrops. Cantabrian Zone (CZ); West Asturian-Leonese Zone (WALZ), Galicia-Trás-os-Montes Zone (GTMZ), Central Iberian Zone (CIZ), Ossa-Morena Zone (OMZ), South Portuguese Zone (SPZ).

Gondwanan margins and differences in the volume and age of magmatism are generally interpreted as reflecting their proximity to Cadomian-Pan-African Arcs and the diachronic nature of Rift-to-Drift igneous processes during the Lower Paleozoic ([Álvaro *et al.*, 2014, 2020a, b](#); [Cambeses *et al.*, 2017](#); [Casas and Murphy, 2018](#)).

Both the Cantabrian Zone (CZ) and the West Asturian-Leonese Zone (WALZ) present Ediacaran-to-Cambrian strata characteristic of shallow-water platform sedimentation in proximity to the Northern Gondwana margin, whereas the Central Iberian Zone (CIZ) and Galicia-Trás-os-Montes Zone (Schistose Domain) (GTMZ) presents tectonostratigraphy which is external ([Aramburu *et al.*, 2004](#); [Martínez-Catalán *et al.*, 1996](#); [Pérez-Estaún *et al.*, 1990](#); [Quesada, 1990a, b](#); [Quesada *et al.*, 1991](#);

[Ribeiro *et al.*, 1990b](#); [Robardet, 2002, 2003](#); [Robardet and Gutiérrez-Marco, 1990a, b](#)). The Ossa-Morena Zone (OMZ) is interpreted as reflecting relative proximity to the Cadomian Arc ([Eguiluz *et al.*, 2000](#); [Pereira *et al.*, 2008](#)). The South-Portuguese Zone, whose oldest basement is Devonian, is regarded as being an exotic terrane and beyond the scope of the present study (see [Lains Amaral *et al.*, 2022](#)).

The oldest known igneous crust in the Iberian Massif is of Ediacaran age ([Quesada, 1990a, b](#)). These rocks, mostly exposed in the northern OMZ along the Mérida-Abrantes belt, have been interpreted as being Cadomian arc-related plutonic and/or belonging to a late evolutionary phase (late extensional collapse) of Cadomian Orogeny ([Bandrés *et al.*, 2002](#); [Eguiluz, 1987](#); [Henriques, 2015](#); [Quesada](#)

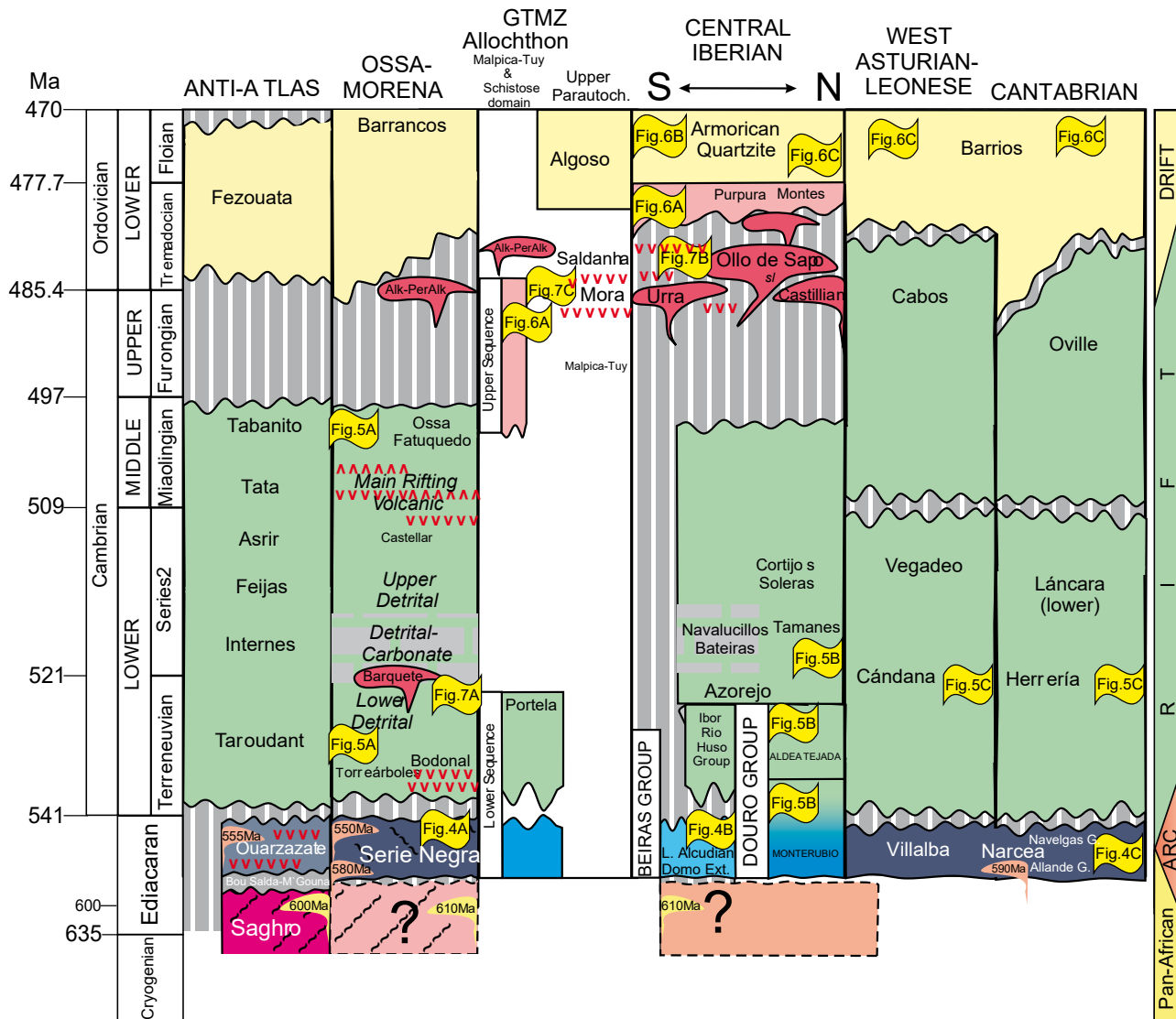


FIGURE 3. Insertion of samples used in composite distribution age data from the tectonostratigraphic correlation chart of the Cadomian Arc and Rift-to-Drift related successions of the Iberian Massif. Comparison of stratigraphic columns representative of the syn-Rift, Rift-to-Drift and Drift successions in the four Gondwanan zones of the Iberian Massif (OMZ, CIZ, WALZ and CZ).

and Munhá, 1990). These scarce igneous remnants of the magmatic arc occur in parallel with large volumes of syn-arc- and back-arc-related sediments (the so-called Série Negra [SN] Formation). The OMZ is bounded to the North by the CIZ, whereas the Douro-Beiras Supergroup features the oldest outcrops, including the Beiras and Douro Groups, which consist of Neoproterozoic-to-early-Cambrian metasedimentary rocks (Ferreira et al., 2022; Medina et al., 1998; Meireles, 2020; Sousa and Sequeira, 1993).

The OMZ is usually interpreted as representing a Cadomian magmatic arc and back-arc setting along the Gondwana margin (Bandres et al., 2002; Eguíluz et al., 2000; Linnemann et al., 2008), whereas the Ediacaran

basin in the CIZ represents either a back-arc setting (see, for example, Eguíluz et al., 2015) or a Late Ediacaran-Terreneuvian retro-arc foreland basin (Alvaro et al., 2020).

Immediately following the Cadomian Orogeny, a dramatic change occurred geodynamically, currently interpreted as being associated with the development of a rifting process along the northern margin of Gondwana (Quesada, 1991; Quesada et al., 1991; Sánchez García et al., 2003; Simancas et al., 2004). The distribution of Ediacaran sequences (Cadomian) and Cambrian-to-Ordovician Rift-to-Drift-related successions in the Iberian Massif is shown in the tectonostratigraphic correlation chart for the various zones in the Iberian Massif (Fig. 3).

DATA SOURCES AND METHODS

A large set of zircon data based on detrital and inherited zircon from several units of the Iberian Massif was compiled and used in this study (Table 1) and its stratigraphic positions are plotted in Figure 3. In this study, the following data from the sources detailed are presented:

i) zircon analysis of Neoproterozoic metasediments (Pan-African-Cadomian cycle) from Série Negra in the OMZ (nine samples), Beiras Group greywackes of the southwest CIZ and the Allande and Navelgas units of the Narcea Antiform (WALZ-CZ transition) (Fig. 3; Table 1).

ii) zircon analysis of Lower Paleozoic metasediments (Rift cycle). These were also compiled in accordance with the period during which they were formed. Samples are representative of the initial stages of the Cambrian intra-continental Rift period and were obtained from Lower Cambrian siliciclastic rocks of: a1) OMZ, Lower-to-Upper Detrital Groups (the present study; Linnemann *et al.*, 2008; Pereira *et al.*, 2011, 2012a, b); a2) CIZ, Lower Cambrian sandstones from the Douro Group (Monterrubio Formation and Aldeatejada Formation; Azorejo-Tamanes sandstones (Gutiérrez-Alonso *et al.*, 2003; Fernández-Suárez *et al.*, 2014) and a3) WALZ and CZ, Lower Cambrian Cándana Group arkoses (eastern WALZ) and Cándana-Herrería sandstones (CZ) (Fernández-Suárez *et al.*, 2000, 2014).

iii) zircon analysis of the detrital component of samples representative of Rift-to-Drift period units were obtained from Lower Ordovician arkoses and pelites (overlain by Armorican quartzite) that characterize the Rift-Drift transition stage in both the CIZ and the GTMZ. Sources were Sarnelhas arkosic sandstones (SW-CIZ, Pereira *et al.*, 2012a), Malpica do Tejo Shales (Central CIZ, Talavera *et al.*, 2012), Villalcampo schists (Talavera *et al.*, 2012), Arkoses from the Mora-Saldanha Volcano-Sedimentary Complex (Upper parautochthon, GTMZ, Dias da Silva *et al.*, 2015), and the upper sequence of the GTMZ (Díez-Fernández *et al.*, 2010).

iv) zircon data for Drift-related sequences: Early Ordovician Armorican quartzites are from the Southwest CIZ (Linnemann *et al.*, 2008; Pereira *et al.*, 2012a) and the CZ, WALZ, and Central and Northern CIZ (Shaw *et al.*, 2014). Two samples from the Luso-Alcudian Southern subdivision are distinct in terms of Stenian-Tonian representativeness. One sample (LAZ-26, see Table 1) appears in the N-CIZ, WALZ, and CZ data diagram (Fig. 6C) while sample LAZ-5 is included in SW-CIZ plots (Fig. 6B). These differences were previously interpreted as either being the response to gradual source variations along the margin or as underlining a paleogeographic limit separating two independent sectors inside the Luso-Alcudian Southern zone (Solá *et al.*, 2017).

v) inherited zircon ages in Cambrian-to-Lower Ordovician igneous rocks (Rift-to-Drift cycle) are derived from Furongian to Lower Ordovician peraluminous and calc-alkaline and alkaline suites from the CIZ (Urta Fm., Solá *et al.*, 2008; Portalegre granites, Solá, 2007; the Ollo de Sapo Formation, Bea *et al.*, 2007; the Castilian region, Bea *et al.*, 2006; Talavera *et al.*, 2013; Villaseca *et al.*, 2016) the GTMZ (Schistose Domain: Talavera *et al.*, 2008, 2013; Díez-Fernández *et al.*, 2012) and Malpica-Tuy Basal Allochthonous Units, Díez-Fernández *et al.*, 2012). In the OMZ, inherited zircons were extracted from igneous protoliths (granites, metagranites, felsic orthogneisses, and leptinites) representing Early Cambrian felsic volcanic rocks and cogenetic shallow plutonic rocks (Alcáçovas Orthogneiss, Chichorro *et al.*, 2008; Barquete granite, Pereira *et al.*, 2011; Bodonal-Cala, Pallares granite and other felsic orthogneisses, Ordoñez-Casado, 1998).

RESULTS

Detrital zircon

Neoproterozoic metasedimentary rocks (Late Cadomian arc)

The stratigraphy of the southwestern Iberian Massif contains well-exposed Ediacaran detrital substrate: the so-called SN in the OMZ, the Douro-Beiras Supergroup (DBSG) in the Central Iberian Zone and the Allande and Navelgas units of the Narcea Antiform (Transition from Cantabrian Zone to West Asturian Leonese Zone) (Figs. 2; 3). Figure 4 provides a comparison of populations of detrital zircon from late Ediacaran greywackes of the OMZ (Fig. 4A), the southern domains of the CIZ (Beiras Group - Lower Alcudian/Domo Extremeño - Fig. 4B) and NW Iberia (Narcea Antiform - WALZ-CZ transition, Fig. 4C) (Stratigraphic positions are plotted in Figure 3, data and references from Table 1). The Neoproterozoic detrital zircon age pattern for the OMZ (SN greywackes; 9 samples, N=309), SW-CIZ (Beiras Group greywackes; 5 samples, N=446), and the WALZ-CZ transition (3 samples, N=621) are not significantly distinct (Fig. 4).

The 620-605Ma interval peaking around ~610Ma is systematically present in all zones, being predominant in the OMZ and in WALZ-CZ transition. In the SW-CIZ, a ~586Ma peak is predominant. Late Ediacaran ages (Cadomian ages ~595-550Ma) are also present in all zones but significantly depleted in the CIZ-WALZ. These peaks are interpreted as representing sources dominated by Cadomian/Pan-African tectonothermal events and suggest that OMZ, SW-CIZ and WALZ-CZ transition basins were fed by igneous and sedimentary rocks rich in ~610Ma zircons and that the WALZ-CZ transition basin occupies a

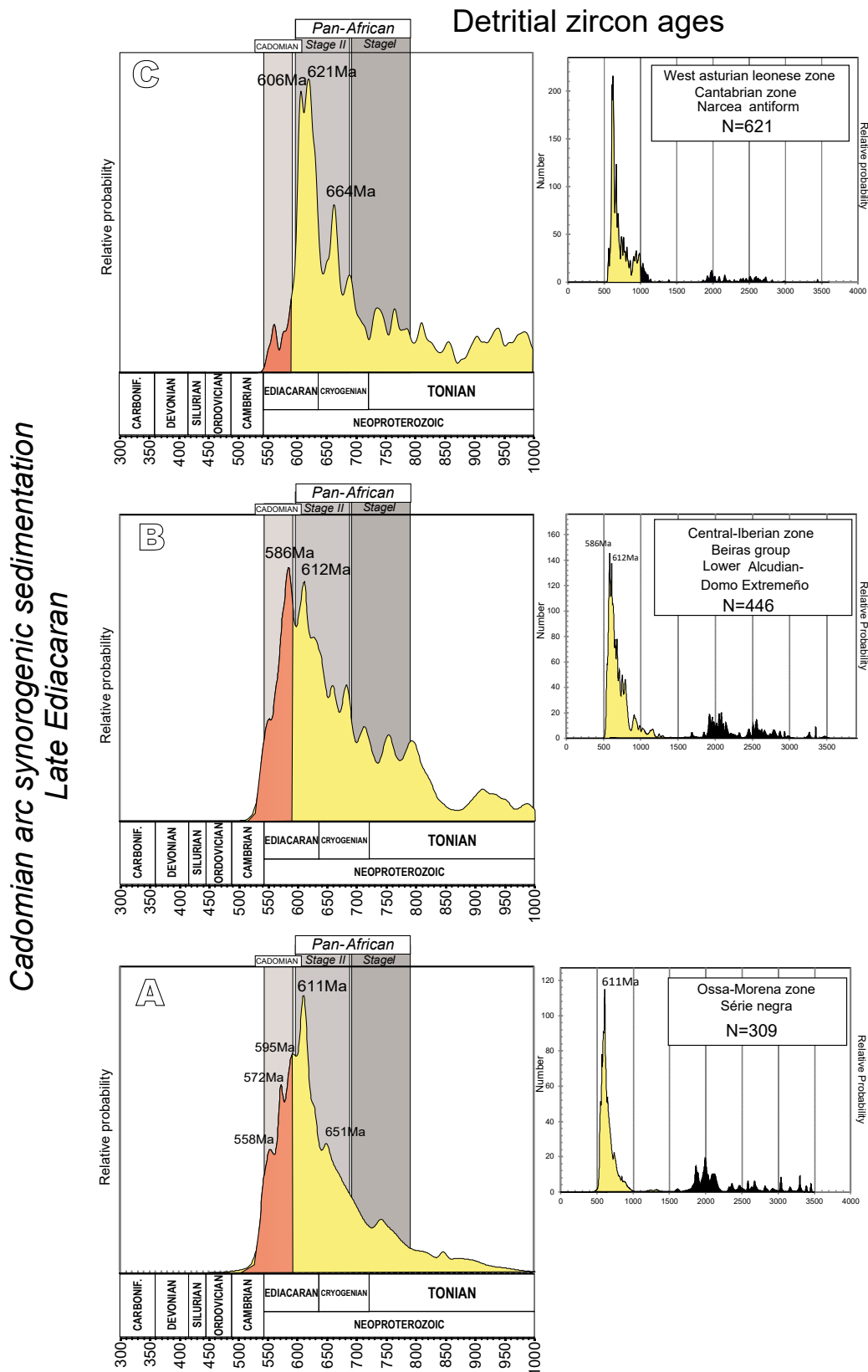


FIGURE 4. Combined probability density plots of U-Pb detrital zircon ages for the Neoproterozoic metasedimentary rocks of the SW-Iberian Massif: A) OMZ; B) SW-CIZ and C) WALZ+CZ. The diagrams on the left represent the magnification of the plots on the right, displaying solely the 300-1,000Ma interval. See Section 3 and Table 1 for zircon data sources and references.

more markedly distal position in relation to the Cadomian arc setting.

The lack of representation of Stenian-Tonian (1.2Ga to ~720Ma) zircon-forming events (Grenvillian Orogeny), referred to as a typical feature of the OMZ, is evident in all the diagrams, suggesting relative proximity as regards the three basins, although there is a slight increase in the number of Stenian-Tonian zircons in the SW-CIZ, while they are more perceptibly evident in the WALZ-CZ transition (Fig. 4B, C). All distributions suggest contributions of minor importance of older crustal growth events (Eburnean Orogeny ~1.8-2.4Ga) and traces of Liberian Orogeny (~2.5-2.9Ga), which are perceptible to a greater degree in the Beiras Group.

The Rift Stage (lower-to-middle Cambrian metasedimentary rock)

The distribution of Rift Stage lower-to-middle Cambrian clastic rocks resembles that of underlying Ediacaran greywackes in the OMZ and CIZ, but this is not the case with the CZ-WALZ, where the following can be seen (Fig. 5): i) there is a much greater influence of Eburnean and Liberian sources as compared with the OMZ and the CIZ; ii) there is a marked increase in Cadomian ages; iii) Stenian-Tonian (1.2Ga to ~720Ma) zircon-forming events (late Grenvillian Orogeny) do not present a significant change in relation to Ediacaran sediments in the OMZ and the CIZ. In the CZ-WALZ a typical WAC signature are virtually completely absent.

The ~610Ma peak persists in Cambrian records for both the CIZ and the OMZ (Fig. 5), the second peak in the WALZ/CZ following the main 566Ma peak. Ages proximal to the Ediacaran-Cambrian transition (558-544Ma) are present in all cases, whereas Cryogenian zircon ages are less abundant in the WALZ/CZ (Fig. 5C) relative to both the CIZ and the OMZ.

Rift-to-Drift (upper Cambrian-to-Lower Ordovician)

The age distribution of detrital zircons from Rift-to-Drift upper Cambrian-to-Lower Ordovician (arkoses and pelites) overlain by Armorican Quartzite (Fig. 6A), as well as the upper Cambrian-Lower Ordovician schists of the Upper Sequence of the Basal Allochthonous Units, incorporates a high percentage (~18%) of syn-rift zircon. The Neoproterozoic zircon distribution displays a prevalence of Ediacaran zircons relative to Cryogenian peaks, while both the intermediate representatives of Stenian-Tonian zircons and Eburnean-Liberian signatures resemble a mixed distribution of previous Rift-detrital zircon ages in the OMZ and the CIZ, which is typical of WAC provenance.

The Drift Stage (Lower Ordovician)

The composite age distribution of detrital zircons from Drift-Stage Lower Ordovician sandstones shows that the Neoproterozoic age distribution of detrital zircons from the Armorican Quartzite in the SW-CIZ and northern Iberian domains (N-CIZ - Castillian Zone, Spanish Central System, Eastern Iberia Cordillera, WALZ, and CZ) is once again marked by a prominent ~610Ma peak (Fig. 6B-C). However, late Cryogenian ages of ~640-670Ma acquire more importance in both Iberian domains.

There are significant differences with major paleogeographic implications between Armorican Quartzite units from the CZ, WALZ, and N-CIZ as compared with those observed in the SW-CIZ:

i) the former zones show a significant percentage of Stenian-Tonian detrital zircons, and a relative increase in Liberian-Eburnean ages;

ii) there is a significant discrepancy between these two domains as far as the percentage of (Rift-Stage) Cambrian zircons is concerned. The Cambrian zircons found in the Lower Ordovician Armorican quartzites from SW-CIZ (20%) fall within the interval of the Early (ca. 535-515Ma) and Main (ca. 515-490Ma) stages of magmatic activity in the OMZ (absent in the N-CIZ, WALZ, and CZ), representing the onset of rifting in North Gondwana (Sánchez-García *et al.*, 2019, and references therein).

Inherited Zircons

The inherited zircon ages recorded in Cambrian-to-Lower Ordovician igneous rocks also provide indirect evidence of Pan-African and Cadomian magmatism incorporated in subsequent Paleozoic magmas. A compilation of selected samples (Table 1) shows typical Cadomian ages (595-545Ma), and, once again, a remarkable peak dated at ~610Ma in the OMZ (Fig. 7A) and the CIZ (Fig. 7B). In the GTMZ, the ~610Ma peak is less significant as compared with the prominent ~590Ma peak (Fig. 7C). Stenian-Tonian zircons are scarce and older occurrences, such as Eburnean (1.9-2.2Ga) and Liberian (~2.5Ga) events, are less evident, as compared with the detrital record (Figs. 4; 5; 6).

DISCUSSION

Paleogeographic reconstruction

Detrital zircon age spectra have been used as a means of recreating the position of Iberian terranes in peri-Gondwana margin paleogeography. In general, paleogeographic

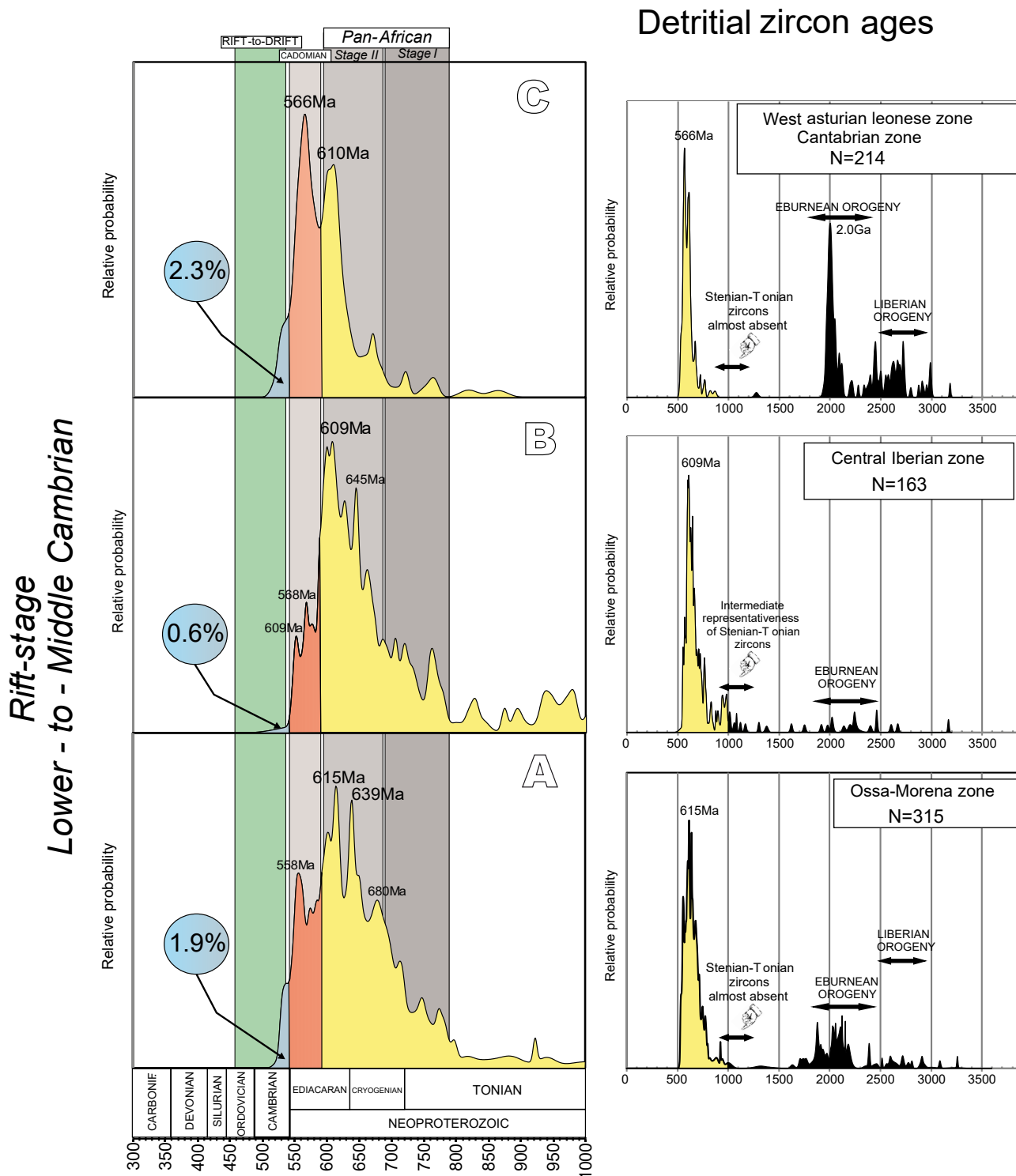


FIGURE 5. Combined probability density plots of U-Pb detrital zircon ages for the Rift Stage units from the Iberian Massif. The diagrams on the left represent the magnification of the plots on the right, displaying solely the 300-1,000Ma interval. A) OMZ; B) CIZ; C) WALZ+CZ. See Section 3 and Table 1 for zircon data sources and references.

reconstructions correctly assume small variations in the percentage of zircon age groups associated with specific previous orogenic cycles or sub-cycles. However, changes in sediment transport systems had an extremely profound

impact on the provenance of formations (Zimmermann *et al.*, 2015). Detrital zircon age spectra can reflect: i) the distance over which rocks were transported relative to their sources; ii) the extent of the reach of different types

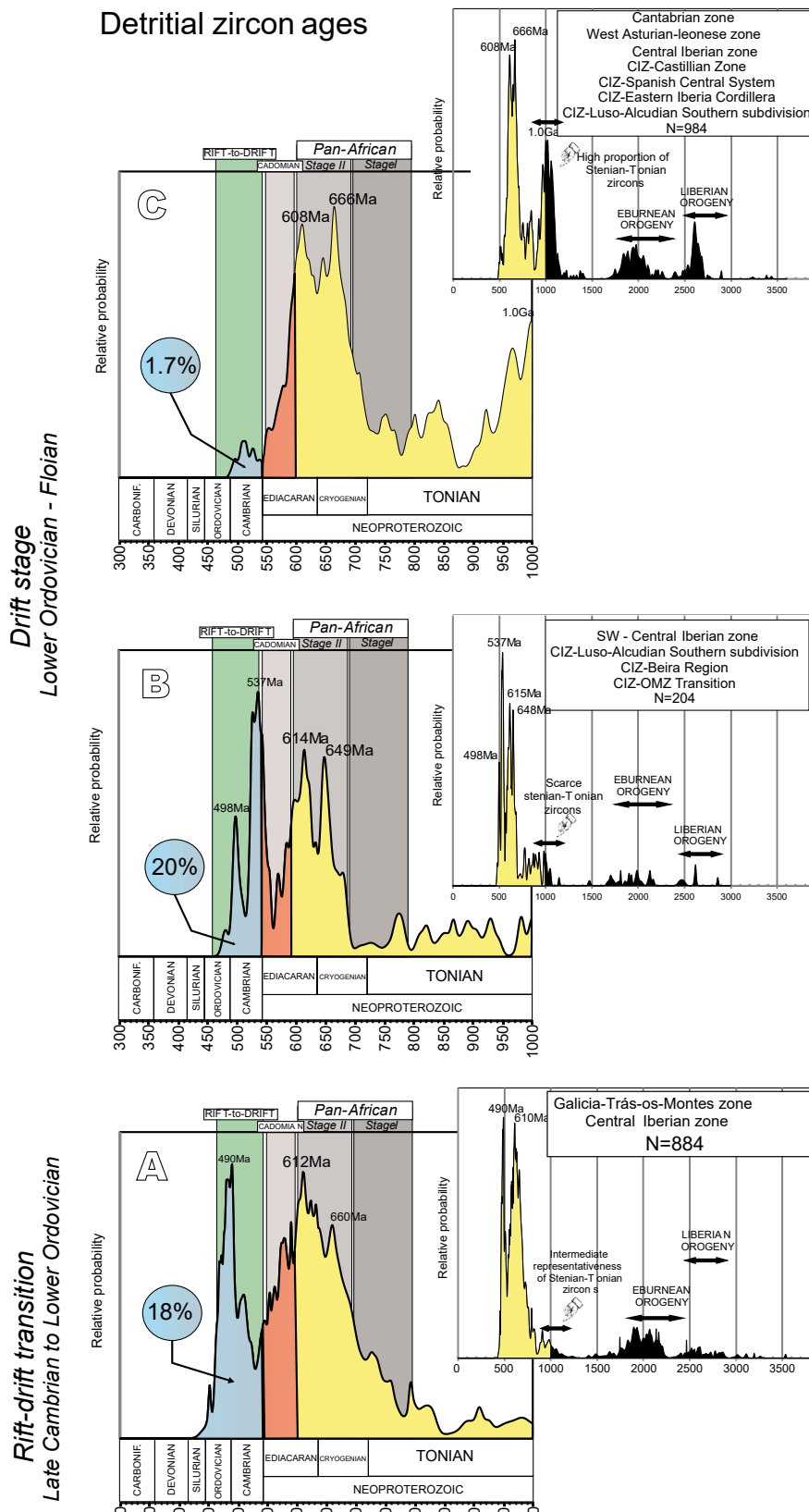


FIGURE 6. A) Combined probability density plots of U-Pb detrital zircon ages for the Rift-to-Drift Stage units from GTMZ and CIZ; B, C) Combined probability density plots of U-Pb detrital zircon ages for the Drift Stage units from SW-CIZ (B) and aggregated CZ, WALZ and N-CIZ (C). The diagrams on the left represent the magnification of the plots on the right, displaying solely the 300-1,000Ma interval. See Section 3 and Table 1 for zircon data sources and references.

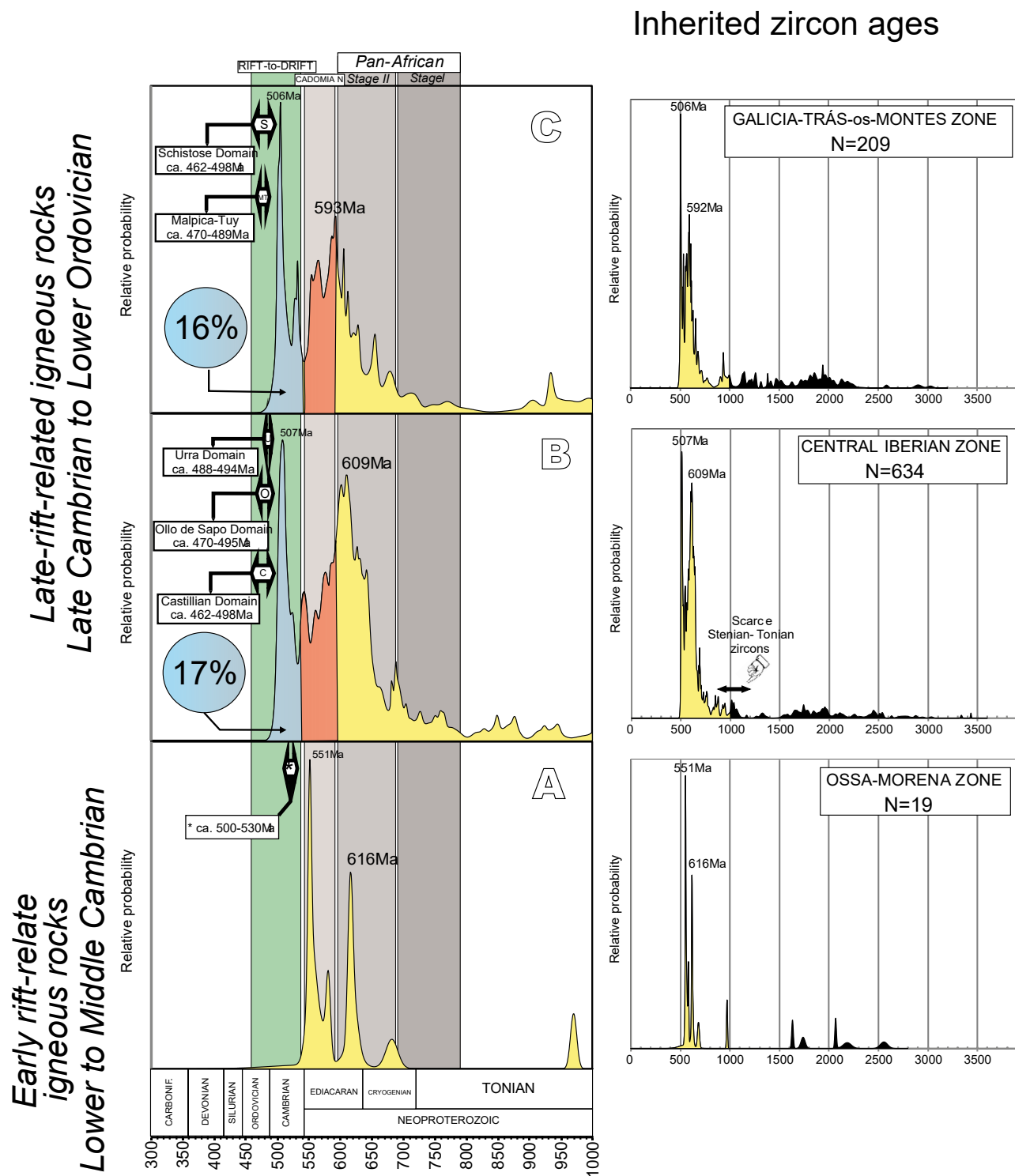


FIGURE 7. Combined probability density plots of U-Pb pre-magmatic (inherited) zircon ages obtained in igneous rocks representative of rift (OMZ) and rift-to-drift transition stages (GTMZ and CIZ). A) OMZ; B) CIZ and C) GTMZ. The diagrams on the left represent the magnification of the plots on the right, displaying solely the 300-1,000Ma interval. See Section 3 and Table 1 for zircon data sources and references. Time intervals of U-Pb crystallization ages based on syn-magmatic zircons.

of exposed bedrock; iii) variability in bedrock zircon proportions; iv) the cumulative input of various sources by erosion occurring along the transport path and v) the

differential erosion rates of source rocks (Amidon *et al.*, 2005; Dickinson, 2008; Myrow *et al.*, 2010). Attempts to interpret geodynamic and paleogeographic evidence based

on detrital and igneous zircon should focus initially on major peaks, their consistency over time, and the abrupt changes in zircon-age data as they ascend the stratigraphic column. The long-distance transport of sediments and the high degree of sediment mixing and homogenization should always be assumed as a means of dilution of the proportion of similar significant ages (Avigad *et al.*, 2003).

The similarity between the detrital-zircon age pattern of the Neoproterozoic sediments of the OMZ, SW-CIZ and CZ-WALZ suggests a degree of relative proximity between their basins by the end of the Neoproterozoic (Fig. 8A-B Transverse). The lack of Mesoproterozoic zircon is generally assumed as providing evidence for peri-West African Craton paleopositioning (Fernández-Suárez *et al.*, 2002; Gutiérrez-Alonso *et al.*, 2003; Linnemann *et al.*, 2008; Pereira *et al.*, 2008). The slight increase in the number of Stenian-Tonian zircons in the SW-CIZ and mainly in the CZ-WALZ (Fig. 4B, C) generally indicates the location of the respective sedimentary basins in different Late-Ediacaran paleogeographic scenarios. The prevailing consensus is that the Stenian-Tonian signature indicates proximity to the Arabian-Nubian Shield (ANS) (Altumi *et al.*, 2013; Avigad *et al.*, 2003; Casas and Murphy, 2018; Ferreira *et al.*, 2022; Goodge *et al.*, 2004; Keppie *et al.*, 1998; Lains Amaral *et al.*, 2022; Linnemann *et al.*, 2004; Williams *et al.*, 2012); however, a mechanism producing long-distance sediment dispersion from the ANS or other sources where late Stenian-Tonian phenomena are described as a major event could provide an alternative interpretation (Fig. 8).

The oldest Nd model ages (ca. 2.15-1.5Ga) of the Ediacaran series (autochthonous or allochthonous) sediments from the OMZ (Série Negra) provide evidence for locating their sedimentary basins in a paleoposition influenced by the input of cratonic sources of the WAC (Díez Fernández *et al.*, 2017; Fuenlabrada *et al.*, 2020) (Fig. 8). According to the same authors, the range of Sm-Nd model ages of the Ediacaran autochthonous series of the Central Iberian Zone is younger (1.25-1.33Ga), suggesting both a more easterly location, far from the influence of cratons, and a contribution from more juvenile isotopic sources (Díez Fernández *et al.*, 2017; Fuenlabrada *et al.*, 2020) (Fig. 8). Younger Depleted Mantle Model TDM ages are also linked to the Tuareg Shield included in the Trans-Sahara Belt (Figs. 8; 9) where, supposedly, younger magmatic rocks, more juvenile than in the WAC are described (see, for example, Bea *et al.*, 2010; Ennih and Liégeois, 2008). The schematic reconstructions of the Gondwanan active margin during Ediacaran-Cambrian times shown in the present paper are based on U-Pb and Sm-Nd systematics, highlighting proximity with the WAC and its transition to the Trans-Sahara Belt.

The onset of the diachronous progressive stretching of the Gondwana margin is focused on the Cadomian back-

arc thinned continental lithosphere (Eguíluz *et al.*, 2015; Linnemann *et al.*, 2008) beginning in the axial Ossa-Morena Zone (the locus of early rift-stage magmatism) progressively affecting the Central-Iberian, West Asturian-Leonese, and Cantabrian zones (Díaz-García, 2002; Díez-Montes, 2006, 2010; Martínez-Catalán *et al.*, 1992; Murphy *et al.*, 2008; Pérez-Estaún *et al.*, 1990; Sánchez-García *et al.*, 2019; Valverde-Vaquero *et al.*, 2005).

Rift-to-Drift basins dominated by normal faulting and horst-and-graben geometry are increasingly evident throughout Cadomian basinal settings, explaining the similarity between detrital zircon age patterns. In this extensional tectonic regime, large lateral transfers along Northern Gondwana margins are not required for explaining minor contamination from other sources. Under such conditions, the interpretation of Rift-to-Drift detrital age spectra also suggests Late-Ediacaran basin paleopositions.

A shift to a transtensional regime (see, for example, Dewey, 2002; Fossen and Tikoff, 1998), or the reactivation of older, pre-existing fault/shear systems by oblique shortening along shear zone boundaries, may induce the lateral transfer of syn-rift-to-drift basins and yield a statistically robust new interval of detrital zircon ages, a tectonic process proposed by some authors (Cambeses *et al.*, 2017) for assigning the CIZ-WALZ/CZ a location proximal to the ANS in the Ordovician. Our interpretation assumes that OMZ and SW-CIZ Cadomian basins evolved together (but were sufficiently separate to account for the small differences in their detrital zircon content) along the active margin of Gondwana in Ediacaran and Cambrian times (Pereira *et al.*, 2012a). As argued below, the long-distance transport of sediments is assumed as the explanation for contamination with exotic zircons.

The lower-to-middle Cambrian Rift Stage sediments of the OMZ (Fig. 5A) and the CIZ (Fig. 5B) present a remarkable degree of similarity with underlying Neoproterozoic successions, indicating that Cambrian sources remain essentially coincident: that is, both Ediacaran and Cambrian units are derived directly, by means of recycling, from sources characterized predominantly by Cadomian/Pan-African tectonothermal events. In the CZ/WALZ, however, there is an increase in the Cadomian record (Fig. 5C) which suggests a more proximal position in relation to a Cadomian arc setting (perhaps the OMZ).

Stenian-Tonian (1.2Ga to ~720Ma) zircon-forming events (of late Grenvillian Orogeny) in both the OMZ and the CIZ also point to the general maintenance of rift basins in a peri-West African craton paleoposition during early-to-mid Cambrian times. This Grenvillian record is almost absent in the WALZ/CZ, which also reinforces the WAC signature and, possibly a transtensional tectonic transfer to the west. The

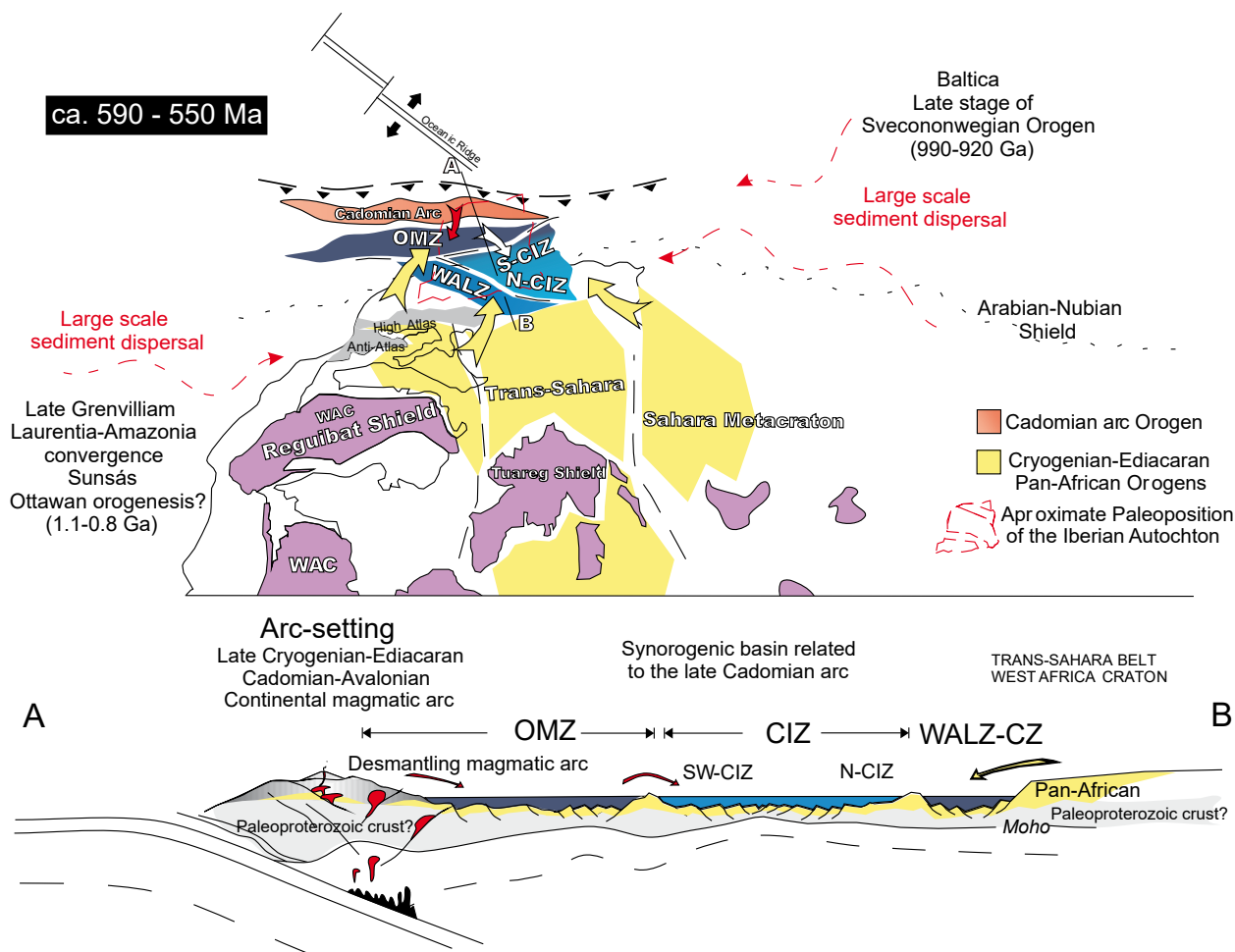


FIGURE 8. Paleogeographic reconstruction based on the U-Pb age record of Northern Gondwana blocks and Iberian terranes. Like the orogenic belts currently in the NW Africa, the Iberian crust also includes remnants of the main Pan-African igneous events (~610Ma) overlapped by Cadomian subduction-related igneous rocks and sediments deposited in a transpressive back-arc setting. (modified after Fuenlabrada *et al.*, 2020; Orejana *et al.*, 2015; Rubio-Ordóñez *et al.*, 2013; Shaw *et al.*, 2014).

much greater influence of Eburnean and Liberian sources, as compared with the OMZ and the CIZ, points to greater proximity to internal exposed parts of the WAC (Fig. 8). Gutiérrez-Alonso *et al.* (2021) regarded the change in these expressive sediment sources as an ephemeral phenomenon due to possible rift-shoulder uplift and erosion of the local Gondwanan basement. In turn, Azor *et al.* (2021) argue in favour of the eastward translation, controlled by transcurrent tectonics, of the continental ribbon represented by the OMZ from an Ediacaran position close to the WAC to an Ordovician-Devonian location close to the Sahara metacraton. Although we do not advocate the requirement for such extensive translation, we nevertheless do not exclude the possibility of considering a mechanism involving kinematically opposed lateral displacements, that is, as the OMZ moved to the east, the WALZ underwent a westward translation, explaining the scarcity of Stenian-Tonian rocks and a relative increase in the proportion of Cadomian ages.

In addition to the recycling of underlying syn-Cadomian arc sediments, an evident potential source of detrital zircons is c. 605-615Ma crystalline rocks exposed across northern Gondwana, including ages c. 555-570Ma that can be correlated with the remnants of the Cadomian magmatic arc, exposed mainly in northern sectors of the OMZ (West-African margin).

Rift-to-Drift late Cambrian-to-Early Ordovician (Furongian-to-Tremadocian) arkoses and pelites from the CIZ and the GTMZ incorporate a high percentage (~18%) of syn-Rift (ca. 535-490Ma) zircon. The presence of Furongian-Lower Ordovician zircon in CIZ Rift-to-Drift sediments indicates the partial erosion of coeval Late rift-related igneous rocks (Ollo-de-Sapo s.l.) (Sánchez-García *et al.*, 2019). The presence of zircons associated with the three igneous events (Early, Main, and Late-Rift) that together only occur in the OMZ (Sánchez-García *et al.*,

2019) points to the influence of the OMZ in feeding CIZ depocentres, suggesting, once again, the proximity of the two basins during late Cambrian-to-Early Ordovician times. Once again, the most common peak occurs at ~610Ma, as observed in older Neoproterozoic and Rift metasediments. This observation, as well as the other Late Ediacaran ages, strongly suggests the maintenance of the same Cadomian/Pan-African sources, fertile at c. 610Ma, and a paleoposition not very different from that which has been established for Neoproterozoic times. The average degree of representativeness of the Stenian-Tonian zircon population suggests that the potential main source of detrital zircons is the WAC, which seems to be proximal, while not excluding the contribution of other more distal sources by means of medium-to-long-distance sediment dispersion. Possible sources could be the Arabian-Nubian shield (Abbo *et al.*, 2020; Avigad *et al.*, 2003) and/or Amazonia/Laurentia and Baltica (Fernández-Suárez *et al.*, 2002; Slagstad *et al.*, 2017; Volkert *et al.*, 2005; Volkert and Rivers, 2019). It should be noted that small differences in the proportion of Stenian-Tonian zircons were used to transfer terranes over great distances along Northern Gondwana margins, while the suggestion of long-distance transport and sediment dispersion is indisputable (Myrow *et al.*, 2010).

Drift-stage Lower Ordovician Armorican Quartzites in the SW-CIZ and northern Iberian domains (N-CIZ, WALZ and CZ) are once again marked by a prominent ~610Ma peak (Fig. 6B-C). Late Cryogenian ages of ~640-670Ma present a greater degree of significance in the N-CIZ, WALZ, and CZ, suggesting that the Pan-African crystalline basement is proximal, and apparently surface abrasion reaches deeper. A significant decrease in the number of syn-Rift (535-490Ma) zircons in the Armorican quartzites of NW Iberia (Fig. 6C, -1.7%) as compared to the number of such zircons in the underlying Tremadocian sediments (Fig. 6A, -18%), supports the scenario of the progressive migration of the rift towards the innermost parts of the Gondwanan continent, as previously proposed by Álvaro *et al.* (2014), Díez-Montes *et al.* (2015), Martí *et al.* (2019), Cambeses *et al.* (2017) and Sánchez-García *et al.* (2019) along with the establishment of stable platform conditions on the newly-formed Gondwanan passive margin facing the Rheic Ocean (Álvarez *et al.*, 2007; Gasquet *et al.*, 2005).

There are two marked differences with major paleogeographic implications between the Armorican quartzites of the N-CIZ, WALZ, and CZ as compared with those observed in the SW-CIZ:

i) the lower-to-middle Cambrian zircons in Armorican quartzites from the SW-CIZ (20% - Fig. 6B) fall within the interval of Early- and Main-stages Rift-related magmatic activity typical of the OMZ and this suggests that the main source of detrital input is the OMZ. This provides

further evidence that the SW-CIZ sedimentary basin cannot be located substantially distally from OMZ Drift basins, although controlled by distinct basinal settings.

ii) for the first time, N-CIZ, WALZ, and CZ Floian Armorican quartzites present a statistically significant peak as regards Stenian-Tonian ages, a feature which is much less salient in the SW-CIZ. The opening of the system to ~1.0Ga sources, together with Liberian-Eburnean ages, indicates a closer degree of proximity of North-Iberia sedimentary basins to emerged parts of northern Gondwana margin close to the uplifted Stenian-Tonian Basement (the Arabian-Nubian shield and/or Baltica-Sveconorwegian orogen) far from the influence of the peri-WAC realm. Since a link is maintained between the SW-CIZ and the Ossa-Morena Realm, the slight increase in the percentage of Stenian-Tonian zircons recorded in SW-CIZ (Fig. 6B) may be explained by a more marked distal location in relation to the source.

Late rift-related Cambrian-Lower Ordovician igneous rocks from the CIZ and the GTMZ (Fig. 7B, C) are fertile in pre-magmatic zircons that remained when magma temperature was not high enough to dissolve the zircon from the source which underwent partial melting (Bea *et al.*, 2007; Castro *et al.*, 2009; Díaz-Alvarado *et al.*, 2016; Talavera, 2009). A greater degree of zircon inheritance found in igneous units (ca. 490-460Ma) exposed in the CIZ (Ollo-de-Sapo and Urra Domains) and the GTMZ, sits quite well with the Neoproterozoic peaks obtained for host Ediacaran and Cambrian clastic host rocks, with a notable peak at around 610Ma, while there are also typically Cadomian ages. A good example of this can be observed in Ollo de Sapo metavolcanic rocks (ca. 492-486Ma), where ages of around 610Ma account for about 80% of all inherited ages (Montero *et al.*, 2009b). The presence of Early- to Main-Rift (535-490Ma), Cadomian (593-550Ma) and Pan-African (609Ma) peaks in such Late Rift-related igneous rocks from the CIZ and the GTMZ, where such magmas are not apparently represented in the basement provides intriguing evidence. Abundant lower-to-middle Cambrian ages, which have not been described to date in the CIZ, were reported by Díaz-Alvarado *et al.* (2016) in Variscan granitoids of the Gredos massif (Spanish Central System batholith).

Such Cambrian inheritance could be explained by the melting of Ediacaran and Cambrian metasedimentary rocks (Melleton *et al.*, 2010). However, Cambrian zircons are almost completely absent in the rift Cambrian siliciclastic units of the CIZ and the CZ/WALZ (Fig. 5B, C), contrary to the case with Lower Ordovician magmas presenting ~17% of syn-Rift Stage-inherited zircons (peaking at 507Ma - see Fig. 7B, C). Therefore, what is the provenance of these Rift-related and Cadomian-Pan-African zircons?

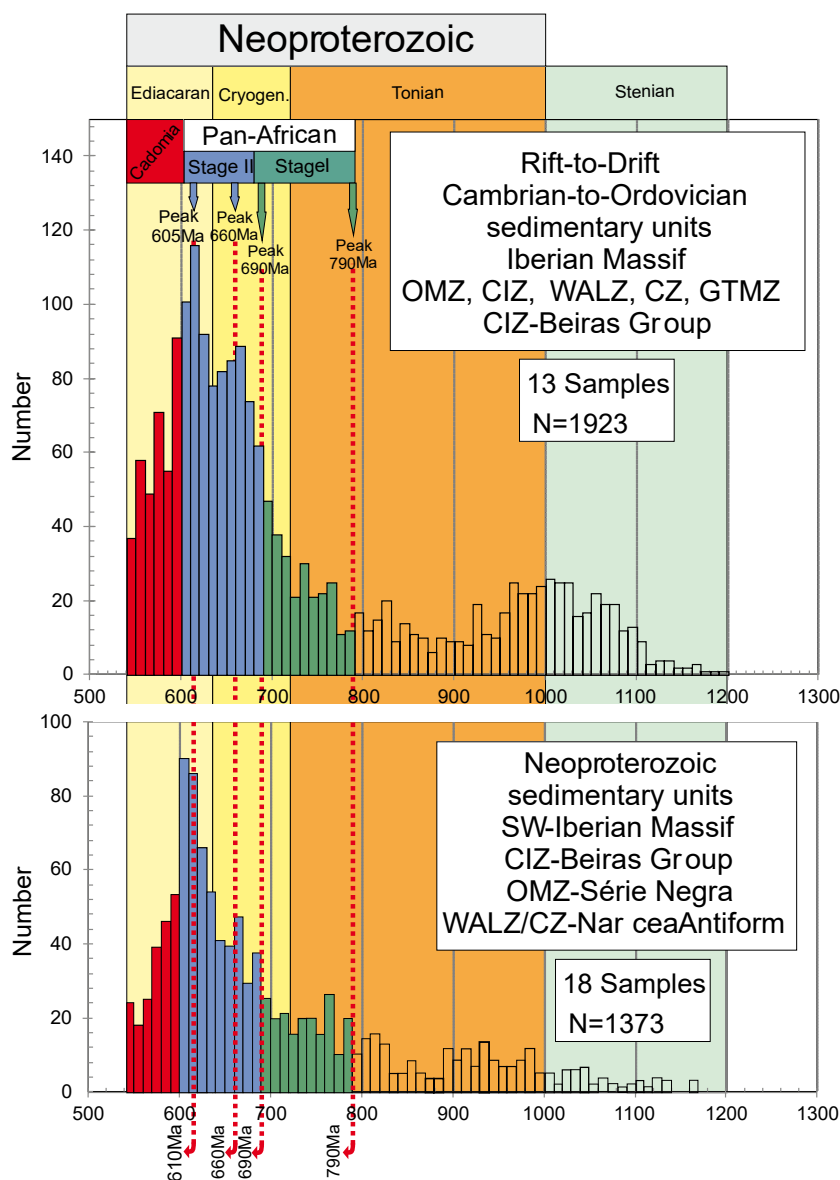


FIGURE 9. Composite age histogram data compilation for the 1,200-542Ma interval, by collating the age data of 14 Neoproterozoic Sedimentary Units from the SW-Iberian Massif (CIZ and OMZ) and 13 Rift-to-Drift sediments of the OMZ-CIZ-WALZ-CA-GTMZ.

A significant number of such zircons in felsic magmas may have originated by means of melting Early- and Main-Rift magmas entrapped in the lower crust and crust-mantle transition, as proposed by [Sánchez-García *et al.* \(2019\)](#). In Ollo de Sapo metavolcanic rocks, zircon inheritance and isotopic compositions ($^{87}\text{Sr}/^{86}\text{Sr}$) $i = 0.707\text{--}0.713$, $\epsilon\text{Nd}t = -5.8$ to -3.3 indicate that the source of such magmas is Ediacaran meta-igneous rocks or young, immature sediments derived from them. The Cambrian-Ordovician (ca. 490-460Ma) melt precipitated zircons, found in Urra Igneous rocks, presenting $\delta^{18}\text{O}_{\text{Zrn}}$ values ($>7.5\%$), 49% of the data showing $\delta^{18}\text{O}_{\text{Zrn}} > 8.5\%$ ([Chichorro *et al.*, 2015](#)), which is consistent with crustal-

metasigneous-to-crustal metasedimentary-derived magmas. So the involvement of a meta-sedimentary and meta-igneous crustal source is consistent with the markedly inherited component of these magmas, and thus the proposal that late Cambrian-Lower Ordovician magmas reproduce, to a large extent, the presence, volume, and nature not only of Cambrian magmas entrapped in the lower crust but also the existence of Cadomian and Pan-African magmas underplated in the crust-mantle transition of the CIZ and the OMZ is valid. In conclusion, it can be stated that Ediacaran (~610Ma and ~590Ma) zircons incorporated in Paleozoic magmas provide indirect evidence of Pan-African and Cadomian

magmatism, suggesting that these magmas constitute the deep basement of the Iberian Massif (Fig. 8).

~610Ma: a critical age for the consolidation of Iberia

The previous section discusses the main, systematically-occurring peak in detrital zircon age spectra at ca. 610Ma over a 120m-year stratigraphic interval (late Ediacaran to Early Ordovician) (Fig. 9). The only difference between Neoproterozoic and Cambrian-Ordovician sediments is a detectable increase in Stenian-Tonian ages (Fig. 9). Furthermore, the inherited zircon ages recorded in Cambrian-to-Lower Ordovician igneous rocks (Fig. 7) also coincide well with the Neoproterozoic peaks observed, and a significant peak always occurs at around 610Ma. Therefore, in Iberia the Pan-African record generally predominates over the Cadomian record and ~610Ma ages represent a prominent period of crustal growth, providing evidence of a critical magmatic burst.

The age spectra presented show that, even when other crustal growth periods can be differentiated on the basis of other age peaks, the 610Ma peak consistently occurs throughout the stratigraphic record. This phenomenon may be associated with very low rates of erosion, probably controlled by the intense Rift-to-Drift lithospheric stretching and subsidence that culminated in the opening of a new oceanic tract, pertaining to the Rheic Ocean in the Early Ordovician (Chichorro *et al.*, 2008; Díez-Montes *et al.*, 2010; Linnemann *et al.*, 2008; Murphy *et al.*, 2006; Nance *et al.*, 2010, 2012; Pereira *et al.*, 2007, 2012a, b; Sánchez-García *et al.*, 2003, 2008a, 2010).

Arc tectonic studies which accounted for the detrital zircon age record in sedimentary packages associated with arc dismantling and the reworking of older arcs suggest that a single protracted subduction system tends to produce prominent peaks over time that can be grouped within circumscribed magmatic flare-up periods (Pastor-Galán *et al.*, 2021). However, mechanisms such as lithospheric delamination/tectonic erosion and burial below newer arc-intruded material generally play a significant role in the progressive depletion of older magmatic pulses over time (Pastor-Galán *et al.*, 2021).

Although such mechanisms could explain the progressive depletion of 790-690Ma Cryogenic arcs, the same scenarios do not hold for the persistence of a well-preserved new ca. 610Ma “arc” which represents a Pan-African thermal climax and post-collisional magmatism, with little involvement of arc magmatism *s.s.* Therefore, here we are probably dealing with two different orogenic edifices with the Cadomian arc built “on top of” the Pan-African basement separated by angular unconformity, as described by Errami *et al.* (2020), in the Eastern Sagro inlier (Anti-Atlas, Morocco) (Fig. 8).

Igneous and Detrital zircon ages from northwestern Gondwana

Igneous zircon ages

In order to track the position of Iberian terranes in peri-Gondwana margin paleogeography, composite probability and histogram plots of zircon ages from north-western Gondwana (SMC, TSB, and AA-WAC) are presented in Figure 10. This data compilation serves two purposes:

i) igneous zircon age distributions enable an assessment of exposed crystalline basement ages in North Africa;

ii) and detrital zircon age distributions enable an assessment of proximal-to-distal erosional, recycling, and depositional systems with regard to cratonic and pericratonic areas, in relation to main internal Pan-African crystalline sources and main Cadomian-Avalonian igneous source areas.

Igneous zircon age distributions show that the most likely source of the ~610Ma age peak is the SMC (Fig. 10C). The TSB is also a possible source, although it appears to incorporate an older (~638Ma) crystalline basement (Fig. 10B). In the SMC, Late Ediacaran-Cadomian arc magmatism, although coexisting with Pan-African collisional magmatism, tends to be less significant in terms of representativeness (Fig. 10C). Another typical signature of the SMC is the 705-710Ma age peak, a phenomenon which also occurs in the case of the TSB but which is almost completely absent in the case of the Anti-Atlas (Fig. 10A).

The age distribution in the Anti-Atlas presents features that distinguish it from the SMC and the TSB. There is no record of Lower Cryogenian (~700Ma) igneous rocks, while a bimodal curve clearly separates two Ediacaran magmatic pulses (Fig. 10A). The “Pan-African” peak tends to be slightly more recently occurring (~600Ma), while the most striking characteristic is a marked peak at around 555Ma, therefore typically Cadomian in terms of age. New U-Pb zircon ages from the Eastern Sagro Massif in the Anti-Atlas of Morocco demonstrate that Pan-African magmatic systems are overlapped by Cadomian magmas. Here, the Pan-African transpressive collision of c. 600Ma was replaced by transtension caused by the onset of Cadomian subduction and arc development from c. 570Ma onward (Errami *et al.*, 2020). In the present study, we propose a similar scenario for Iberian Massif terranes (Figs. 8; 11).

Contrary to what is customarily assumed for Iberia, in the AA the two Neoproterozoic orogenic processes described above are not difficult to distinguish and never

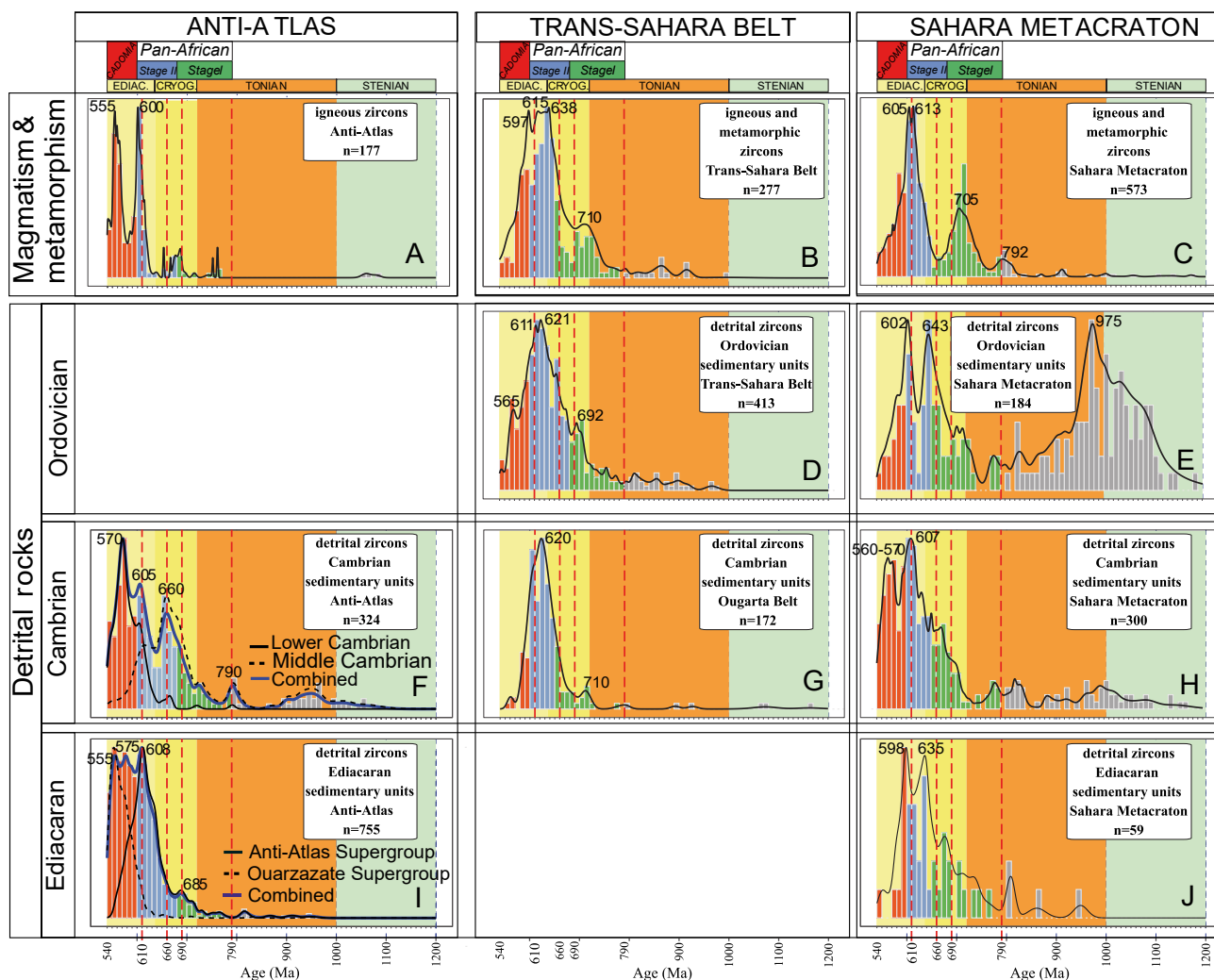


FIGURE 10. Composite probability and histogram plots of U-Pb detrital, igneous, and metamorphic zircon ages from western Northern Gondwana (SMC, TSB and AA Realm) for comparison with our data. Igneous zircon ages: Anti-Atlas (compiled by [Cambeses et al., 2017](#)). Igneous and metamorphic zircon ages: Trans-Sahara Belt and Sahara Metacraton (compiled by [Cambeses et al., 2017](#) and [Žák et al., 2021](#)). Detrital zircon ages: Anti-Atlas Cambrian ([Avigad et al., 2012](#)) and Ediacaran ([Abati et al., 2010](#); [Errami et al., 2020](#); [Karaoui et al., 2015](#)); Trans-Sahara Belt Ordovician ([Linnemann et al., 2011](#)); Ougarta Cambrian ([Wang et al., 2020](#)); Sahara Metacraton Ordovician ([Meinhold et al., 2011, 2013](#)), Cambrian ([Altumi et al., 2013](#); [Meinhold et al., 2011](#)) and Ediacaran ([Altumi et al., 2013](#); [Meinhold et al., 2011](#)). Dashed red lines indicate Iberian peaks (610, 660, 690, 790Ma) (see text).

overlapped in time or in terms of location. Based on this paradigm, in [Figure 11](#) we seek to show that the Pan-African belts extending through North Africa, close to the northern Gondwana margin, occur in an Avalonian-Cadomian arc setting.

In conclusion, Stage I Pan-African igneous rocks are redundant in the AA while Pan-African Stage II rocks are slightly younger ([Fig. 10A](#)). Cadomian igneous ages tend to increase as a proportion of ages from the SMC to the AA, where Pan-African and Cadomian peaks are distinctly separate. In the Late Ediacaran, Cadomian magmatism has a minor impact in the SMC, while it is evident at an early stage in the TSB and reaches its maximum expression

in the AA realm at 555Ma. This evidence points to a scenario of the oblique propagation of subduction along the Gondwana margin from east to west ([Fig. 11](#)). Such a scenario was proposed by [Linnemann et al. \(2008\)](#), who described a diacronic arc-continent collision caused by an oblique vector of subduction, a phenomenon which was initially evident in the east of Peri-Gondwana at c. 560-570Ma and resulted in the formation of a short-lived Cadomian retro-arc basin in the Saxo-Thuringian Zone at c. 543Ma. In contrast, more westerly in the OMZ, the Cadomian back-arc basin was longer active, at least until c. 545Ma ([Linnemann et al., 2008](#)). More westerly in the AA, a single magmatic flare-up of the Cadomian magmatic arc at c. 555Ma marks the final subduction stage prior to

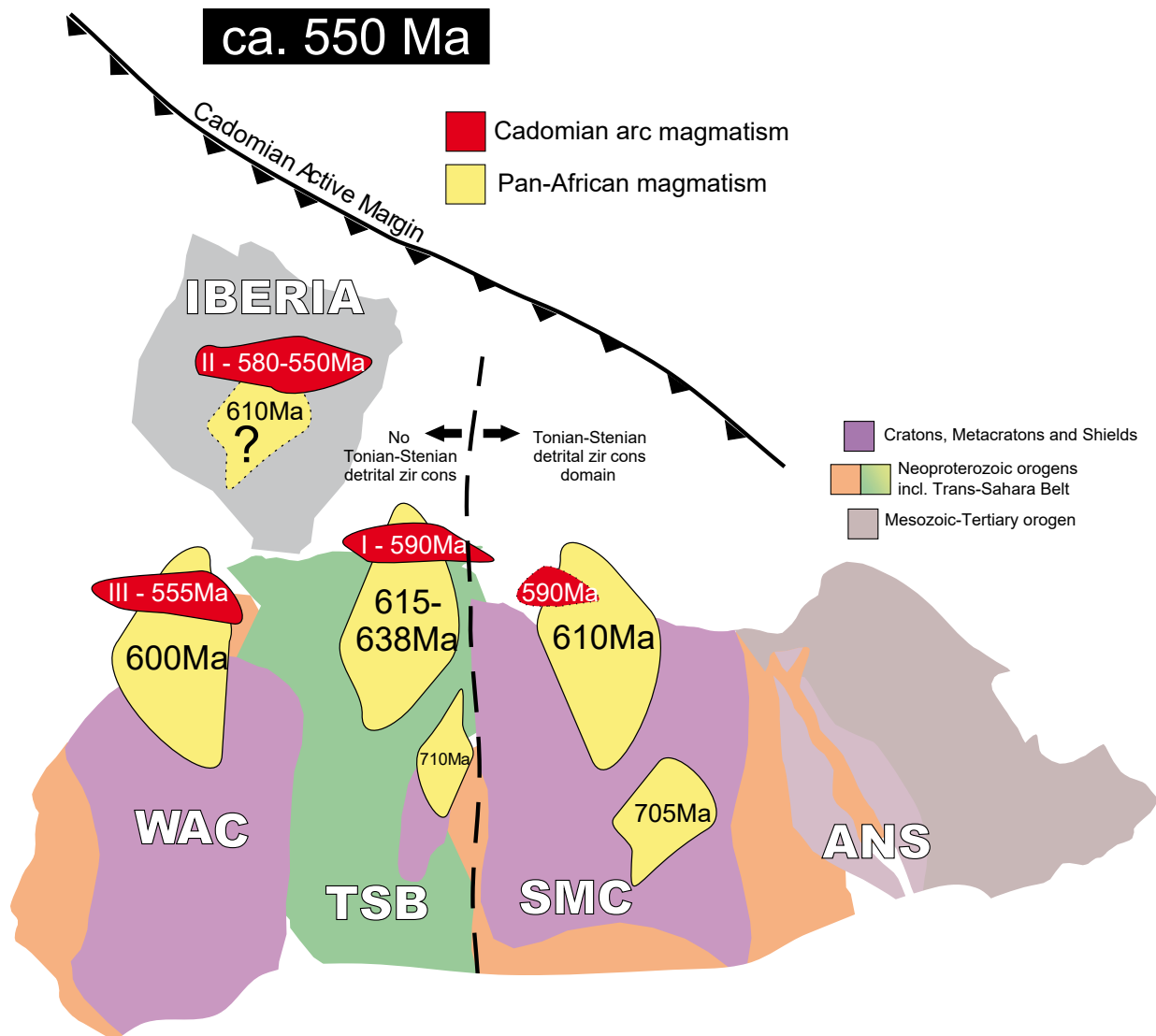


FIGURE 11. Schematic reconstruction of north-western Gondwana, proposing a relative paleoposition of the Iberian autochthonous crust during the Late Neoproterozoic, assuming that the cryptic Iberian crust is a fragment of Pan-African orogen (modified after [Cambeses *et al.*, 2017](#); [Casas and Murphy, 2018](#)).

lithospheric stretching and continental breakup triggered by oblique incision of the oceanic ridge accompanied by slab break-off of the subducted oceanic plate ([Sánchez-García *et al.*, 2003](#)). The formation of rift basins during the early to mid Cambrian (c. 530–500Ma) is thenceforth assisted by Rift-related Cambrian plutonism at c. 530Ma ([Chichorro *et al.*, 2008](#); [Pereira *et al.*, 2012b](#); [Sánchez-García *et al.*, 2003, 2010, 2013](#)).

In the northern OMZ, along the Mérida-Abrantes belt, the SN is impacted by several plutonic intrusions ([Fig. 2](#)) which are interpreted as being remnants of Ediacaran (Cadomian) arc magmatism ([Quesada, 1990a, b](#); [Quesada, 1991](#); [Schäfer, 1990](#)). Most of these are anatectic calc-alkaline granitoids/orthogneisses dated from ca. 640Ma to

540Ma (Ahillones Granite -550 ± 10 Ma, [Ordoñez-Casado, 1998](#); 585 ± 5 Ma, [Schäfer, 1990](#); Serena granite -573 ± 4 Ma, [Ordoñez-Casado, 1998](#); Endreiros granite -544.6 ± 2.5 Ma, Maiorga granite -569 ± 6 Ma, [Mateus *et al.*, 2015](#); Abrantes Anatectic granitoids -544 ± 2 Ma, [Henriques *et al.*, 2015](#); Merida diorite -577 ± 0.6 Ma, [Bandrés *et al.*, 2004](#); Mosquil tonalite -544 ± 6.5 Ma, [Oschner, 1993](#); El Cuartel amphibolite -610 ± 13 Ma; 585 ± 9 Ma; La Cardenchoa amphibolite -580 ± 8.9 Ma, [Sánchez-Lorda *et al.*, 2016](#). In the CIZ there are a few outcrops of supposedly Cadomian igneous rocks (Late Ediacaran ca. 590–545Ma) ([Crispim *et al.*, 2021](#); [Gomes and Antunes, 2011](#); [Reis *et al.*, 2010](#); [Rodríguez-Alonso *et al.*, 2004](#); [Zeck *et al.*, 2004](#)). The Allande and Navelgas units of the Narcea Antiform (WALZ-CZ transition) includes abundant interbedded

volcanic rocks and are intruded by Ediacaran granitoids whose intrusion ages range from ca. 580 to 590Ma (Rubio-Ordóñez *et al.*, 2015). There is a consensus that in Iberia nearly all supposedly Cadomian igneous rocks are Late Ediacaran (ca. 580-544Ma), most of these outcropping in the Merida-Abrantes Belt being representative of the Cadomian arc system. Some recently dated ~610Ma amphibolites (Sánchez-Lorda *et al.*, 2016) suggest that these may be representative of Pan-African events. The sample analysed is not very reliable but indicates that most Neoproterozoic igneous rocks in the OMZ fall within a wider (ca. 580-554Ma) Cadomian age interval than is the case for the Anti-Atlas, where 555Ma clearly predominates (Fig. 10). If the assumption that Cadomian igneous ages tend to be younger as we move from east to west, the OMZ crust would be located between the TSB and the Peri-WAC realm (Fig. 11).

Detrital zircon ages

Ediacaran sediments in the SMC provide evidence of self-recycling of the Pan-African crystalline basement and cannot objectively be presented as syn-Cadomian arc sediments, that is to say that the sedimentary basin was located further away from the Cadomian arc setting (Fig. 10J). In contrast, during Cambrian times the sedimentary system swiftly opens to the influence of the Cadomian Arc, incorporating 560-570Ma zircons (Fig. 10H). The ~610Ma igneous basement was still being actively eroded at this stage. As it occurs in northern Iberian Armorican Quartzite, SMC Ordovician sediments show that passive-margin sedimentary systems abruptly open to Stenian-Tonian sources (Fig. 10E). Since the peak occurring (~975Ma) is of the same order of magnitude as Cryogenian-Ediacaran peaks, Stenian-Tonian sources appear to be relatively closer (the ANS and/or Baltica), as compared with the area in which the Armorican Quartzites of Iberia were deposited. The most plausible provenance of 0.90 to 1.0Ga zircons is likely to be N-CIZ, WALZ and CZ mature Armorican Quartzites, and to a lesser degree SW-CIZ Quartzites, and CIZ Lower-to-Middle Cambrian siliciclastic units in the ANS which evolved from 0.90 to 0.53Ga during Neoproterozoic Pan-African orogeny (Avigad *et al.*, 2003, 2012, and references therein). The Baltica Late stage of Svecononwegian Orogen (990-920Ma, Slagstad *et al.*, 2017 and references therein), and to a lesser extent Late Grenvillian Laurentia-Amazonia convergence (Sunsás-Ottawan orogenesis, 1.1-0.8Ga, Volkert *et al.*, 2005 and references therein) may be the sources of these zircons (Fig. 8), involving a mechanism of long-distance sediment dispersal. A small number of mesoproterozoic zircons recently reported in middle Cambrian sandstones of the Anti-Atlas belt have also been interpreted as being associated with great distance of sediment transport (Morag *et al.*, 2011).

In contrast with the SMC during the Cambrian, the TSB seems to be mostly closed to the dismantling of the Cadomian Arc system, incorporating few zircons from such sources (Fig. 10G). In fact, in the TSB, self-erosion/recycling of the ~610Ma crystalline basement is persistent up until Ordovician times (Fig. 10D). In the Ordovician, it starts to incorporate more material from the Cadomian Arc system (Fig. 10D). Surprisingly, TSB Ordovician sediments do not incorporate zircons from Stenian-Tonian sources. The closed-system behaviour of the TSB may also be explained by this acting as a barrier to separating in paleogeographic terms the SMC from other domains (Fig. 11). As reported above (Figs. 4; 5), Ediacaran and Cambrian siliciclastic sediments from the OMZ WALZ and CZ do not present Stenian-Tonian zircons. In Ediacaran and Cambrian greywackes/arkoses of the CIZ, Stenian-Tonian zircons are present in limited numbers. This indicates that the TSB was probably a very large mountainous range that separated these domains. Eastern domains were able to receive sediments from the internal East African orogen, including the juvenile ANS, whereas other domains, located further to the east of the TSB, were protected from these sources. This is in keeping with the Himalayan-type collisional setting that led to the formation of the TSB in the late Neoproterozoic (~630-610Ma, Linnemann *et al.*, 2011, and references therein), and the dozens (if not hundreds) of Ma during which such cordillera were dismantled. The first massive entry of non-autochthonous zircons into the passive-margin sandstones of NW-Iberia (Fig. 6C) provide evidence which can be used to infer when the TSB constituted an uplifted, sufficiently eroded vast peneplain for receiving external zircons, that is, when the erosive process was already taking place, a sufficiently long interval having occurred following the building of the mountain range. In fact, this erosional process may be constrained by the introduction of such external zircon in the NW-CIZ basin, Ordovician times being the most likely candidate. It is therefore suggested that, paleogeographically speaking, Iberian Neoproterozoic and Cambrian-to-Ordovician basins were dependent to a greater extent on TSB-WAC scenarios than as we move towards the east of the TSB (Fig. 11).

The U-Pb detrital zircon age record from the Anti-Atlas realm features a curve which results from the combination of the Ouarzazate supergroup with the Anti-Atlas supergroup (Fig. 10I). The period of deposition of the Anti-Atlas Supergroup (maximum depositional age: 612-604 Ma) age distributions (Abati *et al.*, 2010; Errami *et al.*, 2020; Liegeois *et al.*, 2006) is contemporaneous with the large-scale thermal climax associated with the final orogenic event of the Pan-African Orogeny and displays a peak at ~608Ma (Fig. 10I). In turn, the Ouarzazate Group, whose maximum depositional age is ~550Ma, shows an age distribution with a peak at 555Ma (Fig. 10I) supporting a scenario of deposition in a back-arc basin formed during the Cadomian Orogeny.

However, the distribution of the Ouarzazate supergroup is remarkably different from the SN, a 610Ma age peak being absent (Fig. 10I). The only similarity between the two is the Eburnean record and the absence of Mesoproterozoic ages. The combination of the two distributions (the Ouarzazate supergroup and the AA supergroup) suggests that the AA realm is dependent on the Pan-African and Cadomian orogens, as is indicated by the igneous zircon distribution (Fig. 10A).

Contrary to that which occurs in the TSB, in the Cambrian, rift-related sedimentary basins are open to the dismantling of the late Ediacaran-Cadomian Arc, and continue to receive, either directly or by means of recycling, material from the Pan-African crystalline basement (Fig. 10F). The SN maximum depositional age interval, from c. 590 to 545Ma (Chichorro *et al.*, 2006; Linnemann *et al.*, 2008; Ochsner, 1993; Ordóñez-Casado *et al.*, 1998; Pereira *et al.*, 2008, 2012a; Schäfer *et al.*, 1993), an essentially arc-related immature turbiditic sequence (Pereira *et al.*, 2006), is similar to that which is observed in the Ouarzazate Groups, an Anti-Atlas late Ediacaran volcano-sedimentary succession (Alvaro *et al.*, 2014). Alvaro *et al.* (2014) emphasizing the similarities between the sedimentary facies of the turbidites of the Saghro Group and Bou Salda Formation and those of the Serie Negra Group, since they were deposited in synorogenic basins of the North Gondwanan active margin. However, the difference between the maximum depositional ages of the Saghro and Bou Salda units (c. 630-610Ma), as compared with the Serie Negra Group (c. 590-545Ma), suggests the diachronic development of magmatic arcs and accretion to the continental margin, which occurred initially in the Anti-Atlas and later in the Ossa-Morena Zone. Furthermore, the detrital component of the SN may be inherited from the erosion of the Saghro and Bou Salda units (Alvaro *et al.*, 2014). This interpretation does not invalidate the existence of Saghro and Bou Salda-M'Gouna equivalent units below the SN (Fig. 3); it merely suggests that SN-like turbiditic units may, in the OMZ, be much thicker and reach the stratigraphic level of the Saghro Group. This interpretation points to the possibility that these synorogenic (associated with ~610-600Ma Pan-African magmatism; Errami, *et al.*, 2020), laterally equivalent siliciclastic rocks and coeval Pan-African igneous rocks may be the main fertile zircon (~610Ma) source which underwent partial melting in Cambrian-Lower Ordovician times. In conclusion, the Ediacaran (~610Ma) zircons incorporated in Paleozoic magmas provide indirect evidence of Pan-African and Cadomian magmatism, suggesting that these magmas and synorogenic sediments are likely to constitute the cryptic stratigraphic infrastructure of the Central-Iberian Zone and the Ossa-Morena Zone.

CONCLUSIONS

This study describes an approach to determining the nature of Cadomian-Pan-African events using detrital and inherited zircon populations from Neoproterozoic-to-Lower Paleozoic (Rift-to-Drift cycle) stratigraphic records in the Iberian Massif. Studies have shown that throughout a 120Ma stratigraphic record (late Ediacaran to Early Ordovician), the main peak which systematically occurs in detrital zircon age spectra is dated at ca. 610Ma. The inherited zircon ages recorded in Cambrian to lower Ordovician igneous rocks also correspond well with Neoproterozoic peaks, with a notable peak always occurring around 610Ma.

Generally, ~610Ma is assumed as a main period representative of the Cadomian Arc, but this age is in fact a critical age of the internal domains of North Africa (for example, the Anti-Atlas in Morocco), where two main stages of Pan-African magmatic activity are described: i) an ocean opening followed by subduction-related arc magmatism (790-690Ma); ii) an ocean closure followed by arc-continent and continent-continent collisions (690-605Ma), with peaks at 660 and 615Ma.

The paleoposition of each Iberian terrane relative to internal and peri-Gondwana magmatic arcs is solidly supported by five systematic and statistically significant pieces of evidence:

- i) The similarity between the detrital zircon age pattern of the Neoproterozoic sediments of both the OMZ and the SW-CIZ suggests proximity between the two basins by the end of the Neoproterozoic.
- ii) The most fertile period in terms of magma production is the age interval of ca. 624-574Ma.
- iii) The high proportion of Eburnean sources in rift-related lower-to-middle Cambrian arkoses and sandstones from the West Asturian-Leonese Zone (WALZ) and Cantabrian Zone (CZ) clearly suggests proximity to the most internal sectors of the Gondwana paleocontinent cratons, including the West African Craton.
- iv) The relative low proportion of Mesoproterozoic zircons in the OMZ and the WALZ-CZ, suggesting proximity to the West African Craton (WAC). The opening of the system to Stenian-Tonian zircons is only statistically significant in the Early Ordovician (both in Iberia and North Africa) and probably indicates the influence of the Arabian-Nubian shield (ANS) (Altumi *et al.*, 2013; Avigad *et al.*, 2003; Casas and Murphy, 2018; Ferreira *et al.*, 2022; Goodge *et al.*, 2004; Keppie *et al.*, 1998; Lains Amaral *et al.*, 2022; Linnemann *et al.*, 2004; Williams *et al.*, 2012). In the Ediacaran and the Cambrian, the relatively

minor subpopulation of these grains may be explained by assuming the long-distance transport of sediments and the high degree of sediment mixing as a means of dilution of the proportion of these ages (Avigad *et al.*, 2003).

v) The closed-system behaviour for these ages of the Trans-Saharan Belt (TSB) (Fig. 10G, D) may also be explained by the TSB acting as a barrier paleogeographically separating the SMC from other domains. Ediacaran and Cambrian siliciclastic sediments from the OMZ, WALZ and CZ do not present Stenian-Tonian zircons. In the Ediacaran and Cambrian greywackes/arkoses of the CIZ, Stenian-Tonian ages, although present, are scarce. This indicates that the TSB was probably a huge mountainous range that separated these domains. The appearance of external zircons in the Ordovician sediments of the NW-Iberian indicates that the uplifted TSB was, at the time, a vast peneplain fomenting large drainage systems and long-distance transport feeding passive continental margins.

Ediacaran (~610Ma and 590-550Ma) zircons incorporated in Paleozoic magmas provide indirect evidence of Pan-African and Cadomian magmatism, suggesting that these magmas and synorogenic sediments are likely to constitute the cryptic stratigraphic infrastructure (or basement) of the Central-Iberian Zone and the Ossa-Morena Zone.

The present study proposes the Iberian crust as the continuation of the TSB and the WAC, matured by post-collisional syn-orogenic magmatism (Pan-African event), on which a Cadomian accretionary arc system was superimposed. In accordance with the zircon data set analysed and taking into account the evidence of North African peri-cratonic inliers, it is proposed that the main source of ~610Ma inherited zircons is likely to be the lateral chrono-equivalents of Sagro and Bou Salda-M'Gouna turbidites and coeval -610Ma Pan-African igneous rocks of the WAC and/or TSB, fertile in such zircons, emplaced at a stratigraphic level below OMZ and CIZ late-Ediacaran sediments (Figs. 3; 8).

Assuming that the Iberian crust is a fragment of Pan-African orogen, its relative paleoposition during the Late Neoproterozoic is proposed as being between the West African Craton and the Trans-Saharan Belt (Fig. 11).

ACKNOWLEDGMENTS

Martim Chichorro is grateful for the funding provided by GeoBioTec (UIDB/04035/2020). We acknowledge the support of Portuguese Fundação para a Ciência e a Tecnologia (FCT) through PhD grant SFRH/BD/138791/2018 to João Lains Amaral. This work was funded by the FCT I.P./MCTES through national

funds (PIDDAC) - UIDB/50019/2020 to Telmo M. Bento dos Santos via IDL - Instituto Dom Luiz. Geopark Naturtejo is also gratefully acknowledged for long-term logistic support. Insightful comments, suggestions and corrections provided by Josep Maria Casas and an anonymous reviewer are kindly acknowledged. Finally, the authors would like to express their gratitude to the Guest Editor.

REFERENCES

- Abati, J., Aghzer, A.M., Gerdes, A., Ennih, N., 2010. Detrital zircon ages of Neoproterozoic sequences of the Moroccan Anti-Atlas belt. *Precambrian Research*, 181(1), 115-128. DOI: <https://doi.org/https://doi.org/10.1016/j.precamres.2010.05.018>
- Abbo, A., Avigad, D., Gerdes, A., Morag, N., Vainer, S., 2020. Cadomian (ca. 550 Ma) magmatic and thermal imprint on the North Arabian-Nubian Shield (south and central Israel): New age and isotopic constrains. *Precambrian Research*, 346, 105804.
- Abdelsalam, M.G., Liégeois, J.P., Stern, R.J., 2002. The SaharanMetacraton. *Journal of African Earth Sciences*, 34, 109-117.
- Altumi, M.M., Elicki, O., Linnemann, U., Hofmann, M., Sagawe, A., Gartner, A., 2013. U-Pb LA-ICP-MS detrital zircon ages from the Cambrian of Al Qarqaf Arch, central-western Libya: Provenance of the West Gondwanan sand sea at the dawn of the Early Palaeozoic. *Journal of African Earth Sciences*, 79, 74-97.
- Álvarez, J.J., Ferretti, E., González-Gómez, C., Serpagli, E., Tortello, M.F., Vecoli, M., Vizcaino, D., 2007. A review of the Late Cambrian (Furongian) paleogeography in the western Mediterranean region, NW Gondwana. *Earth-Science Reviews*, 85, 47-81.
- Álvarez, J.J., Bellido, E., Gasquet, D., Pereira, F., Quesada, C., Sánchez-García, T., 2014. Diachronism of late Neoproterozoic-Cambrian arc-rift transition of North Gondwana: a comparison of Morocco and the Iberian Ossa-Morena Zone. *Journal of African Earth Sciences*, 98, 113-132.
- Álvarez, J.J., Sánchez-García, T., Puddu, C., Casas, J.M., Díez-Montes, A., Liesa, M., Oggiano, G., 2020a. Comparative geochemical study on Furongian-earliest Ordovician (Toledanian) and Ordovician (Sardic) felsic magmatic events in south-western Europe: underplating of hot mafic magmas linked to the opening of the Rheic Ocean. *Solid Earth*, 11, 2377-2409. DOI: <https://doi.org/10.5194/se-11-2377-2020>
- Álvarez, J.J., Casas, J.M., Quesada, C., 2020b. Reconstructing the pre-Variscan puzzle of Cambro-Ordovician basement rocks in the southwestern European margin of Gondwana. In: Murphy, J.B., Strachan, R.A., Quesada, C. (eds.). *From Pannotia to Pangaea: Neoproterozoic and Paleozoic Orogenic Cycles in the Circum-Atlantic Region*. London, The Geological Society, 503 (Special Publications), 531-562. DOI: <https://doi.org/10.1144/SP503-2020-89>

- Amidon, W.H., Burbank, D.W., Gehrels, G.E., 2005. Construction of detrital mineral populations: Insights from mixing of U-Pb zircon ages in Himalayan rivers. *Basin Research*, 17, 463-485. DOI: 10.1111/j.1365-2117.2005.00279.x
- Aramburu, C., Méndez-Bedia, I., Arbizu, M., García López, S., 2004. Zona Cantábrica. Estratigrafía. La secuencia preorogénica. In: Vera, J.A. (ed.). *Geología de España*. Madrid, Sociedad Geográfica Española and Instituto Geológico y Minero de España, 27-34.
- Avigad, D., Kolodner, K., McWilliams, M., Persing, H., Weissbrod, T., 2003. Origin of northern Gondwana Cambrian sandstone revealed by detrital zircon SHRIMP dating. *Geology*, 33, 227-230.
- Avigad, D., Gerdes, A., Morag, N., Bechstadt, T., 2012. Coupled U-Pb-Hf of detrital zircons of Cambrian sandstones from Morocco and Sardinia: Implications for provenance and Precambrian crustal evolution of North Africa. *Gondwana Research*, 21, 690-703.
- Azor, A., Martínez Poyatos, D., Accotto, C., Simancas, F., González Lodeiro, E., Talavera, C., Evans, N.J., 2021. Transcurrent displacement of the Cadomian magmatic arc. *Precambrian Research*, 361, 106251. ISSN 0301-9268. DOI: <https://doi.org/10.1016/j.precamres.2021.106251>
- Bandrés, A., Eguiluz, L., Gil-Ibarguchi, J.I., Palacios, T., 2002. Geodynamic evolution of a Cadomian arc region: the northern Ossa-Morena Zone, Iberian Massif. *Tectonophysics*, 352, 105-120.
- Bandrés, A., Eguiluz, L., Pin, C., Paquette, J.L., Ordóñez, B., Le Fèvre, B., Ortega, L.A., Gil-Ibarguchi, J.I., 2004. The northern Ossa-Morena Cadomian batholith magmatic arc origin and early evolution. *International Journal of Earth Sciences (Geologische Rundsch)*, 93, 860-885. DOI: <http://dx.doi.org/10.1007/s00531-004-0423-6>
- Bea, E., Montero, P., Talavera, C., Zinger, T., 2006. A revised Ordovician age for the Miranda do Douro orthogneiss, Portugal. *Zircon U-Pb ion-microprobe and LA-ICPMS dating*. *Geologica Acta*, 4(3), 395-401.
- Bea, E., Montero, P., González-Lodeiro, E., Talavera, C., 2007. Zircon inheritance reveals exceptionally fast crustal magma generation processes in central Iberia during the Cambro-Ordovician. *Journal of Petrology*, 48, 2327-2339. DOI: 10.1093/petrology/egm061
- Bea, E., Montero, P., Talavera, C., Abu Anbar, M., Scarrow, J., Molina, J.E., Moreno, J.A., 2010. The palaeogeographic position of Central Iberia in Gondwana during the Ordovician: evidence from zircon geochronology and Nd isotopes. *Terra Nova*, 22, 341-346.
- Bento dos Santos, T., Tassinari, C.C.G., Fonseca, P.E., 2015. Diachronic collision, slab break-off and long-term high thermal flux in the Brasiliano - Pan-African orogeny: Implications for the geodynamic evolution of the Mantiqueira Province. *Precambrian Research*, 260, 1-22.
- Black, R., Latouche, L., Liégeois, J.P., Caby, R., Bertrand, J.M., 1994. Pan-African displaced terranes in the Tuareg shield (central Sahara). *Geology*, 22, 641-644.
- Boullier, A.M., 1991. The Pan-African Trans-Saharan Belt in the Hoggar Shield (Algeria, Mali, Niger): A Review. In: Dallmeyer, R.D., Lécorché, J.P. (eds.). *The West African Orogens and Circum-Atlantic Correlatives*. The International Geoscience Programme (IGP), Project 233 Book Series, 85-105.
- Cahen, L., Snelling, N.J., Delhal, J., Vail, J.R., 1984. *The Geochronology and Evolution of Africa*. Oxford, Clarendon Press, 512pp.
- Cambeses, A., Scarrow, J.H., Montero, P., Lázaro, C., Bea, E., 2017. Paleogeography and crustal of the Ossa-Morena Zone, southwest Iberia, and the North Gondwana margin during the Cambro-Ordovician: a review of isotopic evidence. *International Geology Review*, 59(1), 94-130. DOI: <https://doi.org/10.1080/00206814.2016.1219279>
- Casas, J.M., Murphy, B., 2018. Unfolding the arc: the use of pre-orogenic constraints to assess the evolution of the Variscan belt in Western Europe. *Tectonophysics*, 736, 47-61. DOI: <https://doi.org/10.1016/j.tecto.2018.04.012>, 2018
- Castro, A., García-Casco, A., Fernández, C., Corretgé, L.G., Moreno-Ventas, I., Gerya, T., Löw, I., 2009. Ordovician ferro silicic magmas: experimental evidence for ultrahigh temperatures affecting a metagreywacke source. *Gondwana Research*, 16, 622-632.
- Chichorro, M., Pereira, M.E., Williams, I., Silva, J.B., 2006. Clues for Cadomian orogenic events in SW Iberian Massif: U/Pb-SHRIMP zircon evidence from the Serie Negra sediments (Escoural Formation, Ossa-Morena Zone, Portugal). VII Congresso Nacional de Geologia, Estremoz, Livro de resumos 1, 13-16.
- Chichorro, M., Pereira, M.E., Díaz-Azpiroz, M., Williams, I.S., Fernández, C., Pin, Ch., Silva, J.B., 2008. Cambrian ensialic rift-related magmatism in the Ossa-Morena Zone (Évora-Aracena metamorphic belt, SW Iberian Massif): Sm-Nd isotopes and SHRIMP zircon U-Th-Pb geochronology. *Tectonophysics*, 461, 91-113.
- Chichorro, M.; Solá, A.R.; Pereira, M.E.; Ferreira, A.; Sánchez-García, T.; Silva, J.B.; Williams, I.S.; Armstrong, R., 2015. Intra-crustal recycling and crustal-mantle interactions revealed by zircon oxygen isotopic composition of SW Iberia. In: LNEG (ed.). *Livro de Actas do X Congresso Ibérico de Geoquímica. XVIII Semana de Geoquímica*, 413-416. ISBN: 978-989-675-039-8
- Collins, A.S., Pisarevsky, S.A., 2005. Amalgamating eastern Gondwana: the evolution of the Circum-Indian Orogens. *Earth Science Reviews*, 71, 229-270.
- Crispim, L., Chichorro, M., Bento dos Santos, T., Linnemann, U., Hofmann, M., Neto de Carvalho, C., 2021. Geocronologia U-Pb em zircão de rochas metassedimentares e ígneas no sector Penha Garcia-Salvaterra do Extremo Aljezur, Atas do XI Congresso Jovens Investigadores em Geociências - LEG 2021, 8-11.
- Dewey, J.E., 2002. Transtension in arcs and orogens. *International Geology Review*, 44, 402-439.
- Dias da Silva, Í., Linnemann, U., Hofmann, M., González-Clavijo, E., Díez-Montes, A., Martínez Catalán, J.R., 2015. Detrital

- zircon and tectonostratigraphy of the Parautochthon under the Morais Complex (NE Portugal): implications for the Variscan accretionary history of the Iberian Massif, *Journal of the Geological Society*, 172(1), 45-61. DOI: 10.1144/jgs2014-005
- Díaz-Alvarado, J., Fernández, C., Chichorro, M., Castro, A., Pereira, M.E., 2016. Tracing the Cambro-Ordovician ferrosilicic to calc-alkaline magmatic association in Iberia by in situ U–Pb SHRIMP zircon geochronology (Gredos massif, Spanish Central System batholith). *Tectonophysics*, 681, 95-110. DOI: 10.1016/j.tecto.2016.02.031
- Díaz-García, E., 2002. Tectónica y magmatismo Ordovícicos en el área de Sanabria, Macizo Ibérico. *Geogaceta*, 32, 119-122.
- Dickinson, W.R., 2008. Impact of differential zircon fertility of granitoid basement rocks in North America on age populations of detrital zircons and implications for granite petrogenesis. *Earth and Planetary Science Letters*, 275, 80-92. DOI: 10.1016/j.epsl.2008.08.003
- Díez Fernández, R., Martínez Catalán, J.R., Gerdes, A., Abati, J., Arenas, R., Fernández-Suárez, J., 2010. U-Pb ages of detrital zircons from the Basal allochthonous units of NW Iberia: Provenance and paleoposition on the northern margin of Gondwana during the Neoproterozoic and Paleozoic. *Gondwana Research*, 18 (2-3), 385-399. doi: 10.1016/j.gr.2009.12.006
- Díez Fernández, R., Martínez Catalán, J.R., Arenas, R., Abati, J., Gerdes, A., Fernández-Suárez, J., 2012. U-Pb detrital zircon analysis of the lower allochthon of NW Iberia: Age constraints, provenance and links with the Variscan mobile belt and Gondwanan cratons. London, *Journal of the Geological Society*, 169, 655-665.
- Díez Fernández, R., Fuenlabrada, J.M., Chichorro, M., Pereira, M.E., Sánchez-Martínez, S., Silva, J.B., Arenas, R., 2017. Geochemistry and tectonostratigraphy of the basal allochthonous units of SW Iberia (Évora Massif, Portugal): keys to the reconstruction of pre-Pangean paleogeography in southern Europe. *LITHOS*, 268-271. DOI: <http://dx.doi.org/10.1016/j.lithos.2016.10.031>
- Díez-Montes, A., 2006. La geología del Dominio “Ollo de Sapo” en las comarcas de Sanabria y Terra do Bolo. PhD Thesis. Salamanca, University of Salamanca, 1-494.
- Díez-Montes, A., Martínez Catalán, J.R., Bellido Mulas, E., 2010. Role of Ollo de Sapo massive felsic volcanism of NW Iberia in the Early Ordovician dynamics of northern Gondwana. *Gondwana Research*, 17(2-3), 363-376. DOI: 10.1016/j.gr.2009.09.001
- Díez Montes, A., González Clavijo, E., Dias da Silva, Í., Gómez Barreiro, J., Martínez Catalán, J.R., Castiñeiras, P., 2015. Geochemical Evolution of Volcanism during the Upper Cambrian-Ordovician Extension of the North Gondwana Margin. In: LNEG (ed.). *Livro de Actas do X Congresso Ibérico de Geoquímica. Alfragide, XVIII Semana de Geoquímica, Laboratório Nacional de Geologia e Energia*, 54-57.
- Eguiluz, L., 1987. Petrogénesis de rocas ígneas y metamórficas en el antiformal de Burguillos-Monesterio. Macizo Ibérico Meridional. PhD Thesis. Universidad del País Vasco, 649pp.
- Eguiluz, L., Gil Ibarguchi, J.I., Abalos, B., Apraiz, A., 2000. Superposed Hercynian and Cadomian orogenic cycles in the Ossa-Morena zone and related areas of the Iberian Massif. *Geological Society of American Bulletin*, 112, 1398-1413.
- Eguiluz L., Martínez-Torres L.M., Sarrionadia E, Carracedo M., Gil-Ibarguchi J.I., 2015. The Ibero-Armorican Belt: an evolving island-arc along northern Gondwana between ca. 650 and 480 Ma. *Geologie de la France*, 2015(1), 58-59
- Ennih, N., Liégeois, J.P., 2001. The Moroccan Anti-Atlas: the West African craton passive margin with limited Pan-African activity. Implications for the northern limit of the craton. *Precambrian Research*, 112, 289-302.
- Ennih, N., Liégeois, J.P., 2008. The boundaries of the West African craton, with special reference to the basement of the Moroccan metacratonic Anti-Atlas belt. London, *The Geological Society*, 297 (Special Publications), 1-17.
- Erami, E., Linnemann, U., Hofmann, M., Gärtner, A., Zieger, J., Gärtner, J., Mende, K., El Kabouri, J., Gasquet, D., Ennih, N., 2020. From Pan-African Transpression to Cadomian Transtension at the West African Margin: New U-Pb zircon Ages from the Eastern Saghro Inlier (Anti-Atlas, Morocco). London, *The Geological Society*, 503(1, Special Publications), 209-233. DOI: <https://doi.org/10.1144/SP503-2020-105>
- Fernández-Suárez, J., Gutiérrez-Alonso, G., Jenner, G.A., Tubrett, M.N., 2000. New ideas on the Proterozoic-Early Paleozoic evolution of NW Iberia: Insights from U-Pb detrital zircon ages. *Precambrian Research*, 102, 185-206.
- Fernández-Suárez, J., Gutiérrez-Alonso, G., Jeffries, T.E., 2002. The importance of alongmargin terrane transport in northern Gondwana: insights from detrital zircon parentage in Neoproterozoic rocks from Iberia and Brittany. *Earth and Planetary Science Letters*, 204, 75-88.
- Fernández-Suárez, J., Gutiérrez-Alonso, G., Pastor-Galán, D., Hoffman, M., Murphy, J.B., Linnemann, U., 2014. The Ediacaran-Early Cambrian detrital zircon record of NW Iberia: Possible sources and paleogeographic constraints. *International Journal of Earth Sciences*, 103(5), 1335-1357. DOI: 10.1007/s00531-013-0923-3
- Ferré, E., Gleizes, G., Caby, R., 2002. Obliquely convergent tectonics and granite emplacement in the Trans-Saharan belt of Eastern Nigeria: a synthesis. *Precambrian Research*, 114(3-4), 199-219.
- Ferreira, J.A., Pereira, I., Bento dos Santos, T., Mata, J., 2022. U-Pb age constraints on the source, cooling and exhumation of a Variscan middle crust migmatite complex from the Central Iberian Zone: insights into the Variscan metamorphic evolution and Ediacaran paleogeographic implications. *Journal of the Geological Society*, 179(5), 1-20. DOI: 10.1144/jgs2021-072
- Fossen, H., Tikoff, B., 1998. Extended models of transpression and transtension, and application to tectonic settings. In: Holdsworth, R.E., Strachan, R.A., Dewey, J.F. (eds.). *Continental Transpressional and Transtensional Tectonics*. London, *The Geological Society*, 135 (Special Publications), 15-33.

- Fuenlabrada, J.M., Arenas, R., Sánchez Martínez, S., Díez Fernández, R., Pierenc, A.P., Pereira, M.F., Chichorro, M., Silva, J.B., 2020. Geochemical and isotopic (Sm-Nd) provenance of Ediacaran-Cambrian metasedimentary series from the Iberian Massif. Paleoreconstruction of the North Gondwana margin. *Earth-Science Reviews*, 201, 103079. DOI: <https://doi.org/10.1016/j.earscirev.2019.103079>
- Gasquet, D., Levresse, G., Cheilletz, A., Rachid Azizi-Samiz, M., Mouttaqi, A., 2005. Contribution to a geodynamic reconstruction of the Anti-Atlas (Morocco) during Pan-African times with the emphasis on inversion tectonics and metallogenic activity at the Precambrian-Cambrian transition. *Precambrian Research*, 140, 157-182.
- Gomes, E.M.C., Antunes, I.M.H.R., 2011. The granite of Coentral revisited: U-Pb zircon age. *Castelo Branco, Livro de Actas do VIII Congresso Ibérico de Geoquímica, XVII Semana de Geoquímica: 24-28 de setembro 2011*, 235-239.
- Goodge, J.W., Williams, I.S., Myrow, P.M., 2004. Provenance of Neoproterozoic and lower Paleozoic siliciclastic rocks of the central Ross orogen, Antarctica: Detrital record of rift- to active-margin sedimentation. *Geological Society of America Bulletin*, 116, 1253-1279.
- Gutiérrez-Alonso, G., Fernández-Suárez, J., Jeffries, T.E., Jenner, G.A., Tubrett, M.N., Cox, R., Jackson, S.E., 2003. Terrane accretion and dispersal in the northern Gondwana margin. An Early Paleozoic analogue of a long-lived active margin. *Tectonophysics*, 365, 221-232.
- Gutiérrez-Alonso, G., López-Carmona, A., Núñez-Guerrero, E., Martínez García, A., Fernández-Suárez, J., Pastor-Galán, D., Gutiérrez-Marco, J.C., Bernárdez, E., Colmenero, J.R., Hofmann, M., Linnemann, U., 2021. Neoproterozoic-Palaeozoic detrital sources in the Variscan foreland of northern Iberia: primary vs. recycled sediments. *London, The Geological Society*, 503 (Special Publications), 563-588. DOI: <https://doi.org/10.1144/SP503-2020-21>
- Hefferan, K., Soulaïmani, A., Samson, S.D., Admou, H., Inglis, J., Saquaque, A., Latifa, C., Heywood, N., 2014. A reconsideration of Pan African orogenic cycle in the Anti-Atlas Mountains, Morocco. *Journal of African Earth Sciences*, 98, 34-46.
- Henriques, S.B.A., Neiva, S.B.A., Ribeiro, M.L., Dunning, G.R., Tajčmanová, L., 2015. Evolution of a Neoproterozoic suture in the Iberian Massif, Central Portugal: New U-Pb ages of igneous and metamorphic events at the contact between the Ossa Morena Zone and Central Iberian Zone. *Lithos*, 220-223, 43-49.
- Julivert, M., Fonboté, J.M., Ribeiro, A., Conde, L.A., 1974. Mapa Tectónico de la Península Ibérica y Baleares E: 1:1.000.000 y memoria explicativa. *Publicaciones IGME*, 113.
- Karaoui B, Breitzkreuz Ch, Mahmoudi A, Youbi N, Hofmann M, Gärtner A, Linnemann U (2015) U-Pb zircon ages from volcanic and sedimentary rocks of the Ediacaran Bas Draâ inlier (Anti-Atlas Morocco): Chronostratigraphic and provenance implications. *Precambrian Research* 263: 43-58
- Keppie, J.D., Davis, D.W., Krogh, T.E., 1998. U-Pb geochronological constraints on Precambrian stratified units in the Avalon Composite Terrane of Nova Scotia, Canada: tectonic implications. *Canadian Journal of Earth Sciences*, 35, 222-236.
- Kroner, A., Stern, R., 2004. Pan-African Orogeny: *Encyclopedia of Geology*. Amsterdam, Elsevier, 1, 1-12.
- Lains Amaral, J., Solá, A.R., Bento dos Santos, T., Chichorro, M., 2022. Detrital zircon similarities and dissimilarities between the Iberian Pyrite Belt, Ossa-Morena Zone and Meguma. *Geologica Acta*, 20.16.
- Liégeois, J.P., Fekkak, A., Bruguier, O., Errami, E., Ennih, N., 2006. The Lower Ediacaran (630-610 Ma) Sagro group: an orogenic transpressive basin development during the early metacratonic evolution of the Anti-Atlas (Morocco). In: Algiers, International Geoscience Programme 485 4th Meeting, Abstr. vol. 57.
- Linnemann, U., McNaughton, N.J., Romer, R.L., Gehmlich, M., Drost, K., Tonk, C., 2004. West African provenance for Saxo-Thuringia (Bohemian Massif): Did Armorica ever leave pre-Pangean Gondwana? U/Pb-SHRIMP zircon evidence and the Nd isotopic record. *International Journal of Earth Sciences*, 93(5), 683-705.
- Linnemann, U., Pereira, F.C., Jeffries, T.E., Drost, K., Gerdes, A., 2008. The Cadomian Orogeny and the opening of the Rheic Ocean: The diachrony of geotectonic processes constrained by LA-ICP-MS U-Pb zircon dating (Ossa-Morena and Saxo-Thuringian Zones, Iberian and Bohemian Massifs). *Tectonophysics*, 461, 21-43.
- Linnemann U, Ouzegane K, Drareni A, Hofmann M, Becker S, Gärtner A and Sagawe A., 2011. Sands of West Gondwana: an archive of secular magmatism and plate interactions – a case study from the Cambro-Ordovician section of the Tassili Ouan Ahaggar (Algerian Sahara) using U–Pb–LA-ICPMS detrital zircon ages. *Lithos* 123, 188–203.
- Linnemann, U., Gerdes, A., Hofmann, M., Marko, L., 2014. The Cadomian Orogen: Neoproterozoic to Early Cambrian crustal growth and orogenic zoning along the periphery of the West African Craton - constraints from U-Pb zircon ages and Hf isotopes (Schwarzburg Antiform, Germany). *Precambrian Research*. 244, 236-278.
- Linnemann, U., Pieren Pidal, A., Hofmann, M., Drost, K., Quesada, C., Gerdes, A., Marko, L., Gärtner, A., Zieger, J., Ulrich, J., Krause, R., Horak, J., 2018. A ~565 Ma old glaciation in the Ediacaran of peri-Gondwanan West Africa. *International Journal of Earth Sciences*, 107, 885-911.
- Martí, J., Solari, L., Casas, J.M., Chichorro, M., 2019. New late Middle to early Late Ordovician U-Pb zircon ages of extension related felsic volcanic rocks in the Eastern Pyrenees (NE Iberia): tectonic implications. *Geological Magazine*, 156(10), 1783-1792. DOI: <https://doi.org/10.1017/S0016756819000116>
- Martínez Catalán, J.R., Hacer Rodríguez, M.P., Villar Alonso, P., Pérez-Estaún, A., González Lodeiro, E., 1992. Lower Paleozoic extensional tectonics in the limit between the West Asturian-Leonese and the Central Iberian Zones of the Variscan Fold-Belt in NW Spain. *Geologische Rundschau*, 81, 545-560.

- Martínez Catalán, J.R., Arenas, R., Díaz García, E, Rubio Pascual, E.J., Abati, J., Marquínez, J., 1996. Variscan exhumation of a subducted Paleozoic continental margin: The basal units of the Ordenes Complex, Galicia, NW Spain. *Tectonics*, 15, 106-121.
- Martínez Catalán, J.R., Rubio Pascual, E.J., Díez-Montes, A., Díez-Fernández, R., Gómez Bareiro, J., Dias da Silva, Í., González-Clavijo, E., Ayarza, P., Alcook, J.E., 2014. The late Variscan HT/LP metamorphic event in NW and Central Iberia: relationships to crustal thickening, extension, oroclinal development and crustal evolution. London, The Geological Society, 405 (Special Publication), 225-247.
- Mateus, A., Mata, J., Tassinari, C., Rodrigues, P., Ribeiro, A., Romão, J., Moreira, N., 2015. Conciliating U-Pb SHRIMP Zircon Dating with Zircon Saturation and Ti-in-Zircon Thermometry in the Maiorga and Endreiros Granites (Ossa-Morena Zone, Portugal). In: LNEG (eds.). Livro de Resumos do X Congresso Ibérico de Geoquímica. XVIII Semana de Geoquímica, 38-41.
- Medina, J., Sequeira, A., Silva, F., Oliveira, J.T., Rodríguez Alonso, M.D., 1998. O complexo Xisto-Grauvaquico (CXG) da região de V.N. de Poiares-Arganil-Mortagua. In: Oliveira, J.T., Dias, R.P. (eds.). Livro Guia das Excursões. Lisboa (Portugal), V Congresso Nacional de Geologia, 137-158.
- Meinhold, G., Morton, A. C., Fanning, C. M., Frei, D., Howard, J. P., Phillips, R. J., Strogon, D., and Whitham, A. G., 2011. Evidence from detrital zircons for recycling of Mesoproterozoic and Neoproterozoic crust recorded in Paleozoic and Mesozoic sandstones of southern Libya. *Earth and Planetary Science Letters*, <https://doi.org/10.1016/j.epsl.2011.09.056>
- Meiros, C.A.P. (coord.), 2020. Folha 4 da Carta Geológica de Portugal. à escala 1/200000. Lisboa, Laboratório Nacional de Energia e Geologia, 1ª Edição ISBN: 978-989-675-080-0.
- Melleton, J., Cocherie, A., Faure, M., Rossi, P., 2010. Precambrian protoliths and Early Paleozoic magmatism in the French Massif Central: U-Pb data and the North Gondwana connection in the west European Variscan belt. *Gondwana Research*, 17, 13-25.
- Montero, P., Bea, E., Corretgé, L.G., Floor, P., Whitehouse, M.J., 2009a. U-Pb ion microprobe dating and Sr and Nd isotope geology of the Galiñeiro Igneous Complex: A model for the peraluminous/peralkaline duality of the Cambro-Ordovician magmatism of Iberia. *Lithos*, 107(3), 227-238. DOI: 10.1016/j.lithos.2008.10.009
- Montero, P., Talavera, C., Bea, E., Gonzalez Lodeiro, E., Whitehouse, M.J., 2009b. Zircon Geochronology of the Ollo de Sapo Formation and the Age of the Cambrian-Ordovician Rifting in Iberia. *The Journal of Geology*, 117, 174-191.
- Morag, N., Avigad, D., Gerdes, A., Belousova, E., Harlavan, Y., 2011. Detrital zircon Hf isotopic composition indicates long-distance transport of North Gondwana Cambrian-Ordovician sandstones. *Geology* 39 (10), 955-958. <https://doi.org/10.1130/G32184.1>.
- Murphy, J.B., Gutiérrez-Alonso, G., Nance, R.D., Fernández-Suárez, J., Keppie, J.D., Quesada, C., Strachan, R.A., Dostal, J., 2006. Origin of the Rheic Ocean: Rifting along a Neoproterozoic suture? *Geology*, 34, 325-328.
- Murphy, J.B., Gutiérrez-Alonso, G., Fernández-Suárez, J., Braid, J.A., 2008. Probing crustal and mantle lithosphere origin through Ordovician volcanic rocks along the Iberian passive margin of Gondwana. *Tectonophysics*, 461, 166-180.
- Murphy, J.B., Pisarevsky, S.A., Nance, R.D., 2013. Potential geodynamic relationships between the development of peripheral orogens along the northern margin of Gondwana and the amalgamation of West Gondwana. *Mineralogy and Petrology*, 107, 635-650.
- Myrow, P.M., Hughes, N.C., Goodge, J.W., Fanning, C.M., Williams, I.S., Peng, S., Bhargava, O.N., Parcha, S.K., Pogue, K.R., 2010. Extraordinary transport and mixing of sediment across Himalayan central Gondwana during the Cambrian-Ordovician. *Geological Society of America*, 122, 1660-1670.
- Nance, R.D., Murphy, J.B., Keppie, J.D., 2002. Cordilleran model for the evolution of Avalonia. *Tectonophysics*, 352, 11-31.
- Nance, R.D., Murphy, J.B., Strachan, R.A., Keppie, J.D., Gutiérrez-Alonso, G., Fernández-Suárez, J., Quesada, C., Linnemann, U., D'Lemos, R., Pisarevsky, S.A., 2008. Neoproterozoic-early Palaeozoic tectonostratigraphy and palaeogeography of the Peri-Gondwanan terranes: Amazonian v. West African connections. In: Ennih, N., Liégeois, J.P. (eds.). *The Boundaries of the West African Craton*. London, The Geological Society, 297 (Special Publication), 345-383.
- Nance, R.D., Gutiérrez-Alonso, G., Keppie, J.D., Linnemann, U., Murphy, J.B., Quesada, C., Strachan, R.A., Woodcock, N.H., 2010. Evolution of the Rheic Ocean. *Gondwana Research*, 17, 194-222.
- Nance, R.D., Gutiérrez-Alonso, G., Keppie, J.D., Linnemann, U., Murphy, J.B., Quesada, C., Strachan, R.A., Woodcock, N.H., 2012. A brief history of the Rheic Ocean. *Geoscience Frontiers*, 3, 125-135.
- Nelson, D.R., 2001. An assessment of the determination of depositional ages for precambrian clastic sedimentary rocks by U-Pb dating of detrital zircons. *Sedimentary Geology*, 141-142, 37-60.
- Ochsner, A., 1993. U-Pb Geochronology of the Upper Proterozoic-Lower Paleozoic geodynamic evolution in the Ossa-Morena Zone (SW Ibéria): Constraints on the timing of the Cadomian orogeny. PhD dissertation. Zurich, Eidgenössische Technische Hochschule, 10.392, 430pp.
- Oliveira, J.T., Oliveira, V., Piçarra, J.M., 1991. Traços gerais da evolução tectono-estratigráfica da Zona de Ossa Morena, em Portugal: síntese crítica do estado actual dos conhecimentos. *Comunicações dos Serviços Geológicos de Portugal*, 77, 3-26.
- Ordóñez-Casado, B., 1998. Geochronological studies of the Pre-Mesozoic basement of the Iberian Massif: The Ossa Morena Zone and the Allochthonous Complexes within the Central Iberian Zone. PhD Thesis. Geology, Swiss Federal Institute of Technology, ETH Zurich, 1-207.
- Orejana, D., Martínez, E.M., Villaseca, C., Andersen, T., 2015. Ediacaran-Cambrian paleogeography and geodynamic setting

- of the Central Iberian Zone: Constraints from coupled U-Pb-Hf isotopes of detrital zircons. *Precambrian Research*, 261, 234-251.
- Pastor-Galán, D., Spencer, C.J., Furukawa, T., Tsujimori, T., 2021. Evidence for crustal removal, tectonic erosion and flare-ups from the Japanese evolving forearc sediment provenance. *Earth and Planetary Science Letters*, 564, 116893.
- Pereira MF Chichorro M, Linnemann U, Eguiluz L, Silva JB., 2006. Inherited arc signature in Ediacaran and Early Cambrian basins of the Ossa-Morena Zone (Iberian Massif, Portugal): paleogeographic link with European and North African Cadomian correlatives. *Precambrian Research*, 144, 297-315. doi:10.1016/j.precamres.2005.11.011. WOS:000235110600007
- Pereira, M.F, Silva, J.B., Chichorro, M., Moita, P., Santos, J.F, Apraiz, A., Ribeiro, C., 2007. Crustal growth and deformational processes in the northern Gondwana margin: constraints from the Évora Massif (Ossa Morena Zone, southwest Iberia, Portugal). *Geological Society of America*, 42 (Special Papers), 333-358.
- Pereira, M.F, Chichorro, M., Williams, I.S., Silva, J.B., 2008. Zircon U-Pb geochronology of paragneisses and biotite granites from the SW Iberian Massif (Portugal): evidence for a paleogeographic link between the Ossa-Morena Ediacaran basins and the West African craton. In: Ennih, N., Liégeois, J.P (eds.). *The Boundaries of the West African Craton*. London, The Geological Society, 297 (Special publications), 385-404.
- Pereira, M.F, Chichorro, M., Solá, A.R., Silva, J.B., Sánchez-García, T., Bellido, F., 2011. Tracing the Cadomian magmatism with detrital/inherited zircon ages by in-situ U-Pb SHRIMP geochronology (Ossa-Morena Zone, SW Iberian Massif). *Lithos*, 123(1-4), 204-217.
- Pereira, M.F, Linnemann, U., Hofmann, M., Chichorro, M., Solá, A.R., Medina, J., Silva, J.B., 2012a. The provenance of late Ediacaran and early Ordovician siliciclastic rocks in the Southwest Central Iberian Zone: constraints from detrital zircon data on northern Gondwana margin evolution during the late Neoproterozoic. *Precambrian Research*, 192-195, 166-189. DOI: 10.1016/j.precamres.2011.10.019
- Pereira, M.F, Solá, A.R., Chichorro, M., Lopes, L., Gerdes, A., Silva, J.B., 2012b. North-Gondwana assembly, break-up and paleogeography: U-Pb isotope evidence from detrital and igneous zircons of Ediacaran and Cambrian rocks of SW Iberia. *Gondwana Research*, 22, 866-881.
- Pérez-Estaún, A., Bastida, F, Martínez Catalán, J.R., Gutiérrez Marco, J.C., Marcos, A., Pulgar, J.A., 1990. West Asturian-Leonese Zone: Stratigraphy. In: Dallmeyer, R.D., Martínez García, E., (eds.). *Pre-Mesozoic Geology of Iberia*. Berlin, Springer-Verlag, 92-102.
- Quesada, C., 1990a. Precambrian terranes in the Iberian Variscan Foldbelt. In: Strachan, R.A., Taylor, G.K. (eds.). *Avalonian and Cadomian geology of the North Atlantic*. New York, Blackie, 109-133.
- Quesada, C., 1990b. Precambrian successions in SW Iberia: their relationship to "Cadomian" orogenic events. In: D'Lemos, R.S., Strachan, R.A., Topley, C.G. (eds.). *The Cadomian Orogeny*. Geological Society Special Publication, 51, 353-362.
- Quesada, C., Munhá, J., 1990. Metamorphism in the Ossa-Morena Zone. In: Dallmeyer, R.D., Martínez García, E. (eds.). *Pre-Mesozoic Geology of Iberia*. Berlin, Springer-Verlag, 314-320.
- Quesada, C., 1991. Geological constraints on the Paleozoic tectonic evolution of tectonostratigraphic terranes in the Iberian Massif. *Tectonophysics*, 185, 225-245.
- Quesada, C., Bellido, F, Dallmeyer, R.D., Gil Ibarguchi, I., Oliveira, J.T., Pérez Estaun, A., Ribeiro, A., Robardet, M., Silva, J.B., 1991. Terranes within the Iberian Massif: correlations with West African sequences. In: Dallmeyer, R.D., Lecorché, J.P (eds.). *The West African Orogens and Circum-Atlantic Correlations*. Berlin, Springer, 251-277.
- Reis, A.I.M., Silva, M.M.V.G., Antunes, I.M.H.R., 2010. The Precambrian/Lower Cambrian pluton from Vila Nova (Central Portugal). *Estudios Geológicos*, 66(1), 51-56.
- Ribeiro, A., Quesada, C., Dallmeyer, R.D., 1990a. Geodynamic evolution of the Iberian Massif. In: Dallmeyer R.D., Martínez García, E. (eds.). *Pre-Mesozoic Geology of Iberia*. Berlin, Springer, 399-410.
- Ribeiro, A., Pereira, E., Dias, R., 1990b. Allochthonous sequences - Structure in the Northwest of the Iberian Peninsula. In: Dallmeyer, R.D., Martínez García, E. (eds.). *Pre-Mesozoic Geology of Iberia*. Berlin-Heidelberg, Springer, 222-236.
- Rino, S., Kon, Y., Sato, W., Maruyama, S., Santosh, M., Zhao, D., 2008. The Grenvillian and Pan-African orogens: world's largest orogenies through geologic time, and their implications on the origin of superplume. *Gondwana Research*, 14, 51-72.
- Robardet, M., Gutiérrez-Marco, J.C., 1990a. Ossa-Morena Zone, Stratigraphy, Passive Margin Phase (Ordovician - Silurian - Devonian). In: Dallmeyer, R.D., Martínez García, E. (eds.). *Pre-Mesozoic Geology of Iberia*. Berlin, Springer-Verlag, 267-272.
- Robardet, M., Gutiérrez-Marco, J.C., 1990b. Sedimentary and faunal domains in the Iberian Peninsula during Lower Paleozoic times. In: Dallmeyer, R.D., Martínez García, E. (eds.). *Pre-Mesozoic Geology of Iberia*. Berlin, Springer-Verlag, 383-395.
- Robardet, M., 2002. Alternative approach to the Variscan Belt in southwestern Europe: Preorogenic paleobiogeographical constraints. In: Martínez Catalán, J.R., Hatcher, R.D., Arenas, R., Díaz García, F (eds.). *Variscan-Appalachian dynamics: The building of the late Paleozoic basement*. Geological Society of America, 364 (Special Paper), 1-15.
- Robardet, M., 2003. The Armorica 'microplate': fact or fiction? Critical review of the concept and contradictory palaeobiogeographical data. *Palaeogeography Palaeoclimatology Palaeoecology*, 195, 125-148.
- Rodríguez Alonso, M.D., Peinado, M., López-Plaza, M., Franco, P., Carnicero, A., Gonzalo, J.C., 2004a. Neoproterozoic-Cambrian synsedimentary magmatism in the Central Iberian Zone (Spain): geology, petrology and geodynamic significance. *International Journal of Earth Sciences*, 93, 897-920.

- Rubio-Ordóñez, A., Gutiérrez-Alonso, G., Valverde-Vaquero, P., Cuesta, A., Gallastegui, G., Gerdes, A., Cárdenes, V., 2015. Arc-related Ediacaran magmatism along the northern margin of Gondwana: Geochronology and isotopic geochemistry from northern Iberia. *Gondwana Research*, 27, 217-227.
- Sánchez-García, T., Bellido, F., Quesada, C., 2003. Geodynamic setting and geochemical signatures of Cambrian-Ordovician rift-related igneous rocks (Ossa-Morena Zone, SW Iberia). *Tectonophysics*, 365, 233-255.
- Sánchez-García, T., Quesada, C., Bellido, F., Dunning, G., González de Tánago, J., 2008. Two-step magma flooding of the upper crust during rifting: The Early Paleozoic of the Ossa-Morena Zone (SW Iberia). *Tectonophysics*, 461, 72-90.
- Sánchez-García, T., Bellido, F., Pereira, M.F., Chichorro, M., Quesada, C., Pin, Ch., Silva, J.B., 2010. Rift-related volcanism predating the birth of the Rheic Ocean (Ossa-Morena zone, SW Iberia). *Gondwana Research*, 17, 392-407.
- Sánchez-García T, Pereira MF, Bellido F, Chichorro M, Silva JB, Valverde-Vaquero P, Pin Ch, Solá AR., 2013. Early Cambrian granitoids of the Ossa-Morena Zone (SW Iberia) in the transition from a convergent setting to intra-continental rifting in the Northern margin of Gondwana. *International Journal of Earth Sciences (Geologische Rundschau)*, 103, 1203-1218.
- Sánchez-García, T., Chichorro, M., Solá, A.R., Álvaro, J.J., Díez-Montes, A., Bellido, F., Ribeiro, M.L., Quesada, C., Lopes, J.C., Dias da Silva, Í., González-Clavijo, E., Gómez Barreiro, J., López-Carmona, A., 2019. The Cambrian-Early Ordovician rift stage in the Gondwanan units of the Iberian Massif. Chapter 2. In: Quesada, C., Oliveira, J.T. (eds.). *The Geology of Iberia: A Geodynamic Approach, Volume 2 - The Variscan Cycle*. Regional Geology Reviews, Springer, 67pp. DOI: 10.1007/978-3-030-10519-8
- Sánchez-Lorda, M.E., Ábalos, B., García de Madinabeitia, S., Eguíluz, L., Gil Ibarguchi, J.I., Paquette, J.L., 2016. Radiometric discrimination of pre-Variscan amphibolites in the Ediacaran Serie Negra (Ossa-Morena Zone, SW Iberia). *Tectonophysics*, 681, 31-46.
- Schäfer, H.J., 1990. Geochronological investigations in the Ossa-Morena Zone, SW Spain. Ph.D. Thesis. Zurich, Swiss Federal Institute of Technology, 153pp.
- Schäfer, H.J., Gebauer, D., Nagler, T.F., Eguíluz, L. 1993. Conventional and ion microprobe U-Pb dating of detrital zircons of the Tentudía Group (Serie Negra, SW Spain): implications for zircon systematics, stratigraphy, tectonics and the Precambrian/Cambrian boundary. *Contributions to Mineralogy and Petrology*, 113: 289-299.
- Shaw, J., Gutiérrez-Alonso, G., Johnston, S.T., Pastor-Galán, D., 2014. Provenance variability along the Early Ordovician north Gondwana margin: paleogeographic and tectonic implications of U-Pb detrital zircon ages from the Armorican Quartzite of the Iberian Variscan belt. *Geological Society of America Bulletin*, 125(5-6), 702-719. DOI: 10.1130/B30935.1
- Simancas, J.F., Expósito, I., Azor, A., Martínez Poyatos, D., González Lodeiro, E., 2004. From the Cadomian orogenesis to the early Paleozoic Variscan rifting in Southwest Iberia. *Journal Iberian Geology*, 30, 53-71.
- Slagstad, T., Roberts, N.M.W., Kulakov, E., 2017. Linking orogenesis across a supercontinent; the Grenvillian and Sveconorwegian margins on Rodinia. *Gondwana Research*, 44, 109-115.
- Solá, A.R., 2007. *Relações Petrogeoquímicas dos Maciços Graníticos do NE Alentejano*. PhD Thesis. Coimbra, Universidade de Coimbra, 1-405.
- Solá, A.R., Pereira, M.F., Williams, I.S., Ribeiro, M.L., Neiva, A.M.R., Montero, P., Bea, E., Zinger, T., 2008. New insights from U-Pb zircon dating of Early Ordovician magmatism on the northern Gondwana margin: the Urra Formation (SW Iberian Massif, Portugal). *Tectonophysics*, 461, 114-129.
- Solá, A.R., Chichorro, M., Álvaro, J.J., Díez-Montes, A., Sánchez-García, T., Quesada, C., 2017. Provenance of Ordovician Armorican quartzite in Iberia: the linkage with West African Craton. In: Álvaro, J.J., Casas, J.M., Clausen, S. (eds.). *Ordovician Geodynamics: The Sardinian Phase in the Pyrenees, Mouthoumet and Montagne Noire massifs*. *Géologie de la France*, 1(4), 31. Last accessed: November 2022 Website: http://geolfrance.brgm.fr/sites/default/files/upload/documents/g4-1-2017_1.pdf
- Sousa, M.B., Sequeira, A.J.D., 1993. O limite Precâmbrico - Câmbrio na Zona Centro Ibérica, em Portugal. XII Reunião de Geologia do Oeste Peninsular, I, 17-28.
- Talavera, C., Bea, E., Montero, P.G., Whitehouse, M., 2008. A revised Ordovician age for the Sisargas orthogneiss, Galicia (Spain). *Zircon U-Pb ion-microprobe and LA-ICPMS dating*. *Geologica Acta*, 6(4), 313-317.
- Talavera, C., 2009. *Pre-Variscan Magmatism of the Central Iberian Zone: Chemical and Isotope Composition, Geochronology and Geodynamic Significance*. Ph.D. Thesis. Granada, University of Granada, 252pp.
- Talavera, C., Montero, P., Martínez Poyatos, D., Williams, I.S., 2012. Ediacaran to Lower Ordovician age for rocks ascribed to the Schist-Graywacke Complex (Iberian Massif, Spain): Evidence from detrital zircon SHRIMP U-Pb geochronology. *Gondwana Research*, 22, 928-942.
- Talavera, C., Montero, P., Bea, E., González-Lodeiro, E., Whitehouse, M., 2013. U-Pb Zircon geochronology of the Cambrian-Ordovician metagranites and metavolcanic rocks of central and NW Iberia. *International Journal of Earth Sciences (Geologische Rundschau)*, 102, 1-23.
- Tikoff, B., Fossen, H., 1993. Simultaneous pure and simple shear: the unifying deformation matrix. *Tectonophysics*, 217, 267-283.
- Valverde Vaquero, P., Marcos, A., Farias, P., Gallastegui, G., 2005. U-Pb dating of Ordovician felsic volcanism in the schistose Domain of the Galicia-Trás-os-Montes Zone near Cabo Ortegal (NW Spain). *Geologica Acta*, 3(1), 27-37. DOI: 10.1344/105.000001412
- Villaseca, C., Merino Martínez, E., Orejana, D., Andersen, T., Belousova, E., 2016. Zircon Hf signatures from granitic orthogneisses of the Spanish Central System: Significance

- and sources of the Cambrian-Ordovician magmatism in the Iberian Variscan Belt. *Gondwana Research*, 34, 60-83.
- Volkert, R.A., Zartman, R.E., Moore, P.B., 2005. U-Pb zircon geochronology of Mesoproterozoic postorogenic rocks and implications for post-Ottawan magmatism and metallogenesis, New Jersey Highlands and contiguous areas, USA. *Precambrian Research*, 139, 1-19.
- Volkert, R.A., Rivers, T., 2019. Protracted late- to post-Ottawan cooling and exhumation of the mid crust in a Grenvillian inlier, central Appalachians, USA - New data and a new hypothesis. *Precambrian Research*, 331, 105355.
- Wang, Q., Spencer, C. J., Hamdidouche, R., Zhao, G., Evans, N. J., and McDonald, B. J., 2020. Detrital zircon U–Pb–Hf data from Cambrian sandstones of the Ougarta Mountains Algeria: Implication for palaeoenvironment. *Geological Journal*, 55(12), 7760-7774. <https://doi.org/https://doi.org/10.1002/gj.3899>
- Williams, I.S., Fiannacca, P., Cirrincione, R., Pezzino, A., 2012. Peri-Gondwanan origin and early geodynamic history of NE Sicily: a zircon tale from the basement of the Peloritani Mountains. *Gondwana Research*, 22, 855-865.
- Zeck, H.P., Wingate, M.T.D., Pooley, G.D., Ugidos, J.M., 2004. A Sequence of Pan-African and Hercynian Events Recorded in Zircons from an Orthogneiss from the Hercynian Belt of Western Central Iberia—an Ion Microprobe U-Pb Study. *Journal of Petrology*, 45(8), 1613-1629. DOI: 10.1093/petrology/egh026
- Zimmermann, U., Andersen, T., Vadla Madland, M., Skipenes Larsen, I., 2015. The role of U-Pb ages of detrital zircons in sedimentology—An alarming case study for the impact of sampling for provenance interpretation. *Sedimentary Geology*, 320, 38-50. DOI: <http://dx.doi.org/10.1016/j.sedgeo.2015.02.006>

**Manuscript received January 2022;
revision accepted September 2022;
published Online November 2022.**