GeoScienceWorld
Lithosphere
Volume 2022, Article ID 6187518, 24 pages
https://doi.org/10.2113/2022/6187518

Lithosphere

Research Article

Reorganization of Northern Peri-Gondwanan Terranes at Cambrian–Ordovician Times: Insights from the Detrital Zircon Record of the Ossa-Morena Zone (SW Iberian Massif)

Cristina Accotto,[1] **Antonio Azor**,[1] **David Martínez Poyatos**,[1] **Antonio Pedrera**,[2] **and Francisco González Lodeiro**[1]

[1]*Departamento de Geodinámica, Universidad de Granada, Granada 18071, Spain*
[2]*Instituto Geológico y Minero de España, Sevilla 41013, Spain*

Correspondence should be addressed to Antonio Azor; azor@ugr.es

Received 2 August 2022; Revised 2 November 2022; Accepted 22 November 2022; Published 19 December 2022

Academic Editor: Mahmoud Hassan

The Ossa-Morena Zone constitutes a fringe Gondwana-related terrane all along the Paleozoic. This continental block has been classically interpreted as being attached to a portion of the northern Gondwanan margin located close to the West African Craton. We report here the results of U-Pb dating on detrital zircon grains from 15 metasedimentary rocks collected in two well-exposed and well-dated Cambrian sections (Córdoba and Zafra) of the Ossa-Morena Zone. The studied samples show a dominant late Tonian-Ediacaran population peaked at c. 600 Ma. Secondary populations are Rhyacian-early Orosirian and late Orosirian-Statherian in age, with maxima at c. 2.1 and 1.9 Ga. Minor detrital zircon populations are Mesoarchean-early Siderian in age, with peaks between c. 3.05 and 2.45 Ga. Most of the studied samples lack a Stenian-early Tonian population, except for two of them with a minor peak at c. 1 Ga. Our results corroborate previous studies that locate the Ossa-Morena Zone close to the West African Craton and/or the Tuareg Shield (i.e., in a western position with respect to other Variscan zones of the Iberian Massif) at the onset of the rifting stage that opened the Rheic Ocean. Nevertheless, the absence of a significant Stenian-early Tonian population in the Cambrian Ossa-Morena rocks contrasts with the reported results on middle Ordovician-Lower Devonian rocks of this zone, which systematically contain an important population with a peak at c. 1 Ga. We relate this change to the latest Ediacaran-early Ordovician paleogeographic/paleotectonic evolution of the Ossa-Morena Zone, which might have recorded a significant eastward displacement, together with a reorganization of the drainage systems. Thus, the vanishing stages of the Cadomian orogeny could have translated eastward the Ossa-Morena Zone terrane at latest Ediacaran-earliest Cambrian time due to change in plate kinematics from subduction to right-lateral shearing. This translation would have shifted the Ossa-Morena Zone from an Ediacaran location close to the West African Craton to a Cambrian position close to the Tuareg Shield. Finally, the rift-to-drift transition occurred at late Cambrian-early Ordovician time along the northern Gondwanan margin would have reorganized the drainage systems, facilitating sediment supply from an eastern source with abundant Stenian-early Tonian detrital zircon grains, probably the Saharan Metacraton.

1. Introduction

Orogens often result from the amalgamation of a number of far-traveled continental pieces with different origin and age (e.g., [1]). Identifying and unraveling the evolution of each one of these pieces are usually difficult because a combination of diverse geological, geochronological, and paleomagnetic data is required. Nevertheless, a good characterization of the various terranes accreted in mountain belts is the key to elaborate reliable paleotectonic and paleogeographic reconstructions. In this regard, the number and width of oceanic domains opened at preorogenic times are on many occasions a matter of debate, which leads to contradictory plate reconstructions, especially for pre-Mesozoic times (e.g., [2–5]).

The multidisciplinary approach required to address paleogeographic/paleotectonic reconstructions has incorporated the systematic study of detrital zircon populations as a valuable tool to establish sediment provenance from different primary and/or recycled sources (e.g., [6, 7]). Despite a good number of limitations (e.g., [8–14]), detrital zircon studies have contributed to a better understanding of the preorogenic architecture of Paleozoic orogens (e.g., [15–18]). This is the case of the Late Paleozoic Variscan orogen in Western and Central Europe, in which the paleogeographic attribution of the different zones is mostly based on the comparison of detrital zircon spectra with the putative cratonic source areas (e.g., [19–23]). All the studies on the Variscan orogen support the presence of Gondwana-derived and Avalonia-derived terranes, which would have been separated by a large ocean, namely, the Rheic Ocean, opened at late Cambrian-early Ordovician time (e.g., [24–27]). The intervention of other lesser-scale oceans separating any Gondwanan-derived ribbon continental pieces is still under discussion (e.g., [2, 5]). With or without the intervention of narrow oceanic realms, there are marked differences in the detrital zircon record between Gondwanan-derived zones; some of them systematically contain a 1 Ga population interpreted to be sourced from the Arabian-Nubian Shield and/or the Saharan Metacraton, while others lack this 1 Ga population and have been interpreted as attached to the West African Craton (WAC) during the preorogenic evolution (e.g., [19, 21, 26, 28–31]).

Among the Variscan zones in the Iberian Massif (Figure 1(a)), most of them (Cantabrian Zone, West Asturian-Leonese Zone, and Central Iberian Zone) show detrital zircon spectra akin to Paleozoic rocks directly overlying the Saharan Metacraton [15, 16, 32]. In the southern sector of the Iberian Massif, some of the formations of the South Portuguese Zone (SPZ) show Avalonian affinity [17, 33], thus favoring the location of the Rheic suture along the contact between this zone and the Ossa-Morena Zone (OMZ) [34]. The latter is generally considered as a Gondwana-related continental piece, with or without a narrow Paleozoic oceanic realm in between it and the Central Iberian Zone (CIZ) (e.g., [35, 36]). Furthermore, the OMZ would have been located close to the WAC all along the pre-Variscan evolution, based on the lack of a 1 Ga detrital zircon population [26, 28, 30, 37]. Nevertheless, we recently reported the presence of a noticeable (c. 20%) 1 Ga detrital zircon population in Ordovician and Devonian rocks of the OMZ, thus proposing an eastward displacement of the OMZ (and counterparts through the Cantabrian Arc) related to the vanishing stages of the Cadomian orogeny [23]. In this paper, we present a wealth of U-Pb detrital zircon ages from the complete and very well-dated Cambrian sequence of the OMZ. The results serve to elaborate on the paleogeographic reorganization of northern peri-Gondwanan terranes during the Cambrian-Ordovician transition.

2. Geological Setting

The Variscan belt constitutes a curved orogen that extends from Central and Western Europe to Northwestern Africa. This orogen resulted from the Devonian-Permian collision between Gondwana and Laurussia, with a number of peri-Gondwanan terranes also amalgamated in-between the two main plates (e.g., [5, 38–40]). Among the different transects of the Variscan belt, the Iberian Massif (central and western part of the Iberian Peninsula) is the most complete one and has been traditionally divided into two sectors: (i) a northern one with east vergence towards the Gondwanan foreland and (ii) a southern one with dominant SW vergence towards the Laurussian foreland. The northern sector is made up of three zones: Cantabrian, West Asturian-Leonese, and part of the CIZ [36], which appear overthrusted by the allochthonous ophiolite-bearing Galicia-Tras-os-Montes Zone (GTMZ), interpreted as an unrooted orogenic suture (Figure 1(a)) (e.g., [40]). The southern sector includes part of the CIZ, the OMZ, and the SPZ, with the contacts between the three zones representing orogenic sutures (Figure 1(a)) (e.g., [36, 41]).

The SPZ is considered to be part of the deformed Avalonian foreland, together with other terranes exposed in Southern England, Belgium, and Germany, in the so-called Rheno-Hercynian Zone (e.g., [39, 42–44]). As for the OMZ, it is usually correlated with the Saxo-Thuringian Zone (STZ) cropping out in northernmost Brittany, Belgium, Germany, and Czech Republic (e.g., [40] and references therein).

The OMZ-SPZ contact is usually considered to represent the Rheic Ocean suture [36, 45–49], although it rather appears as a cryptic suture [34] since the MORB-featured amphibolitic unit exposed along this boundary yielded Carboniferous ages [50]. To the north, the OMZ is separated from the CIZ by the Badajoz-Córdoba Shear Zone (BCSZ; Figure 1(b)) [36, 41, 51–55]. The interpretation of this tectonic boundary is controversial, with some authors considering it as a Variscan intracontinental shear zone (e.g., [35, 56–58]), others interpreting it as the root zone of the allochthonous units exposed in NW Iberia (e.g., [42, 59]), and others still interpreting it as being unrooted and part of the ophiolitic units of the GTMZ [60, 61].

2.1. Stratigraphy of the Ossa-Morena Zone. The OMZ has specific stratigraphic and magmatic features that have been the base with which to decipher its paleogeographic and paleotectonic meaning. In this regard, the Ediacaran and Lower Paleozoic sequences in the OMZ are distinctive with respect to other Variscan zones in the Iberian Massif (e.g., [62, 63]). Furthermore, the OMZ is also characterized by prominent late Ediacaran and early-middle Cambrian to Ordovician magmatism (Figure 1(b)) (e.g., [64–66]).

The oldest rocks exposed in the OMZ are the slates, schists, and greywackes with minor amphibolite and black quartzite intercalations of the so-called Serie Negra Group (Figures 2 and 3) (e.g., [63]). These rocks were dated at late Ediacaran, based on its stratigraphic position underlying the Cambrian sequence, detrital zircon geochronological data [26, 28, 30, 67, 68], amphibolitic protolith radiometric dating [69], and cross-cutting relationships with Cambrian magmatic rocks [68, 70]. The Serie Negra Group is unconformably overlaid by the uppermost Ediacaran-lowermost Cambrian volcano-sedimentary sequence of the Malcocinado Formation, which is roughly coeval with the emplacement of a number of plutonic bodies [71, 72].

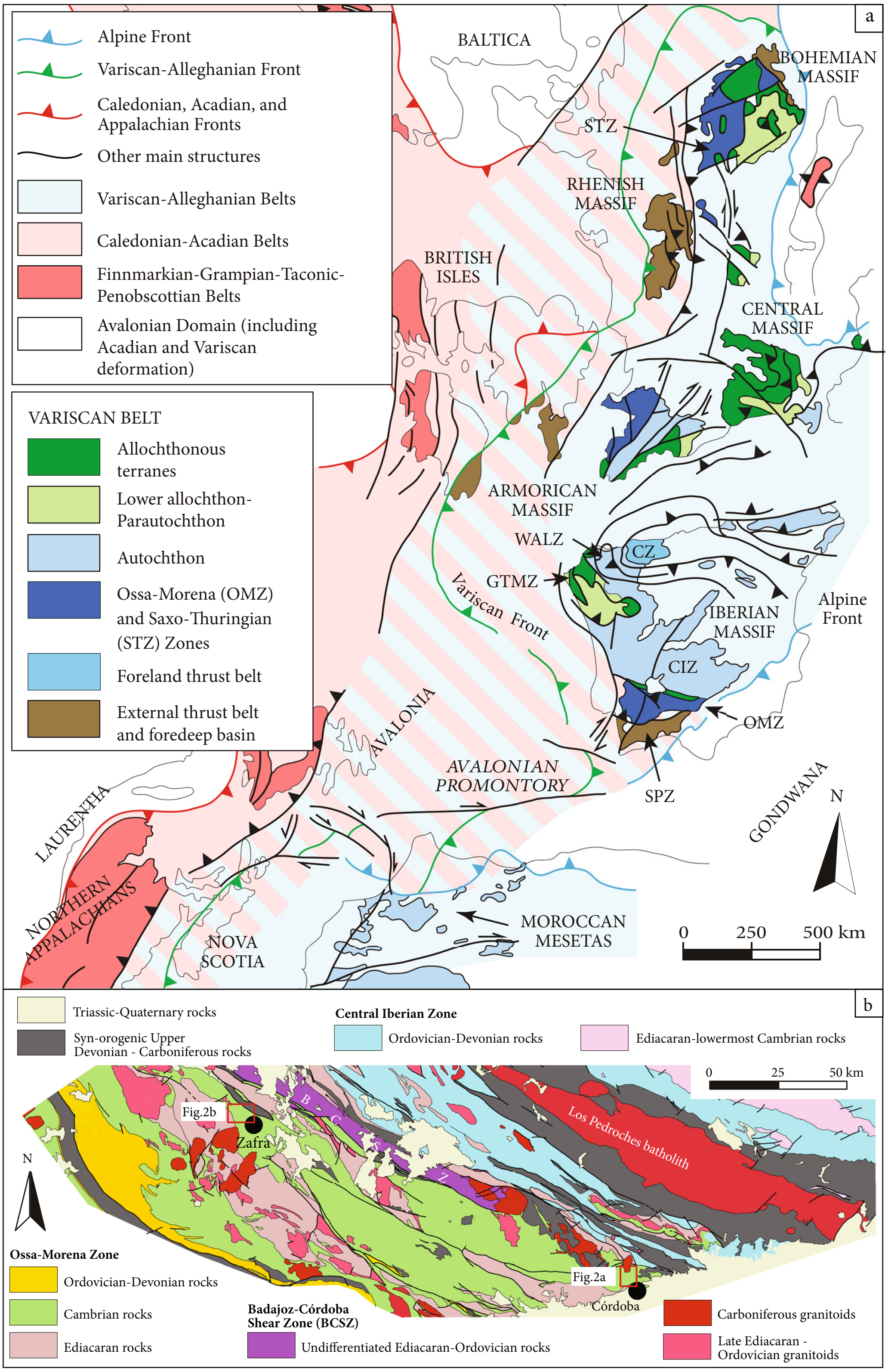

FIGURE 1: (a) Reconstruction of the Variscan/Alleghanian and Caledonian belts at the end of the Paleozoic (modified from [40, 126, 127]). (b) Geological map of the Ossa-Morena Zone with location of the two studied sections; BCSZ: Badajoz-Córdoba Shear Zone; CIZ: Central Iberian Zone; CZ: Cantabrian Zone; GTMZ: Galicia-Tras-os-Montes Zone; OMZ: Ossa-Morena Zone; SPZ: South Portuguese Zone; WALZ: West Asturian-Leonese Zone.

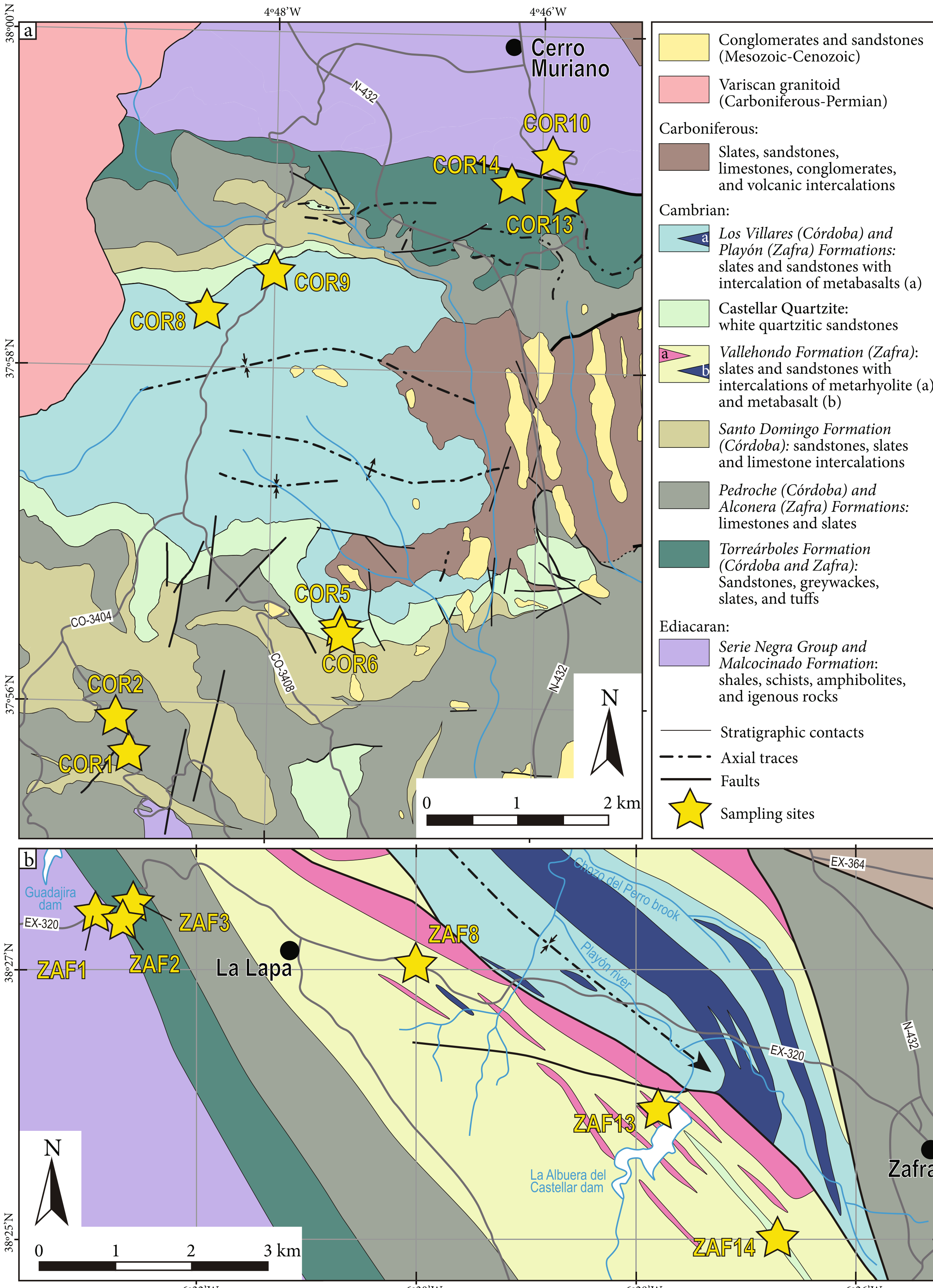

Figure 2: Schematic geological maps of the studied areas with location of the samples: (a) Córdoba area; (b) Zafra area (modified from [90]).

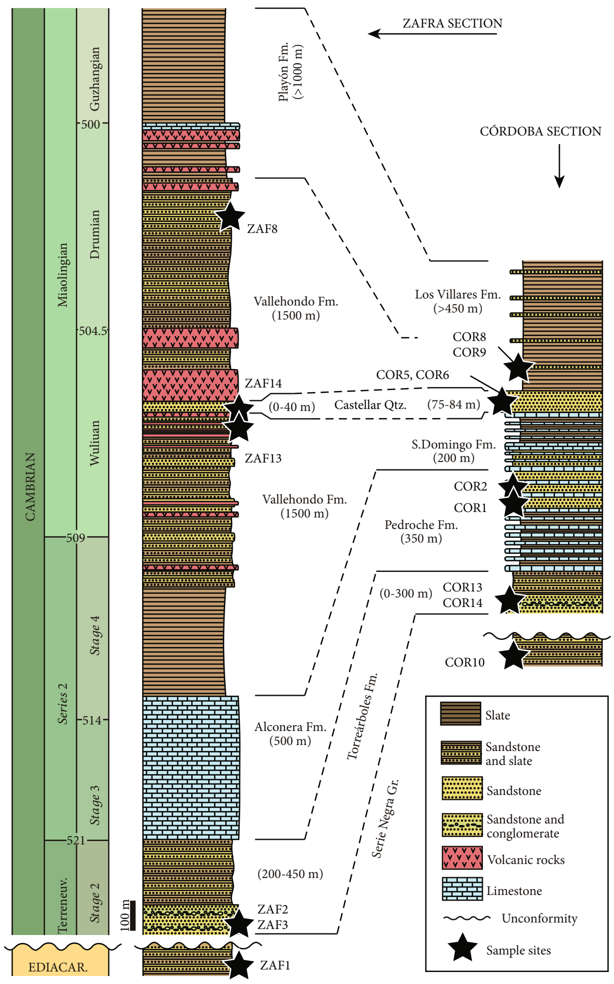

Figure 3: Stratigraphic correlation between the Cambrian sequence in the Córdoba (right) and Zafra (left) sections with location of the studied samples (columns modified from [78] and [90]).

The Lower-middle Cambrian sequence rests unconformably on the Serie Negra Group and the Malcocinado Formation (Figures 2(a) and 3). A more detailed description of the Cambrian sequence is given below.

The Ordovician-Devonian succession is interpreted as a passive margin sequence deposited on the Gondwanan margin (e.g., [73]), coevally with the Rheic and other minor ocean expansion. The Ordovician sequence is made up of slates, siltstones, and sandstones, at times with Katian limestone intercalations (e.g., [62, 74, 75]). The Silurian corresponds to dominant graptolite-bearing black slates, with some chert, sandstone, and limestone intercalations. The Devonian succession consists of slates with siltstone intercalations (e.g., [74, 75]).

The synorogenic deposits are Upper Devonian-Lower Carboniferous greywackes, conglomerates, shales, and limestones, with volcanic intercalations [76–78], although locally Lower Devonian greywackes constitute the very first syncollisional sediments [79–81].

In this study, we have sampled detrital Cambrian rocks from two classical sections with abundant fossiliferous content, namely, the Córdoba and the Zafra sections, whose stratigraphic sequences are described in detail below.

The sedimentary successions in the Córdoba and Zafra areas are equivalent regarding the lower Cambrian but differ in the abundance of volcano-sedimentary rocks of middle Cambrian age.

In the Córdoba area, the Cambrian sedimentary sequence is deformed by an open upright syncline and unconformably overlies metamorphic rocks assigned to the Serie Negra Group (to the north) and vulcanites of the Malcocinado Formation (to the south; Figure 2(a)). The lower Cambrian is composed of conglomerates, sandstones, and shales of the Torreárboles Formation [82], followed by carbonate and siliciclastic alternations of the Pedroche Formation [83, 84] and purple slates (metatuffs?) with minor sandstone and limestone intercalations of the Santo Domingo Formation [85]. The Pedroche formation was dated at series 2 based on its fossiliferous content [86, 87]. Over the Santo Domingo Formation, decametric-thick quartzitic sandstone levels (Castellar Quartzite) grade upwards to an alternation of shales and sandstones (Los Villares Formation) [88], which constitutes the topmost outcropping Cambrian rocks in the Córdoba area (Figures 2(a) and 3(b)).

In the Zafra area, the Cambrian sequence also begins with the Torreárboles Formation, overlaid by the carbonate deposits of the Pedroche Formation (locally known as Alconera Formation) [89], the siliciclastic sediments of the Vallehondo Formation and the Castellar Quartzite. The sequence ends with the slates, sandstones, and metabasalts of the Playón Formation (Figures 2(b) and 3(a)). The Vallehondo Formation [90] includes a lower member mainly made up of slates (equivalent to the Santo Domingo Formation in the Córdoba section; Figure 3) and an upper member characterized by sandy slates with several intercalations of sandstones and volcanic rocks (equivalent to the lowermost Los Villares Formation in the Córdoba section). The upper Miaolingian (late Drumian-Guzhangian) Playón Formation overlies the Vallehondo Formation and consists in a thick sequence of slates and fine-grained sandstones with abundant felsic/mafic volcanic intercalations [91], which attest to the rifting stage that gave way to the opening of the Rheic Ocean [65, 90, 92–94].

3. Samples and Methodology

This work reports detrital zircon U-Pb geochronological data obtained from 15 upper Ediacaran-middle Cambrian samples collected along the Córdoba and Zafra sections. The samples are listed in Table 1.

In the Córdoba area, samples COR13 and COR14 come from the lower levels of the Torreárboles Formation (Figure 3) outcropping in the Torreárboles hill, which is located in the northern limb of an open syncline affecting the Cambrian sequence (Figure 2(a)). Sandstone levels intercalated in the upper part of the Pedroche Formation (COR1 and COR2) were sampled along the CO-3404 road (Figures 2(a) and 3). Samples COR5 and COR6 correspond to sandstones from the Castellar Quartzite (Figure 3) collected close to the Santo Domingo hermitage. The Los Villares Formation was sampled in the northern limb of the syncline

Table 1: Location and brief description of the samples; (*) bold numbers represent concordant data.

Area	Sample	IGSN (IEACC)	Location (UTM,WGS84) Zone	X (m E)	Y (m N)	Unit	Stratigraphic age	Lithology	LA-ICPMS analyses (*)
Cordoba	COR1	S007	30S	340265	4199117	Lower Pedroche Fm.	Series 2	Sandstone	**106**/138
	COR2	S008	30S	340192	4199435	Pedroche Fm.	Series 2	Quartzitic sandstone	**103**/133
	COR5	S009	30S	342345	4200866	Upper Castellar Qtz.	Miaolingian	Quartzitic sandstone	**86**/121
	COR6	S010	30S	342355	4200786	Lower Castellar Qtz.	Miaolingian	Quartzitic sandstone	**119**/174
	COR8	S011	30S	341092	4204399	Upper Villares Fm.	Miaolingian	Quartzitic sandstone	**104**/149
	COR9	S012	30S	341849	4204674	Lower Villares Fm.	Miaolingian	Quartzitic sandstone	**83**/119
	COR10	S013	30S	345044	4205990	Serie Negra gr.	Ediacaran	Quartzitic sandstone	**76**/107
	COR13	S015	30S	345212	4205621	Torrearboles Fm.	Terreneuvian	Arkose	**116**/141
	COR14	S016	30S	344344	4205786	Torrearboles Fm.	Terreneuvian	Arkose	**91**/118
Zafra	ZAF1	S017	29S	713811	4259293	Serie Negra gr.	Ediacaran	Greywackes	**111**/140
	ZAF2	S018	29S	714212	4259225	Lower Torrearboles Fm.	Terreneuvian	Arkose	**107**/140
	ZAF3	S019	29S	714350	4259443	Upper Torrearboles Fm.	Terreneuvian	Arkose	**83**/140
	ZAF8	S020	29S	718942	4258751	Vallehondo Fm., upper Mb.	Miaolingian	Quartzitic sandstone	**109**/140
	ZAF13	S021	29S	721443	4256845	Vallehondo Fm., upper Mb.	Miaolingian	Quartzitic sandstone	**101**/140
	ZAF14	S022	29S	723421	4254691	Upper Castellar Qtz.	Miaolingian	Quartzitic sandstone	**94**/140

(COR8 and COR9; Figure 3). COR10 was sampled along the N-432a road from the Serie Negra Group (Figure 3).

In the Zafra area, samples ZAF13 and ZAF8 were collected from the Vallehondo Formation (upper member; [90]). Sample ZAF13 is located stratigraphically below the Castellar Quartzite (Figure 3) and was collected at the shore of the Albuera del Castellar Lake (Figure 2(b)); sample ZAF8 was taken in the upper part of the Vallehondo Formation (Figure 3), 1 km east of La Lapa along the EX-320 road (Figure 2(b)). Sample ZAF14 was collected 2 km SE of Zafra in the upper part of the Castellar Quartzite (Figures 2(b) and 3). The rest of the samples from the Zafra area were collected along the EX-320 road in the Serie Negra Group (ZAF1) and Torreárboles Formation (ZAF2 and ZAF3; Figures 2(b) and 3).

Almost all the samples are composed of more than 70% of quartz grains with a grain-size varying from 0.05-0.2 mm (COR1, COR2, COR6, and ZAF8) to 0.5-1 mm (COR5, COR8, COR9, COR13, COR14, ZAF13, and ZAF14). These rocks also include oxides, mica, and some grains of K feldspar and plagioclase. COR10 is strongly foliated; about 20% of the grains (mainly of quartz and oxides) are rounded and surrounded by the foliation. ZAF1 is a greywacke composed of quartz, K feldspar, plagioclase, and lithic clasts, included in a very fine-grained matrix; the clasts have grain-sizes between 0.2 and 1 mm. ZAF2 and ZAF3 contain about 30% of quartz grains with 0.1-1 mm size, surrounded by a fine-grained matrix made up of quartz, ores, and mica.

For each sample, 4-5 kg of rock was collected and processed in the laboratories of the University of Granada (Spain) in order to separate detrital zircon grains. This process included mechanical smashing in a jaw-crusher, sieving, density separation by panning of the 0.3-0.05 mm fraction, magnetic separation, and, finally, handpicking. The zircon grains were then mounted in epoxy discs, polished, cleaned, gold-coated, and analyzed using laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) at the John de Laeter Centre (JdLC) of the Curtin University (Perth, Australia). More details about the analytical procedure, including standard materials and references to the methodology, are detailed in Supplementary Material 1.

To grant a robust statistical representativeness of the dates, the zircon grains were imaged by cathodoluminescence (CL), once the U-Th-Pb analyses were performed. The CL images were performed at the JdLC using a Mira3 Field Emission SEM instrument. A selection of CL images, with the analyzed spot and the correspondent age, is included in Figures 4 and 5.

Raw data were statistically analyzed using IsoplotR [95] for calculating the mean square weighted deviation (MSWD) of the youngest detrital zircon population (minimum 3 data) and obtaining Multidimensional Scaling (MDS) plots. DensityPlotter 8.4 [96] was used to obtain the Kernel Density Estimators (KDE) and histograms (bandwidth: 30 Ma; bin: 30 Ma). The error associated with the $^{206}Pb/^{238}U$ ratio in zircon grains older than 1.5 Ga increases rapidly; therefore, this ratio was used only for ages younger than 1.5 Ga, while the $^{207}Pb/^{206}Pb$ ratio was used to calculate ages older than 1.5 Ga. Only data with a discordance value lower than 10% and f206 (common Pb) values lower than 1% were considered for the characterization and analysis of the samples. Errors are expressed at 1σ level. The complete tables of results are included in Supplementary Material 2.

4. Results

4.1. Córdoba Section

4.1.1. Late Ediacaran Sample (COR10)

(1) Serie Negra Group. COR10 is a quartzitic sandstone from the Serie Negra Group (Table 1). From this sample, 127 analyses were carried out, which yielded 76 concordant data (Figure 6(a)). Zircon grains have a length varying from c. 100 to 250 μm; they are rounded to elongated and present continuous oscillatory and sector zoning (Figure 4). The youngest detrital zircon population is late Ediacaran (564.8 ± 2.6 Ma, $n = 5$, and MSDW = 1.51) and, hence, coherent with the stratigraphic age of the sample.

The main detrital zircon population found in sample COR10 is late Tonian-Ediacaran. It includes c. 89% of the data ($n = 68$; c. 848-555 Ma), with an Ediacaran mean age of 628.9 ± 0.8 Ma which roughly coincides with the main peak of the population. Two very minor detrital zircon populations have Orosirian-Statherian (3 grains; c. 1941-1889 Ma) and Rhyacian-Orosirian (4 grains; c. 2171-1951 Ma) ages. A metamorphic rim yielded early Ordovician age.

4.1.2. Terreneuvian Samples (COR13 and COR14)

(1) Torreárboles Formation. Two hundred and fifty-nine analyses were carried out on two samples (141 in COR13 and 118 in COR14) yielding 207 concordant results (Figure 6(b)). Zircon grains from these samples are rounded to elongated, with lengths from c. 70 to 200 μm. The internal structures show frequent continuous oscillatory zoning and cores overgrown by rims, as well as a few sector zoning and homogeneous grains (Figure 4) The youngest detrital zircon populations are late Ediacaran in age (COR13: 567.3 $\pm$ 3.6 Ma, $n = 3$, and MSWD = 0.91; COR14: 575.7 ± 2.6 Ma, $n = 5$, and MSWD = 0.63).

The predominant detrital zircon population in these samples is late Tonian-Ediacaran (c. 810-557 Ma) and includes 41.5% of the data ($n = 86$). The mean age of the population is 629.2 ± 0.7 Ma. Paleoproterozoic zircon grains are also common, and they group into two populations: a late Orosirian-Statherian one (c. 1941-1738 Ma, $n = 28$, 13.5% of the data with a mean age of 1905.8 ± 2.8 Ma) and a Rhyacian-early Orosirian one (c. 2216-1974 Ma, $n = 55$, 26.6% of the data with a mean age of 2108.2 ± 1.9 Ma). The latter is characterized by two second-order peaks at c. 2055 Ma and 2170 Ma. Nineteen data (9.2%) have Meso- to Neoarchean ages (c. 2925-2604 Ma, clustered around c. 2765 Ma). Scattered grains yielded Paleoarchean ($n = 6$), Siderian-Rhyacian ($n = 7$), and Ectasian-early Tonian ($n = 6$) ages.

4.1.3. Series 2 Samples (COR1 and COR2)

(1) Pedroche Formation. A total of 271 analyses were carried out on samples COR1 (138) and COR2 (133) (Table 1),

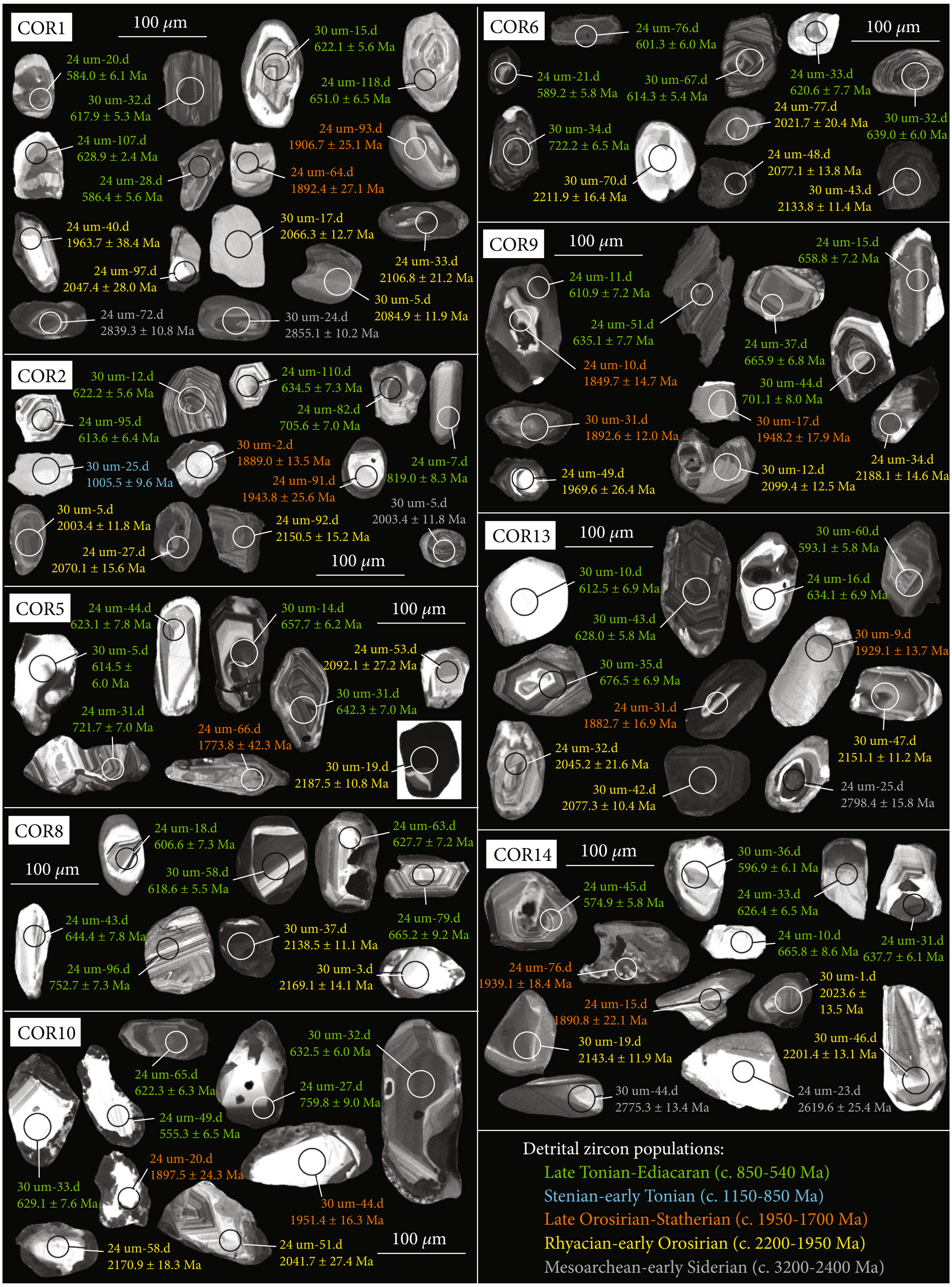

FIGURE 4: Cathodoluminescence images of a selection of zircon grains from the Córdoba samples.

yielding 209 concordant results (Figure 6(c)). Zircon grains have a length varying from c. 50 to 150 μm; they are mainly rounded, and their internal structures can be homogeneous or showing sector and continuous oscillatory zoning and cores overgrown by rims (Figure 4). The youngest detrital zircon populations are 579.0 ± 1.5 Ma (COR1, $n = 16$, and MSWD = 1.35) and 579.6 ± 1.5 Ma (COR2, $n = 16$, and MSWD = 1.25).

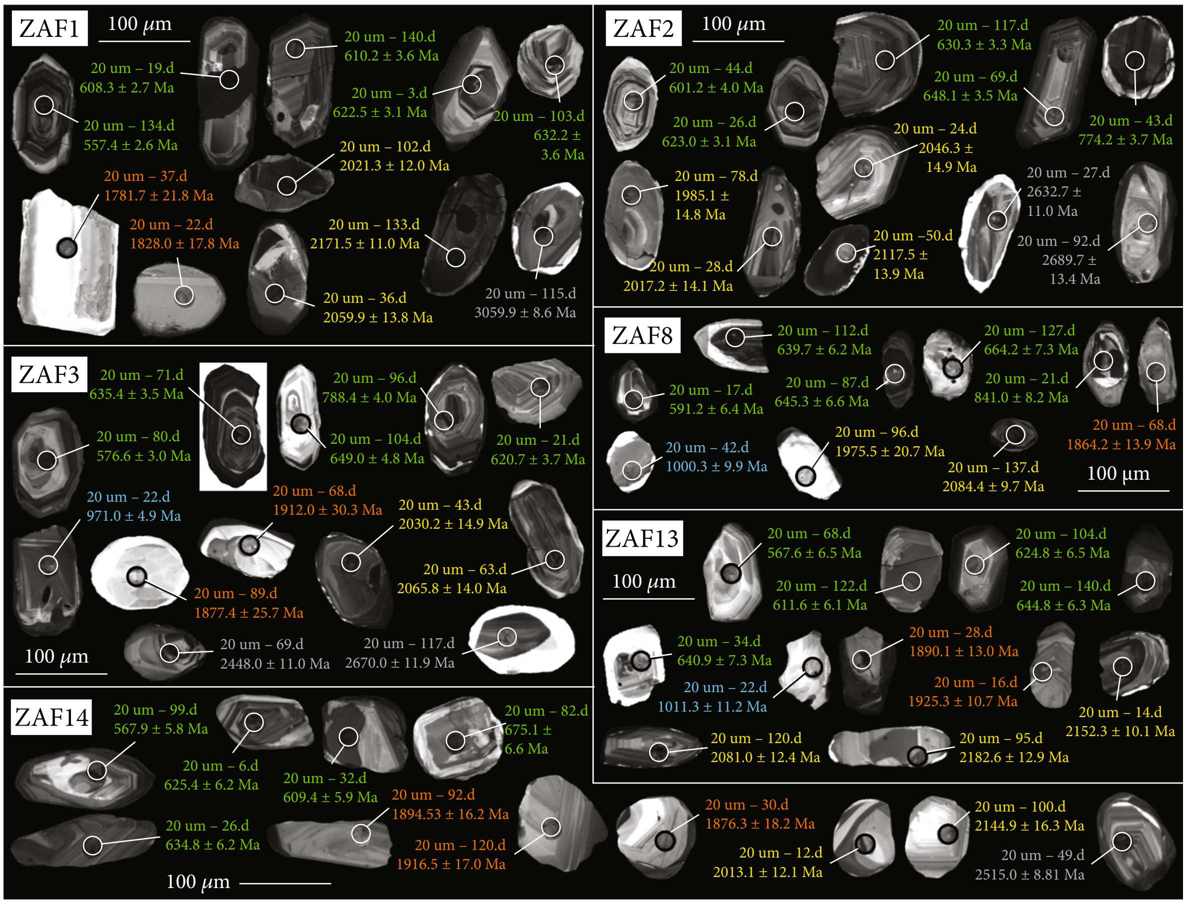

FIGURE 5: Cathodoluminescence images of a selection of zircon grains from the Zafra samples. Different colors correspond to different ages following the same code as shown in Figure 4.

Forty-nine percent of the data ($n = 103$) is included in a late Tonian-Ediacaran (c. 835-543 Ma, mean age of 628.7 ± 0.6 Ma) detrital zircon population, characterized by a main peak at c. 610 Ma and a very minor one at c. 805 Ma. Paleoproterozoic grains define two detrital zircon populations, which include Rhyacian-early Orosirian (c. 2207-1958 Ma, $n = 48$, 23.0% of the data) and late Orosirian-Statherian (c. 1944-1799 Ma, $n = 24$, 11.5% of the data) dates. The mean ages of these populations are 2071.9 ± 2.1 and 1894.3 ± 3.2 Ma, respectively, and correspond to the peaks in the histogram and KDE plots (Figure 6(c)). A few data ($n = 7$, 3.3%) form a very minor detrital zircon population of Stenian-early Tonian (c. 1103-963 Ma) age. Seventeen grains (8.1% of the data) have Meso to Neoarchean ages (c. 2878-2607 Ma) clustered at c. 2670 and 2830 Ma. Finally, very scarce grains yielded Paleoarchean ($n = 1$), late Neoarchean-Siderian ($n = 3$), Ectasian ($n = 3$), and Tonian ($n = 3$) ages.

4.1.4. Miaolingian Samples (COR5, COR6, COR8, and COR9). These samples correspond to the Castellar Quartzite (COR5 and COR6) and Los Villares Formation (COR8 and COR9).

(1) Castellar Quartzite. In samples COR5 and COR6, 295 analyses were carried out (121 and 174, respectively), 205 of which yielded concordant results (Figure 6(d)). Zircon grains from these samples are rounded to elongated with lengths of c. 50-150 μm. Internal structures show frequent continuous oscillatory zoning, rims overgrowing older cores, and some sector zoning (Figure 4). Both samples have late Ediacaran youngest detrital zircon populations (COR5: 559.0 ± 2.3 Ma, $n = 7$, and MSWD = 1.18; COR6: 557.1 ± 3.43 Ma, $n = 3$, and MSWD = 0.85).

The main detrital zircon population includes 143 late Tonian-Ediacaran grains (c. 776-542 Ma, 69.8% of the data) with a peak broadly coinciding with the Ediacaran mean age (628.9 ± 0.5 Ma). Seventeen percent of the data ($n = 34$) have Rhyacian-early Orosirian ages (c. 2213-1962 Ma) clustered in a peak with Orosirian mean age (2089.7 ± 2.4 Ma). Minor detrital zircon populations yielded late Orosirian-Statherian (1806.0 ± 6.3 Ma, $n = 9$, 4.4% of the data between c. 1915 and 1709 Ma) and Neoarchean-early Siderian (scattered data between c. 2682 and 2439 Ma, $n = 9$, 4.4% of the data) ages. Other scattered zircon grains have Mesoarchean ($n = 2$), late Siderian-Rhyacian ($n = 4$), and late Calymmian-Tonian ($n = 4$).

(2) Los Villares Formation. Samples COR8 and COR9 were collected from the upper and lower Los Villares Formation, respectively. Two hundred and sixty-eight analyses were

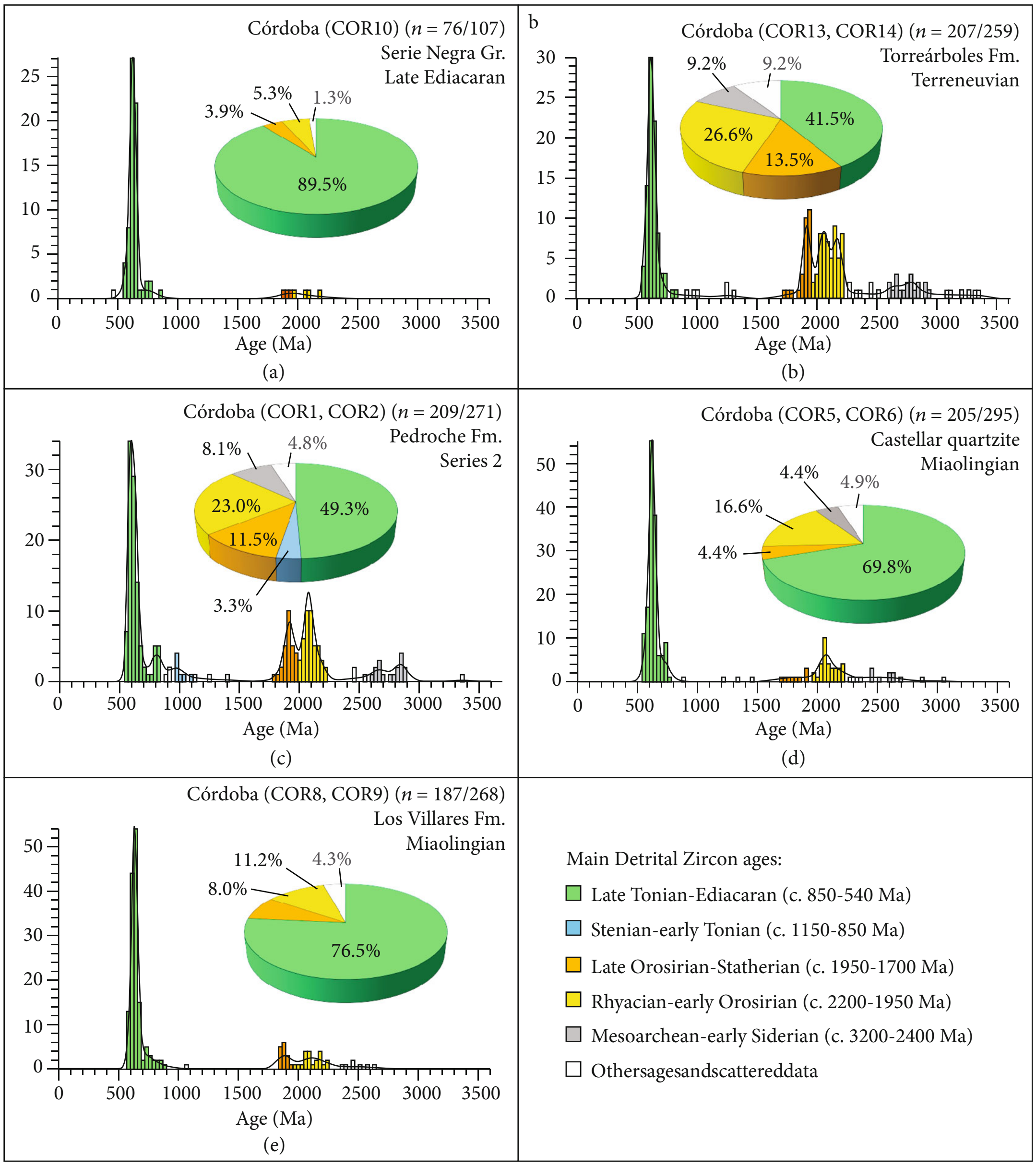

Figure 6: (a–e) U-Pb detrital zircon age distribution in the late Ediacaran-middle Cambrian samples of the Córdoba area (see location in Figure 2). Diagrams include Kernel Density Estimates (KDE, black curves), histograms (colored bars), and pie-charts. Colors represent the main detrital zircon ages. n: number of concordant data (bold)/total number of analyses; percentages were calculated according to the number of concordant data.

carried out (149 in COR8 and 119 in COR9) and yielded 187 concordant results (Figure 6(e)). The grains are mainly elongated, with lengths of c. 70-150 μm, sector and continuous oscillatory zoning, and cores overgrown by rims (Figure 4). The youngest detrital zircon populations in both samples gave very similar late Ediacaran ages (COR8: 583.0 ± 3.3 Ma, $n = 3$, and MSWD = 1.11; COR9: 601.9 ± 1.65 Ma, $n = 15$, and MSWD = 1.3).

In these samples, the late Tonian-Ediacaran detrital zircon population is very dominant and includes 76.5% of the data (c. 884-574 Ma, $n = 143$, mean age of 645.4 ± 0.6 Ma). Minor detrital zircon populations cluster in three peaks at c. 1875, 2055, and 2180 Ma. The youngest of these peaks is defined by 15 data with late Orosirian-Statherian ages (c. 1948-1839 Ma, 8.0% of the data) and a Statherian mean age (1875.8 ± 4.1 Ma). The other two minor peaks include Rhyacian-early Orosirian data ($n = 21$, 11.2% of the data, c. 2229-1969 Ma, mean age of 2127.1 ± 3.0 Ma). Scattered grains yielded Neoarchean-Siderian ($n = 7$) and late Stenian ($n = 1$) ages.

4.2. *Zafra Section*

4.2.1. *Late Ediacaran Sample (ZAF1)*

(1) Serie Negra Goup. Sample ZAF1 was collected from the late Ediacaran Serie Negra Group (Table 1). One hundred

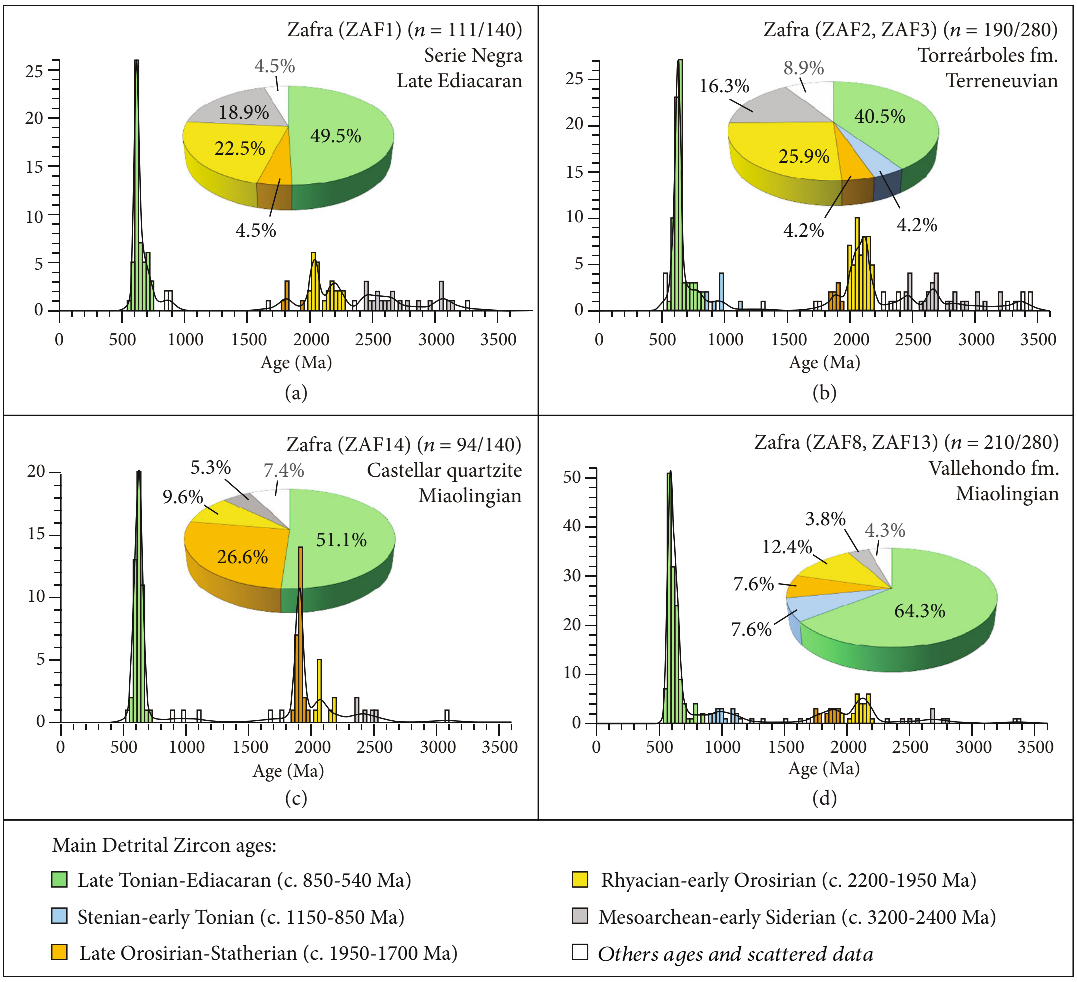

FIGURE 7: (a–d) U-Pb detrital zircon age distribution in late Ediacaran-middle Cambrian samples from the Zafra area (see location in Figure 2). Diagrams include Kernel Density Estimates (KDE, black curves), histograms (colored bars), and pie-charts. Colors represent the main detrital zircon ages. *n*: number of concordant data (bold)/total number of analyses; percentages were calculated according to the number of concordant data.

and forty analyses were carried out on the same number of detrital zircon grains, yielding 111 concordant ages (Figure 7(a)). Zircon grains are elongated, with lengths of c. 100-150 μm. The internal structures (Figure 5) show some cores overgrown by rims and both sector and continuous oscillatory zoning. The youngest detrital zircon population, composed of 4 data between c. 597 and 589 Ma, gave an Ediacaran mean age (593.1 ± 1.6 Ma and MSDW = 1.26).

The predominant detrital zircon population includes 55 data (49.5% of the data) of late Tonian-Ediacaran (c. 847-557 Ma) age and yields a latest Cryogenian mean age (640.7 ± 0.5 *Ma*) with a main Ediacaran peak at c. 630 Ma. The Rhyacian-Orosirian population represents 22.5% of the data (*n* = 25; c. 2260-1985 Ma; mean age of 2129.4 ± 2.5 Ma), which appear clustered around two peaks at c. 2210 and 2045 Ma. Minor detrital zircon populations have Orosirian-Statherian (c. 1920-1782 Ma, *n* = 5, 4.5%, mean age of 1866.4 ± 6.7 Ma) and Mesoarchean-Siderian (c. 3135-2440 Ma, *n* = 21, 18.9%, with two minor peaks at *c.* 3025 and *c.* 2580 Ma) ages. A few scattered zircon grains yielded Paleoarchean (*n* = 1), Siderian (*n* = 1), Statherian (*n* = 1), and Tonian (*n* = 2) ages.

4.2.2. Terreneuvian Samples (ZAF2 and ZAF3)

(1) Torreárboles Formation. Two hundred and eighty analyses (140 in sample ZAF2 and 140 in sample ZAF3) were carried out on detrital zircon grains from these samples, 190 of which yielded concordant results (Figure 7(b)). The zircon grains from these samples have a length from *c.* 80 to 120 μm, and they are mainly elongated. Their internal structures include continuous oscillatory zoning and cores overgrown by rims (Figure 5). The youngest detrital zircon population of these two samples are Ediacaran (ZAF2; 596.6 ± 1.9 Ma, *n* = 4, and MSWD = 1.46) and Early Cambrian (ZAF3; 526.7 ± 1.6 Ma, *n* = 3, and MSWD = 0.61) in age.

The main peak in the distribution plot (*c.* 645 Ma) is defined by 40.5% of the data (*n* = 77), with late Tonian-Ediacaran ages (*c.* 814-555 Ma) and a late Cryogenian mean age (646.7 ± 0.4 Ma). Another important detrital zircon population is the Rhyacian-early Orosirian one, including 25.9% of the data (*n* = 49) between *c.* 2189 and *c.* 1985 Ma (mean age of 2093.7 ± 1.7 Ma). Sixteen percent of the data (*n* = 31) have Mesoarchean-early Siderian ages ranging from *c.* 3194 to *c.* 2367 Ma but show a rather dispersed distribution. Two minor detrital zircon populations yielded Orosirian-Statherian (*c.* 1926-1836 Ma, *n* = 8, 4.2% of the data, mean age of 1889.8 ± 6.5 Ma) and Stenian-early Tonian (*c.* 1113-866 Ma, *n* = 8, 4.2% of the data, mean age of 947.2 ± 1.8 Ma) ages. Finally, several scattered grains have Paleoarchean (*n* = 7), Siderian-early Rhyacian (*n* = 3), Statherian (*n* = 2), Ectasian (*n* = 1), and early Cambrian (*n* = 4) ages.

4.2.3. Miaolingian Samples (ZAF14, ZAF8, and ZAF13). Among the Miaolingian samples from the Zafra area (Table 1), ZAF8 and ZAF13 were collected from the Vallehondo Formation, while ZAF14 belongs to the Castellar Quartzite, which, in this area, has been described as an intercalation within the Vallehondo Formation (Figures 2(b) and 3; Palacios et al., [90]). ZAF13 was collected below the Castellar Quartzite, while ZAF8 is from above. Nevertheless, the two Vallehondo Formation samples yielded very similar results and are described together.

(1) Castellar Quartzite. One hundred and forty analyses were carried out on detrital zircon grains from sample ZAF14 and yielded 94 concordant results (Figure 7(c)). Zircon grains are rounded to elongated, with lengths of *c.* 100-150 μm, cores overgrown by rims, and sector and continuous oscillatory zoning (Figure 5). The youngest detrital zircon population includes 6 dates and is late Ediacaran in age (571.5 ± 2.4 Ma and MSWD = 0.91).

The main peak observable in the KDE plot is marked by the Cryogenian-Ediacaran data (*c.* 712-564 Ma, *n* = 48, 51.1% of the data, mean age of 615.4 ± 0.9 Ma). Similarly, to the other samples so far described, ZAF14 is characterized by a late Orosirian-Statherian detrital zircon population (*c.*1954-1837 Ma, mean age of 1901.9 ± 2.9 Ma), but in this case, it includes up to 26.6% of the data (*n* = 25). Minor populations consist of Rhyacian-early Orosirian (*c.* 2178-2013 Ma, *n* = 9, 9.6% of the data, mean age of 2092.5 ± 4.2 Ma) and late Neoarchean-Siderian (*c.* 2515.0-2358.8 Ma, *n* = 5, 5.3% of the data, peak at *c.* 2410 Ma) dates. Scattered grains have Mesoarchean (*n* = 1), Statherian (*n* = 2), late Stenian-early Tonian (*n* = 3), and early Cambrian (*n* = 1) ages.

(2) Vallehondo Formation. A total of 280 analyses were carried out on samples ZAF8 (140) and ZAF13 (140), yielding 210 concordant results (Figure 7(d)). The zircon grains from these samples have lengths of 100-150 μm and mainly elongated shapes. The internal structures show frequent sector zoning and cores overgrown by rims, as well as some continuous oscillatory zoning (Figure 5). The youngest detrital zircon populations in the two samples are late Ediacaran in age (ZAF8: 574.6 ± 1.2 Ma, *n* = 21, and MSWD = 0.96; ZAF13: 575.7 ± 2.2 Ma, *n* = 7, and MSWD = 0.96).

Sixty-four percent of the data (*n* = 135) have late Tonian-Ediacaran ages (*c.* 845-545 Ma) organized in a main peak at *c.* 595 Ma and with an early Ediacaran mean age (621.5 ± 0.5 Ma). Most of the remaining data are distributed in 4 minor peaks with Stenian-early Tonian (mean age 1006.8 ± 2.6 Ma, *c.* 1118-908 Ma, *n* = 16, 7.6% of the data), late Orosirian-Statherian (mean age 1862.3 ± 3.3 Ma, *c.* 1942-1754 Ma, *n* = 16, 7.6% of the data), Rhyacian-early Orosirian (mean age 2118.6 ± 1.9 Ma, *c.* 2190-1965 Ma, *n* = 26, 12.4% of the data), and Mesoarchean-Siderian (*c.* 2819-2447 Ma, *n* = 8, 3.8% of the data, peaked at *c.* 2705 Ma) ages. Scattered zircon grains have Paleoarchean (*n* = 2), late Siderian (*n* = 1), and Statherian-Stenian (*n* = 6) ages.

5. Discussion

5.1. Maximum versus True Depositional Ages. The youngest detrital zircon populations (YDP) in the studied samples are Ediacaran, except for sample ZAF3 that yielded Terreneuvian age (*c.* 527 Ma). Leaving aside this sample and those from the late Ediacaran Serie Negra Group, no systematic variation in the YDP is observed along the Cambrian stratigraphic sequence, with all values ranging from *c.* 557 to *c.* 602 Ma (Figure 8). YDP are used to constrain maximum depositional ages (MDA) when no true depositional ages (TDA) derived from paleontological dating and/or direct numerical dating of volcanic intercalations are available. This is not the case in the studied samples, which have been accurately dated based on their fossiliferous content [83, 90, 97–99]. Thus, the TDA of the studied samples is generally between *c.* 35 and 60 Ma younger than MDA, with this difference decreasing towards the bottom of the Cambrian stratigraphic sequence (Figure 8). This trend is well in accordance with the results obtained from Ordovician-Devonian OMZ metasedimentary rocks, with YDP ranging from 582 to 592 Ma and differences between MDA and TDA of 100-180 Ma [23].

According to most authors, the Cambrian-Devonian succession of the OMZ represents a pre- (early Cambrian) and synrift (middle Cambrian) to passive margin (Ordovician-Devonian) transition, coeval to the opening of the Rheic, and other minor peri-Gondwanan oceans (e.g., [36, 65, 73]). The comparison between TDA and MDA supports this tectonic interpretation, with the maximum differences between TDA and MDA occurring during early Devonian time, i.e., at the end of the period of oceanic expansion that preceded the Variscan orogeny. Nevertheless, the prominent presence of lower Cambrian to Lower Ordovician plutonic and volcanic rocks outcropping in the OMZ (e.g., [65] and references therein) compared with the absence of these ages in the detrital zircon populations found in coeval and younger sedimentary rocks is intriguing. This is especially true in the case of the Cambrian rocks of this study, supposedly deposited during the rifting stage in the northern Gondwanan margin, when differential block uplift and rotation might have favored the incorporation of synrift igneous material into coeval or slightly younger sediments. The most plausible explanation for the absence of Cambrian detrital zircon populations (only very few scattered grains were

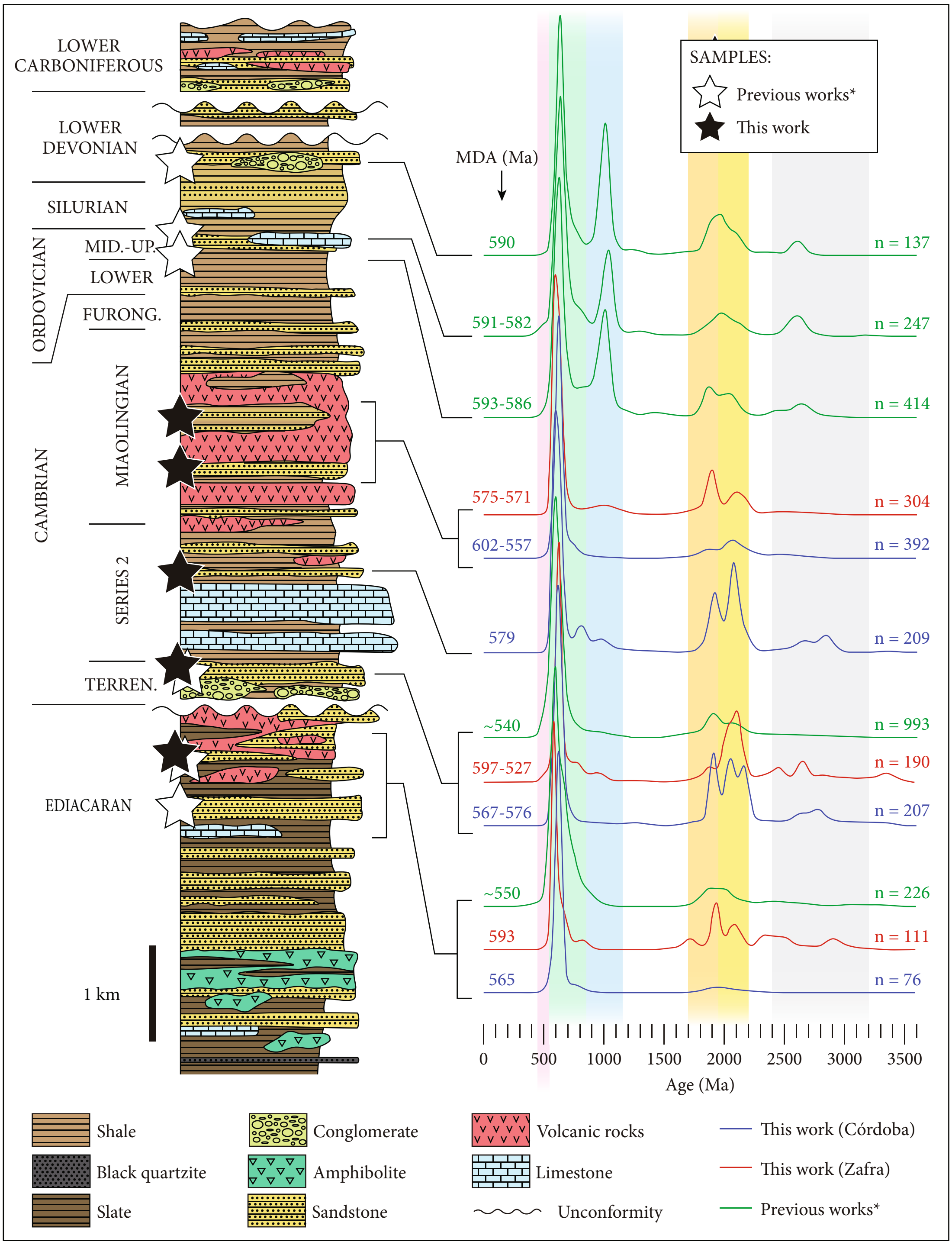

Figure 8: Synthetic stratigraphic column of the OMZ with KDEs of the Cambrian-Devonian samples studied in this (black stars) and previous (white stars) works (*): [23, 26, 28, 37, 68, 128, 129]. MDA: maximum depositional age.

found in the studied samples) is that this magma-rich rift environment was below sea level at that time and was not exhumed to the surface until the collisional and/or postcollisional stages of the Variscan orogeny during Carboniferous-Permian time. Sample ZAF3 from the Torreárboles Formation breaks this rule, since its MDA and TDA are virtually coincident, which probably means that synrift igneous-derived detrital zircons were occasionally incorporated during the deposition of these Terreneuvian detrital sequences of the OMZ.

To sum up, the comparison between MDA and TDA in the Lower Cambrian-Lower Devonian sequence of the OMZ is compatible with a rift to drift transition, in which the difference between TDA and MDA increases upwards from being almost coeval (in a lower Cambrian sample) to c. 180 Ma (Lower Devonian), while the input from intrabasinal-derived rift-related magmatic sources was generally very limited.

5.2. Potential Sources of Detrital Zircon Grains in the Cambrian Rocks of the Ossa-Morena Zone. The Cambrian samples studied in this work were deposited during a time lapse of c. 40 Ma (c. 540-500 Ma), during the rifting process that finally led to the formation of the northern Gondwanan margin. The dominant detrital zircon population in all the samples is the late Tonian-Ediacaran one (850-550 Ma), which represents between 40 and 90% of the concordant analytical results (Figures 6 and 7). Zircon grains from these ages can be attributed to the prominent long-lived Cadomian magmatic arc and the partially coeval Pan-African orogen, whose materials are dominant in the vast majority of Cambrian to Carboniferous metasedimentary rocks of the Variscan orogen (Figure 9) (e.g., [23, 31, 100–104] and references therein, [105–110]).

The second order detrital zircon populations are Rhyacian-early Orosirian and late Orosirian-Statherian (c. 2200-1950 and 1950-1700 Ma, respectively) in age, together accounting for 8-36% of the concordant ages (Figures 6 and 7). Several samples also contain Mesoarchean-early Siderian grains representing up to 19% of the concordant data (Figures 6 and 7). The commonly invoked source for these detrital zircon populations is the WAC (Eburnean and Leonian-Liberian orogenies, respectively) (e.g., [111] and references therein); although, they are also compatible with a Tuareg Shield origin (see [104] and references therein).

Samples ZAF8 and ZAF13 slightly depart from the above-mentioned pattern, with the minor presence of a Stenian-early Tonian detrital zircon population peaked at c. 1 Ga, which represents c. 8% of the concordant results (Figure 7(d)). Similar results to the ones obtained in these two samples were reported from Cambrian-Lower Devonian rocks of the Moroccan Variscides, where the c. 1 Ga subordinate detrital zircon population has been attributed to intermittent and distant sources located at the Saharan Metacraton [100, 102, 103, 107, 108].

Previous geochronological data on detrital zircon grains from Cambrian OMZ rocks (e.g., [26, 30, 68, 110]) yielded results totally coincident with the ones reported here, i.e., a main population of late Tonian-Ediacaran (850-550 Ma; Figure 8) ages, with minor peaks centered at c. 2 Ga, and lack of Stenian-early Tonian detrital zircon grains (except for very minor and local occurrences). These data, combined with the results from samples of the Serie Negra Group, have been used to locate the OMZ close to the WAC during Ediacaran-Cambrian times, in a western position with respect to the other Variscan zones [26, 28, 30, 68]. Nevertheless, Solís-Alulima et al. [110] proposed that the Sierra Albarrana Domain, located in the northern part of the OMZ and made up of poorly dated Cambrian rocks, is akin to the CIZ and was placed close to the Saharan Metacraton at Cambrian times. This proposition is difficult to reconcile with the virtual absence of c. 1 Ga detrital zircon grains in the Sierra Albarrana rocks, since the presence—not the absence—of a noticeable peak of that age is taken as diagnostic of a Saharan Metacraton provenance (e.g., [15]).

5.3. Cambrian to Ordovician Change in the Detrital Zircon Record of the Ossa-Morena Zone. The rift to drift transition in the OMZ deduced from the stratigraphic and magmatic records (e.g., [65, 73, 112]) is also reflected in the available detrital zircon spectra. In this respect, the OMZ middle Ordovician-Lower Devonian rocks contain an important Stenian-early Tonian detrital zircon population (up to 27% of the concordant data; Figures 8 and 9) [23] and, hence, strongly contrast with the Cambrian rocks reported here and in previous works (Figure 10), which have only sporadic Stenian-early Tonian detrital zircon grains, or more frequently show a total absence of these ages. We tentatively attributed the presence of an apparent Stenian-early Tonian detrital zircon population in Ordovician-Lower Devonian OMZ rocks to an Ediacaran-earliest Cambrian eastward translation of this continental piece during the vanishing stages of the Cadomian orogeny, i.e., from an Ediacaran location close to the WAC to a Cambrian position close to the Saharan Metacraton [23].

There is an almost consensus in primarily (Ediacaran time) locating the OMZ close to the WAC [26, 28, 30, 68]. Furthermore, the putative correlation of the OMZ in Iberia with the STZ in Central Europe, which is widely accepted (e.g., [38, 39, 40, 113, 114]), reinforces this paleogeographic attribution. Thus, the OMZ-STZ would constitute an elongated continental terrane (Figure 11(a)), with a c. 2 Ga Paleoproterozoic WAC basement which was dredged in the Galicia Bank [115, 116] and crops out locally in the Cherbourg-Trégor region of NW France [117–119] and the STZ (e.g., [40] and references therein). Finally, the Sm-Nd isotopic signature of Ediacaran rocks from the OMZ and STZ also supports the affinity with the Paleoproterozoic WAC [120, 121].

Given that the available detrital zircon data cover now the whole OMZ preorogenic stratigraphic sequence (Upper Ediacaran-Lower Devonian; Figures 8 and 9), we will try in the next paragraphs to refine our initial hypothesis for the incorporation of a noticeable 1 Ga detrital zircon population at Ordovician time.

In this regard, a first issue to consider is the possibility of intermediate sediment repositories (ISR) [122] for the late Stenian-early Tonian detrital zircon grains, which would prevent from stablishing a direct connection with the primary source. Nevertheless, the lack of a significant unconformity between the Cambrian and Ordovician-Devonian rocks in the OMZ undermines this possibility. Furthermore, the occurrence of a minor 1 Ga detrital zircon population is only occasional in Cambrian OMZ rocks, as well as in coeval rocks from other areas located close to the WAC (e.g., Anti-Atlas). Consequently, these rocks cannot be considered an ISR for the Stenian-early Tonian detrital zircon grains found in the Ordovician-Devonian OMZ sequence (up to 27%), since sediment recycling should maintain the detrital zircon content in the primary/intermediate source [122] but not selectively augment the content of one of the populations.

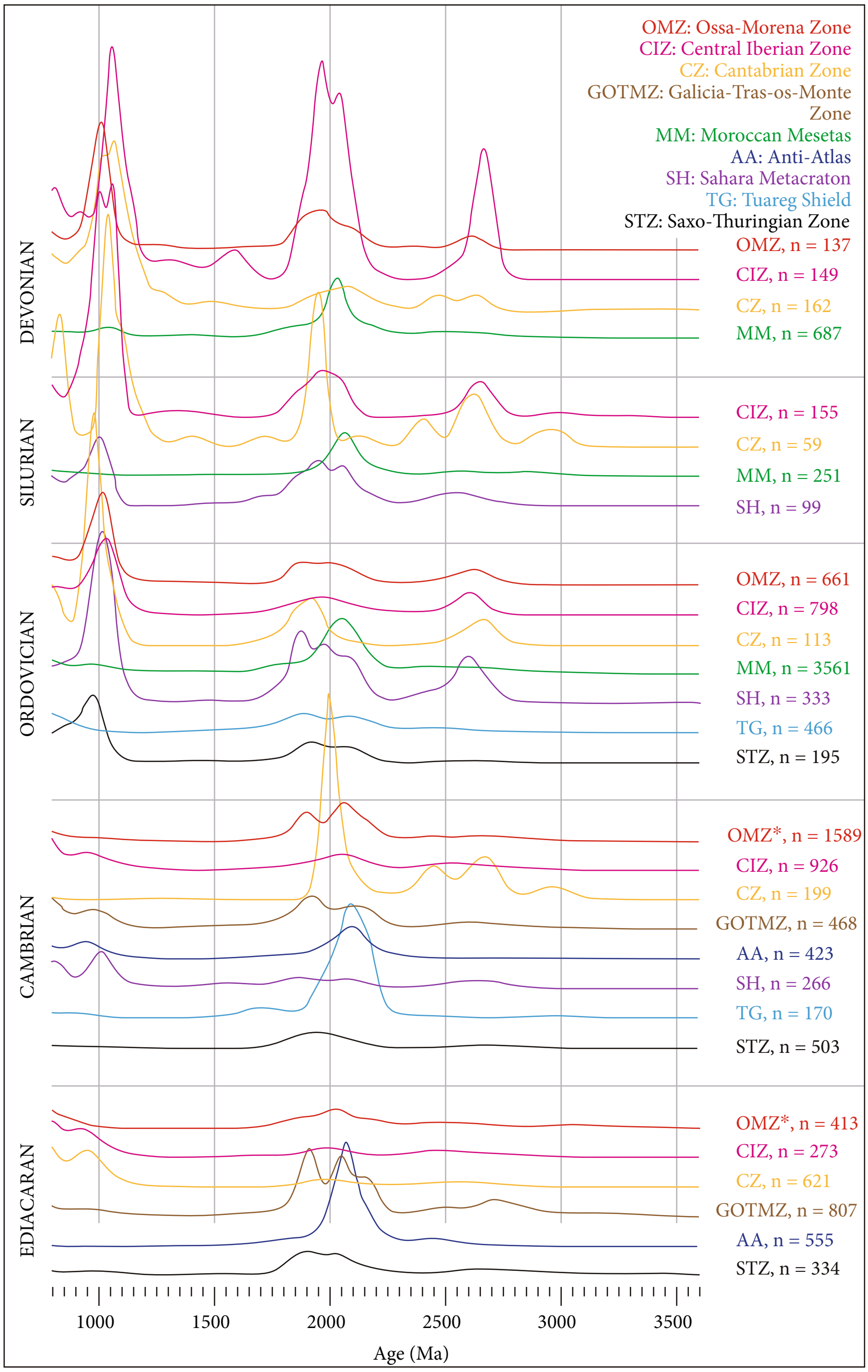

FIGURE 9: Comparison among KDE plots from the OMZ (*include data from this work and from [23, 26, 28, 37, 68, 110]), CIZ (data from [16, 20, 26, 31, 130, 131]), Cantabrian Zone (data from [16, 31, 106]), Galicia-Tras-os-Montes Zone (data from [29]), Moroccan Mesetas (data from [100–103, 107, 108, 132]), Anti-Atlas (data from [133, 134]), Sahara Metacraton (data from [32]), Tuareg Shield (data from [135]), and Saxo-Thuringian Zone (data from [105, 109, 136]). Ages younger than 800 Ma have not been considered in order to highlight the different contribution of putative cratonic sources. n refers to the total number of detrital zircon grains, including those with ages younger than 800 Ma.

Therefore, a direct connection with a primary 1 Ga source seems justified by the high percentage of this population in the Ordovician-Devonian OMZ rocks. Furthermore, an MDS plot of the available Ediacaran-Devonian OMZ samples also supports this fundamental difference between pre-Ordovician and Ordovician-Devonian OMZ rocks (Figure 10). Thus, Ediacaran-Cambrian samples cluster in two groups characterized by a slightly different percentage

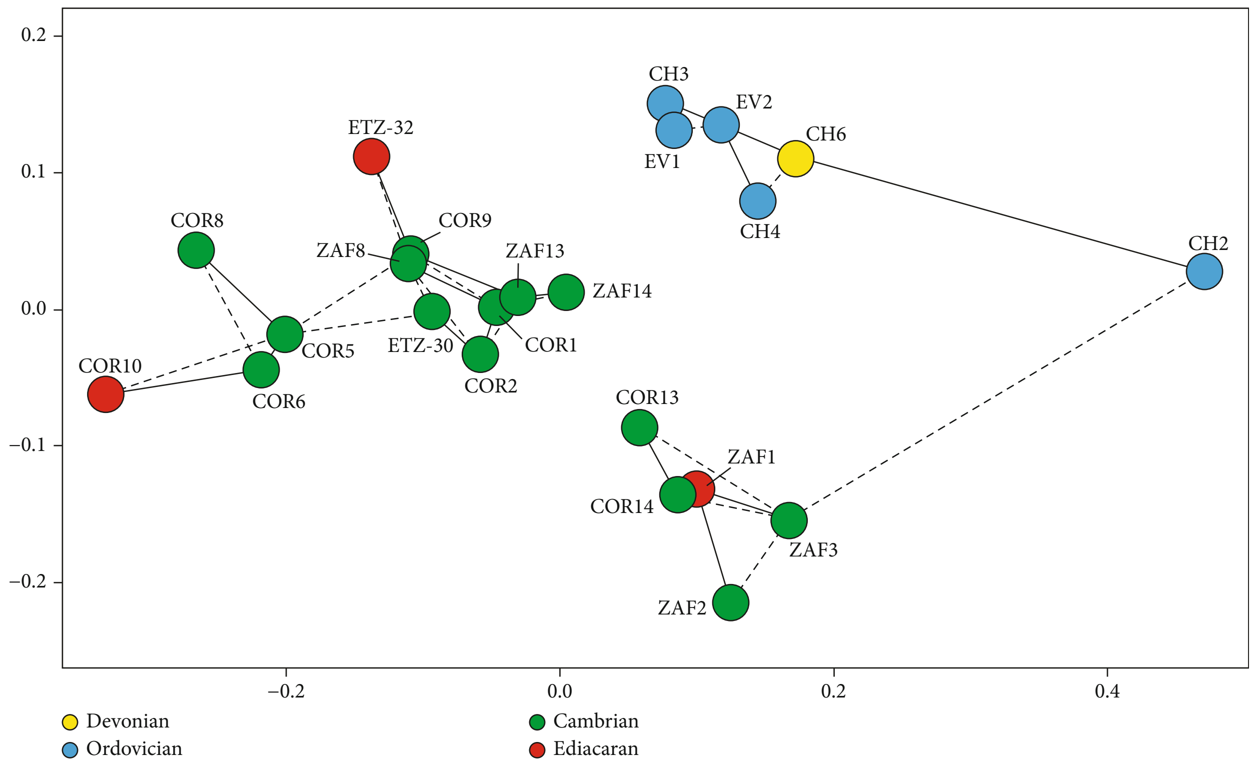

Figure 10: Classic Multidimensional Scaling (MDS) plot of all the samples from the OMZ (for the sake of the statistical significance, we have only included samples with more than 70 concordant dates) ([23, 30], this work).

distribution of the major populations. In contrast, Ordovician-Devonian samples cluster in a clearly separated third group, reflecting the presence of an increasing number (≥20% of the data) of Stenian-early Tonian dates, absent or very scarce in older samples. We can conclude that the most plausible explanation for this contrast in the Stenian-early Tonian detrital zircon content is related to a change in sediment provenance from a WAC source (Cambrian) to a Saharan Metacraton one (Ordovician-Devonian), where these zircon grains were available from a primary source located in the present-day interior of Africa (e.g., [15]).

A second issue to be addressed is whether the Cambrian-Ordovician change in the detrital zircon record of the OMZ is due to a reorganization of the drainage systems and/or to an eastward displacement of the OMZ-STZ terrane. This Cambrian-Ordovician change is coeval to the rift-drift transition culminating in the formation of the northern Gondwanan margin, which, in turn, might have favored sediment input from the Saharan Metacraton. Thus, relief decay associated with passive margin development may have destroyed putative topographic barriers (remains of the Cadomian magmatic arc and Pan-African belt) that impeded sediment supply from the east (Saharan Metacraton). Furthermore, drainage system expansion during this stage is also plausible as attested by the eastern Gondwana super-fan system [15], which might have enlarged its depositional area since Ordovician time. If this was the case, the Cambrian-Ordovician change in the detrital zircon content of OMZ rocks would be simply due to a shift in the sedimentary systems with the addition of an eastern Gondwanan source to the sediment supply.

Alternatively, the change in the OMZ Cambrian-Ordovician detrital zircon record might be due to a tectonically driven eastward displacement that brought this terrane to a closer position with respect to other zones of the Iberian Massif (CIZ, WALZ, and CZ). In this regard, Azor et al. [23] proposed that the eastward translation of the OMZ occurred during the vanishing stages of the Cadomian orogeny (latest Ediacaran-earliest Cambrian). Nevertheless, the data provided here constrains the change in the detrital zircon record at late Cambrian to early Ordovician time, coeval with the rift-to-drift transition and not with the subduction-to-rift one as initially claimed [23].

To sum up, two alternative scenarios can explain the change in the detrital zircon record of the OMZ: (i) a drainage system reorganization favored by the rift to drift transition with no significant translation of the OMZ terrane, or (ii) an eastward displacement of this terrane facilitated by plate tectonic kinematics. In the following paragraphs, we explore an intermediate scenario, which is maybe more likely considering the whole available data.

A first option to be considered is whether the OMZ might have been located close to the WAC all along the Ediacaran-Devonian timespan, or a certain amount of tectonically driven eastward translation to close to the Saharan Metacraton is required. In this regard, the Ediacaran OMZ samples only contain Paleoproterozoic and Neoproterozoic detrital zircon grains, plausibly derived from the WAC and the surrounding Pan-African and Cadomian mountain belts,

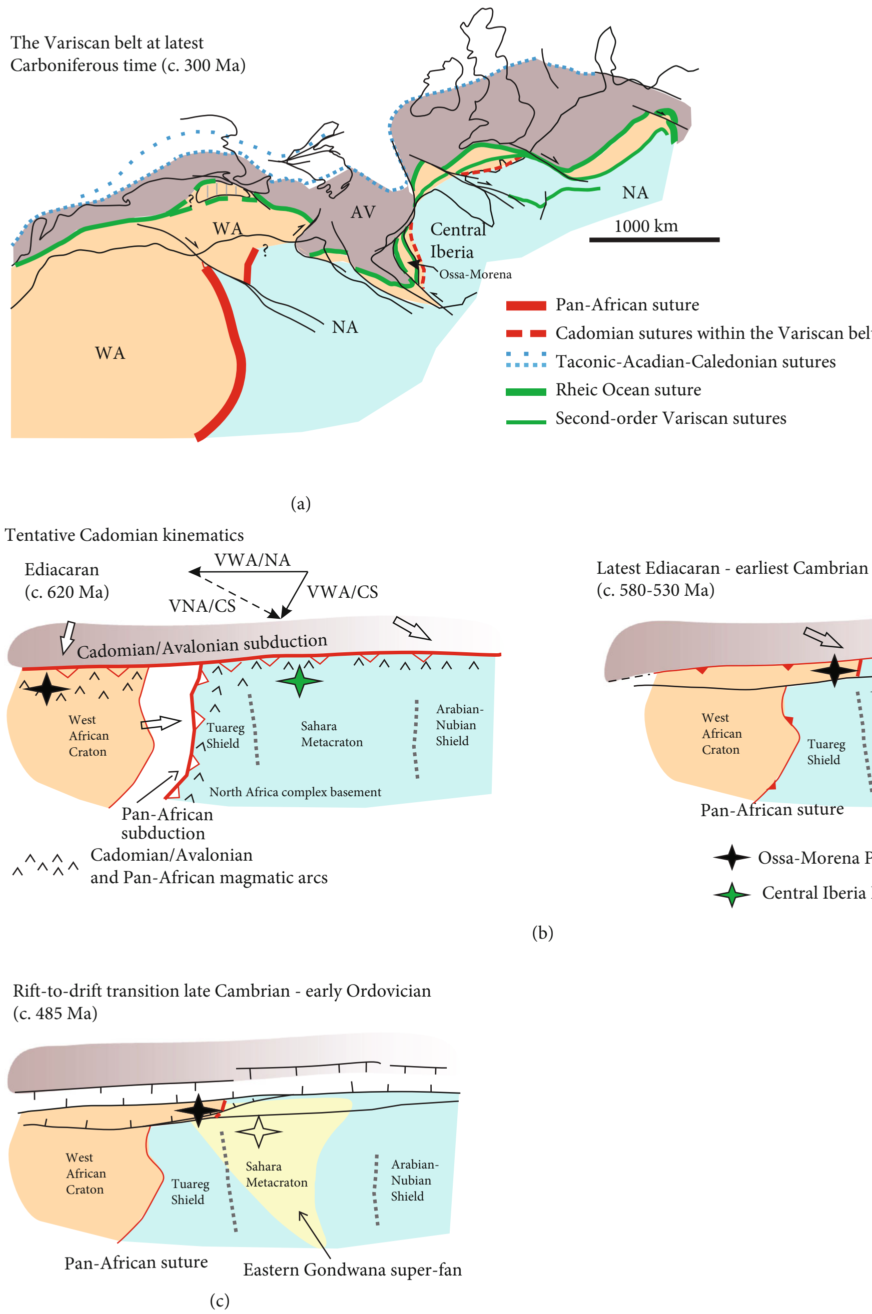

Figure 11: Schematic tectonic/paleogeographic evolution model proposed for the Ossa-Morena Zone (and other European counterparts) to explain the along-time variation in the detrital zircon record. (a) Configuration of the Variscan orogenic belt at latest Carboniferous time, showing the connection of the Ossa-Morena Zone with other European terranes that contain 2 Ga rocks, which plausibly attest a West African Craton basement. WA: West African Craton with ≈2 Ga meta-igneous rocks; NA: North Africa complex basement (Tuareg Shield, Saharan Metacraton, and Arabian-Nubian Shield); AV: Avalonian terranes. (b) Proposal (modified from [23]) of a kinematic scenario for the Cadomian/Pan-African orogeneses highlighting the shift from variably oblique subduction at Ediacaran time to dextral shearing at latest Ediacaran-earliest Cambrian time. Once Pan-African subduction was blocked, strain partitioning would have given way to transcurrent tectonics, translating eastwards a strip of the Cadomian magmatic arc. The translated ribbon-shaped arc fragment represents the crustal basement of the Ossa-Morena Zone. The dextral kinematics would have relocated the Ossa-Morena Zone close to the Tuareg Shield, which, thus would have sourced the detrital zircon grains analyzed in the Cambrian rocks reported here. VNA/CS: assumed motion of the Cadomian-subducted plate with respect to the North Africa complex basement (Tuareg Shield, Saharan Metacraton, and Arabian-Nubian Shield); VWA/NA: assumed motion of the North Africa complex basement with respect to the West African Craton; VWA/CS: assumed motion of the Cadomian-subducted plate with respect to the West African Craton. (c) After the rifting stage that marks the onset of the Variscan cycle (early-middle Cambrian), relief decay and drainage system reorganization occurred at late Cambrian-early Ordovician rift-to-drift transition, facilitated the incorporation of detrital zircon grains sourced at the Saharan Metacraton.

with no input from the Saharan Metacraton. The Cambrian samples reported here have very similar detrital zircon spectra, though in some of them, a minor 1 Ga population is also present. This can be related to a distant and intermittent Saharan Metacraton source, but the tectonic setting might have caused eastward translation that favored the incorporation of the 1 Ga detrital zircon grains. Despite the lack of reliable geometric and kinematic data on the Cadomian orogeny, the distribution and geochemistry of late Ediacaran rocks in the OMZ were unanimously attributed to a magmatic arc formed over a subduction zone affecting the northern Gondwanan margin at that time [26, 64, 121, 123]. Based on the proposal of Linnemann et al. [26] for the Cadomian subduction kinematics and the direct evidence of Pan-African collisional kinematics [124], Azor et al. [23] suggested a scenario with right-lateral displacement at latest Ediacaran-early Cambrian times (Figure 11(b)), shortly after the interruption of the Pan-African convergence. Thus, the OMZ terrane (and its European counterparts) would have undergone eastward displacement during the vanishing stages of the Cadomian orogeny. This displacement would have translated the OMZ close to the Tuareg Shield (Figure 11(b)), which, in turn, would have provided most of the detrital zircon grains found in the Cambrian rocks reported here. Interestingly, the Tuareg Shield is characterized by the absence of c. 1 Ga zircon grains ([104] and references therein), in accordance with the detrital zircon spectra found in the Cambrian rocks of the OMZ. During early-middle Cambrian time, after this dextral displacement of the OMZ, rift-related sedimentation and magmatism prevailed [65, 125].

The rift-to-drift evolution of the OMZ and other European counterparts occurred in the context of Rheic and other minor ocean opening at late Cambrian-early Ordovician times. In this situation, the reorganization of the drainage systems feeding the OMZ might have been the ultimate responsible for the incorporation of 1 Ga detrital zircon grains coming from the Saharan Metacraton (Figure 11(c)). By admitting an eastward translation of the OMZ during the vanishing stages of the Cadomian orogeny to a paleoposition close to the Tuareg Shield, we do not need to invoke additional tectonic displacement during the rift-to-drift transition, and, hence, we claim for the simplest explanation, i.e., a variation of the drainage system caused the change in the OMZ detrital zircon record with no significant tectonic displacement (Figure 11(c)). However, both boundaries of the OMZ are important tectonic contacts with pre-Variscan and Variscan displacement, and, hence, the putative influence of tectonic displacement cannot be excluded.

6. Conclusions

(i) Two classical sections of the Ossa-Morena Zone (Córdoba and Zafra; OMZ) with well-exposed and palaeontologically dated Cambrian rocks, have been analyzed to obtain detrital zircon U-Pb geochronological data. All of the studied samples show a dominant late Tonian-Ediacaran population which represents 40-90% of the concordant ages and peaks at c. 600 Ma. Secondary populations include Rhyacian-early Orosirian and late Orosirian-Statherian ages which account for 8-34% of the concordant data and show peaks centered at c. 2100 and 1900 Ma. Mesoarchean-early Siderian ages usually define a minor population representing 3-19% of the concordant data and show peaks between c. 2450 and 3050 Ma. Most of the studied samples lack a Stenian-early Tonian population, except for two samples that show a minor peak (3-8% of the data) at c. 1000 Ma

(ii) The youngest detrital zircon population in most of the Cambrian rocks of the OMZ is late Ediacaran (c. 557-602 Ma), with no systematic variation along the stratigraphic sequence. By taking these ages as maximum depositional ages (MDA) and comparing them with true depositional ages (TDA) of the Cambrian rocks of the OMZ, it can be inferred that the TDA of the studied samples is about 35-60 Ma younger than the MDA, with this gap increasing towards the top of the stratigraphic sequence. Only one sample yielded a youngest detrital zircon population with early Cambrian age (i.e., close to the stratigraphic age), which can be attributed to detritus derived from intrabasinal magmatic activity during the rifting that affected the northern Gondwana margin at Cambrian time

(iii) The detrital zircon contents found in the Cambrian rocks of the OMZ suggest derivation from the West African Craton and/or the Tuareg Shield and hence can serve to locate this terrane in a western position, with respect to the other Iberian Variscan zones at the onset of the rifting stage that opened the Rheic Ocean and drifted Avalonia from Gondwana

(iv) The detrital zircon spectra of the Cambrian OMZ rocks have a marked difference with middle Ordovician-Lower Devonian ones. The latter contain a noticeable Stenian-early Tonian detrital zircon population with a peak at c. 1000 Ma, while the former lack this population, or it only represents a very minor population. This difference is explained in terms of a reorganization of the drainage systems during the rift-to-drift transition occurred at late Cambrian-early Ordovician time, which would have favored the incorporation of detrital zircon grains derived from the Saharan Metacraton

(v) Previously, the latest Ediacaran-earliest Cambrian evolution of the OMZ involved significant eastward displacement from an initial position close to the West African Craton to a final one close to the Tuareg Shield. This eastward translation occurred during the vanishing stages of the Cadomian orogeny, which might have changed the plate kinematic scenario from subduction to right-lateral shearing

Data Availability

All data supporting the results of our study can be found in the figures, tables, and supplementary material submitted to the journal.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

This study was funded by the Consejería de Transformación Económica, Industria, Conocimiento y Universidades de la Junta de Andalucía through grants (P20_00063 and PY20-01387) and the Ministerio de Ciencia e Innovación of the Spanish government through grants (PID2020-118822GB-I00 and PID2020-119651RB-I00). Comments and suggestions made by an anonymous reviewer and Dr. Tobias Stephan have greatly contributed to improve the discussion and conclusions of this paper. We also thank Dr. Lorenzo Valetti for revision of the English style. We want to thank specially Noreen Evans, Hugo Olierook, and Bradley McDonald for the geochronological work carried out at the John de Laeter Centre (Curtin University, Perth, Australia).

Supplementary Materials

Supplementary Material 1: is a word file with details on the analytical procedure, including standard materials and references to the methodology. Supplementary material 2: is an excel file with the complete tables of analytical U-Pb results on detrital zircon grains. *(Supplementary Materials)*

References

[1] S. Lin, G. Xing, D. W. Davis et al., "Appalachian-style multi-terrane Wilson cycle model for the assembly of South China," *Geology*, vol. 46, no. 4, pp. 319–322, 2018.

[2] U. Kroner and R. L. Romer, "Two plates – many subduction zones: the Variscan orogeny reconsidered," *Gondwana Research*, vol. 24, no. 1, pp. 298–329, 2013.

[3] G. M. Stampfli, C. Hochard, C. Vérard, C. Wilhem, and J. vonRaumer, "The formation of Pangea," *Tectonophysics*, vol. 593, pp. 1–19, 2013.

[4] M. Domeier and T. H. Torsvik, "Plate tectonics in the late Paleozoic," *Geoscience Frontiers*, vol. 5, no. 3, pp. 303–350, 2014.

[5] W. Franke, L. R. M. Cocks, and T. H. Torsvik, "The Palaeozoic Variscan oceans revisited," *Gondwana Research*, vol. 48, pp. 257–284, 2017.

[6] T. Andersen, "Detrital zircons as tracers of sedimentary provenance: limiting conditions from statistics and numerical simulation," *Chemical Geology*, vol. 216, no. 3-4, pp. 249–270, 2005.

[7] G. Gehrels, "Detrital zircon U-Pb geochronology applied to tectonics," *Annual Review of Earth and Planetary Sciences*, vol. 42, no. 1, pp. 127–149, 2014.

[8] K. N. Sircombe and M. J. Freeman, "Provenance of detrital zircons on the Western Australia coastline—implications for the geologic history of the Perth basin and denudation of the Yilgarn craton," *Geology*, vol. 27, no. 10, pp. 879–882, 1999.

[9] C. M. Fedo, K. N. Sircombe, and R. H. Rainbird, "Detrital zircon analysis of the sedimentary record," *Reviews in Mineralogy and Geochemistry*, vol. 53, no. 1, pp. 277–303, 2003.

[10] D. Moecher and S. D. Samson, "Differential zircon fertility of source terranes and natural bias in the detrital zircon record: implications for sedimentary provenance analysis," *Earth and Planetary Science Letters*, vol. 247, no. 3-4, pp. 252–266, 2006.

[11] U. Zimmermann, T. Andersen, M. V. Madland, and I. S. Larsen, "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*, vol. 320, pp. 38–50, 2015.

[12] T. Andersen, M. Kristoffersen, and M. A. Elburg, "How far can we trust provenance and crustal evolution information from detrital zircons? A south African case study," *Gondwana Research*, vol. 34, pp. 129–148, 2016.

[13] C. J. Spencer, C. L. Kirkland, and R. J. M. Taylor, "Strategies towards statistically robust interpretations of *in situ* U -Pb zircon geochronology," *Geoscience Frontiers*, vol. 7, no. 4, pp. 581–589, 2016.

[14] T. Andersen, M. A. Elburg, and B. N. Magwaza, "Sources of bias in detrital zircon geochronology: discordance, concealed lead loss and common lead correction," *Earth-Science Reviews*, vol. 197, p. 102899, 2019.

[15] G. Meinhold, A. C. Morton, and D. Avigad, "New insights into peri-Gondwana paleogeography and the Gondwana super-fan system from detrital zircon U-Pb ages," *Gondwana Research*, vol. 23, no. 2, pp. 661–665, 2013.

[16] J. Fernández-Suárez, G. Gutiérrez-Alonso, D. Pastor-Galán, M. Hofmann, J. B. Murphy, and U. Linnemann, "The Ediacaran–early Cambrian detrital zircon record of NW Iberia: possible sources and paleogeographic constraints," *International Journal of Earth Sciences*, vol. 103, no. 5, pp. 1335–1357, 2014.

[17] I. Pérez-Cáceres, D. Martínez Poyatos, J. F. Simancas, and A. Azor, "Testing the Avalonian affinity of the South Portuguese Zone and the Neoproterozoic evolution of SW Iberia through detrital zircon populations," *Gondwana Research*, vol. 42, pp. 177–192, 2017.

[18] T. Stephan, U. Kroner, R. L. Romer, and D. Rösel, "From a bipartite Gondwanan shelf to an arcuate Variscan belt: the early Paleozoic evolution of northern peri-Gondwana," *Earth-Science Reviews*, vol. 192, pp. 491–512, 2019.

[19] F. Bea, P. Montero, C. Talavera et al., "The palaeogeographic position of Central Iberia in Gondwana during the Ordovician: evidence from zircon chronology and Nd isotopes," *Terra Nova*, vol. 22, no. 5, pp. 341–346, 2010.

[20] B. J. Henderson, W. J. Collins, J. B. Murphy, G. Gutierrez-Alonso, and M. Hand, "Gondwanan basement terranes of the Variscan-Appalachian orogen: Baltican, Saharan and West African hafnium isotopic fingerprints in Avalonia, Iberia and the Armorican terranes," *Tectonophysics*, vol. 681, pp. 278–304, 2016.

[21] J. Žák and J. Sláma, "How far did the Cadomian 'terranes' travel from Gondwana during early Palaeozoic? A critical

reappraisal based on detrital zircon geochronology," *International Geology Review*, vol. 60, no. 3, pp. 319–338, 2018.

[22] T. Stephan, U. Kroner, and R. L. Romer, "The pre-orogenic detrital zircon record of the Peri-Gondwanan crust," *Geological Magazine*, vol. 156, no. 2, pp. 281–307, 2019.

[23] A. Azor, D. Martínez Poyatos, C. Accotto et al., "Transcurrent displacement of the Cadomian magmatic arc," *Precambrian Research*, vol. 361, article 106251, 2021.

[24] J. B. Murphy, G. Gutiérrez-Alonso, R. D. Nance et al., "Origin of the Rheic Ocean: rifting along a Neoproterozoic suture?," *Geology*, vol. 34, no. 5, pp. 325–328, 2006.

[25] U. Linnemann, A. Gerdes, K. Drost, and B. Buschmann, "The continuum between Cadomian orogenesis and opening of the Rheic Ocean: Constraints from LA-ICP-MS U-Pb zircon dating and analysis of plate-tectonic setting (Saxo-Thuringian zone, northeastern Bohemian Massif, Germany)," in *The Evolution of the Rheic Ocean: From Avalonian-Cadomian Active Margin to Alleghenian-Variscan Collision*, U. Linnemann, R. D. Nance, P. Kraft, and G. Zulauf, Eds., vol. 423, Geological Society of America, Special Paper, 2007.

[26] U. Linnemann, M. F. Pereira, T. E. Jeffries, K. Drost, and A. Gerdes, "The Cadomian orogeny and the opening of the Rheic Ocean: the diacrony of geotectonic processes constrained by LA-ICP-MS U-Pb zircon dating (Ossa-Morena and Saxo-Thuringian zones, Iberian and Bohemian Massifs)," *Tectonophysics*, vol. 461, no. 1-4, pp. 21–43, 2008.

[27] R. D. Nance, G. Gutiérrez-Alonso, J. D. Keppie et al., "Evolution of the Rheic Ocean," *Gondwana Research*, vol. 17, no. 2-3, pp. 194–222, 2010.

[28] J. Fernández-Suárez, G. Gutiérrez Alonso, and T. T. Jeffries, "The importance of along-margin terrane transport in northern Gondwana: insights from detrital zircon parentage in Neoproterozoic rocks from Iberia and Brittany," *Earth and Planetary Science Letters*, vol. 204, no. 1-2, pp. 75–88, 2002.

[29] R. Díez Fernández, J. R. Martínez Catalán, A. Gerdes, J. Abati, R. Arenas, and J. Fernández-Suárez, "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*, vol. 18, no. 2-3, pp. 385–399, 2010.

[30] M. F. Pereira, A. R. Solá, M. Chichorro, L. Lopes, A. Gerdes, and J. B. Silva, "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*, vol. 22, no. 3-4, pp. 866–881, 2012.

[31] G. Gutiérrez-Alonso, J. Fernández-Suárez, D. Pastor-Galán et al., "Significance of detrital zircons in Siluro-Devonian rocks from Iberia," *Journal of the Geological Society, London*, vol. 172, no. 3, pp. 309–322, 2015.

[32] G. Meinhold, A. C. Morton, C. M. Fanning et al., "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*, vol. 312, no. 1-2, pp. 164–175, 2011.

[33] M. F. Pereira, G. Gutierrez-Alonso, J. B. Murphy, K. Drost, C. Gama, and J. B. Silva, "Birth and demise of the Rheic Ocean magmatic arc(s): combined U–Pb and Hf isotope analyses in detrital zircon from SW Iberia siliciclastic strata," *Lithos*, vol. 278–281, pp. 383–399, 2017.

[34] I. Pérez-Cáceres, D. Martínez Poyatos, J. F. Simancas, and A. Azor, "The elusive nature of the Rheic Ocean suture in SW Iberia," *Tectonics*, vol. 34, no. 12, pp. 2429–2450, 2015.

[35] A. Ribeiro, J. Munhá, R. Dias et al., "Geodynamic evolution of the SW Europe Variscides," *Tectonics*, vol. 26, article TC6009, 2007.

[36] A. Azor, Í. Dias da Silva, J. Gómez Barreiro et al., "Deformation and structure," in *The Geology of Iberia: A Geodynamic Approach, Volume 2: The Variscan Cycle, Regional Geology Reviews*, C. Quesada and J. T. Oliveira, Eds., pp. 307–348, Springer, 2019.

[37] M. F. Pereira, U. Linnemann, M. Hofmann et al., "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*, vol. 192–195, pp. 166–189, 2012.

[38] P. Matte, "The Variscan collage and orogeny (480-290 Ma) and the tectonic definition of the Armorica microplate: a review," *Terra Nova*, vol. 13, no. 2, pp. 122–128, 2001.

[39] J. F. Simancas, A. Tahiri, A. Azor, F. G. Lodeiro, D. J. Martínez Poyatos, and H. el Hadi, "The tectonic frame of the Variscan-Alleghanian orogen in Southern Europe and Northern Africa," *Tectonophysics*, vol. 398, no. 3-4, pp. 181–198, 2005.

[40] J. R. Martínez Catalán, K. Schulmann, and J. F. Ghienne, "The mid-Variscan Allochthon: keys from correlation, partial retrodeformation and plate-tectonic reconstruction to unlock the geometry of a non-cylindrical belt," *Earth-Science Reviews*, vol. 220, p. 103700, 2021.

[41] J. F. Simancas, D. Martínez Poyatos, I. Expósito, A. Azor, and F. González Lodeiro, "The structure of a major suture zone in the SW Iberian Massif: the Ossa- Morena/Central Iberian contact," *Tectonophysics*, vol. 332, no. 1-2, pp. 295–308, 2001.

[42] P. Matte, "Accretionary history and crustal evolution of the Variscan belt in Western Europe," *Tectonophysics*, vol. 196, no. 3-4, pp. 309–337, 1991.

[43] W. Franke, "The mid-European segment of the Variscides: tectonostratigraphic units, terrane boundaries and plate tectonic evolution," *Geological Society of London, Special Publication*, vol. 179, no. 1, pp. 35–61, 2000.

[44] J. B. Murphy, C. Quesada, G. Gutiérrez-Alonso, S. T. Johnston, and A. Weil, "Reconciling competing models for the tectonostratigraphic zonation of the Variscan orogen in Western Europe," *Tectonophysics*, vol. 681, pp. 209–219, 2016.

[45] J. P. Bard, "Signification tectonique des métathleiites d'affinité abysale de la ceinture métamorphique de basse pression d'Aracena (Huelva, Espagne)," *Bulletin de la Société Géologique de France*, vol. 7, no. 2, pp. 385–393, 1977.

[46] A. Crespo-Blanc and M. Orozco, "The southern Iberian shear zone: a major boundary in the Hercynian folded belt," *Tectonophysics*, vol. 148, no. 3-4, pp. 221–227, 1988.

[47] P. E. Fonseca and A. Ribeiro, "Tectonics of the Beja-Acebuches ophiolite: a major suture in the Iberian Variscan foldbelt," *Geologische Rundschau*, vol. 82, no. 3, pp. 440–447, 1993.

[48] C. Quesada, P. E. Fonseca, J. Munha, J. T. Oliveira, and A. Ribeiro, "The Beja-Acebuches ophiolite (southern Iberia Variscan fold belt): geological characterization and geodynamic significance," *Boletín Geológico y Minero*, vol. 105, pp. 3–49, 1994.

[49] A. Castro, C. Fernández, J. D. De la Rosa, I. Moreno-Ventas, and G. Rogers, "Significance of MORB-derived amphibolites

from the Aracena metamorphic belt, Southwest Spain," *Journal of Petrology*, vol. 37, no. 2, pp. 235–260, 1996.

[50] A. Azor, D. Rubatto, J. F. Simancas et al., "Rheic Ocean ophiolitic remnants in southern Iberia questioned by SHRIMP U-Pb zircon ages on the Beja-Acebuches amphibolites," *Tectonics*, vol. 27, no. 5, article TC5006, 2008.

[51] J. P. Burg, M. Iglesias, P. Laurent, P. Matte, and A. Ribeiro, "Variscan intracontinental deformation: the Coimbra–Cordoba shear zone (SW Iberian Peninsula)," *Tectonophysics*, vol. 78, no. 1–4, pp. 161–177, 1981.

[52] A. Azor, A. F. G. Lodeiro, and J. F. Simancas, "Tectonic evolution of the boundary between the Central Iberian and Ossa-Morena Zones (Variscan belt, Southwest Spain)," *Tectonics*, vol. 13, no. 1, pp. 45–61, 1994.

[53] M. T. Gómez-Pugnaire, A. Azor, J. M. Fernández-Soler, and V. López-Sánchez-Vizcaíno, "The amphibolites from the Ossa-Morena/Central Iberian Variscan suture (Southwestern Iberian Massif): geochemistry and tectonic interpretation," *Lithos*, vol. 68, no. 1–2, pp. 23–42, 2003.

[54] V. L. Sanchez-Vizcaino, M. T. Gomez-Pugnaire, A. Azor, and J. M. Fernandez-Soler, "Phase diagram sections applied to amphibolites: a case study from the Ossa-Morena/Central Iberian Variscan suture (southwestern Iberian Massif)," *Lithos*, vol. 68, no. 1–2, pp. 1–21, 2003.

[55] M. F. Pereira, A. Apraiz, M. Chichorro, J. B. Silva, and R. A. Armstrong, "Exhumation of high-pressure rocks in northern Gondwana during the early Carboniferours (Coimbra-Cordoba shear zone, SW Iberian Massif): tectonothermal analysis and U-Th-Pb SHRIMP *in-situ* zircon geochronology," *Gondwana Research*, vol. 17, no. 2-3, pp. 440–460, 2010.

[56] B. Abalos, J. I. Gil Ibarguchi, and L. Eguiluz, "Cadomian subduction/collision and Variscan transpression in the Badajoz-Cordoba shear belt, southwest Spain," *Tectonophysics*, vol. 199, no. 1, pp. 51–72, 1991.

[57] C. Quesada, "Geological constraints on the Paleozoic tectonic evolution of tectonostratigraphic terranes in the Iberian Massif," *Tectonophysics*, vol. 185, no. 3–4, pp. 225–245, 1991.

[58] M. Robardet, "Alternative approach to the Variscan Belt in southwestern Europe: Preorogenic paleobiogeographical constraints," in *Variscan-Appalachian Dynamics: The Building of the Late Paleozoic Basement*, J. R. M. Catalán, R. D. Hatcher, R. Arenas, and F. D. García, Eds., Geological Society of America, Special Paper 364, 2002.

[59] J. F. Simancas, F. González Lodeiro, I. Expósito, A. Azor, and D. Martínez Poyatos, "Opposite subduction polarities connected by transform faults in the Iberian Massif and western European Variscides," in *Variscan-Appalachian Dynamics: The Building of the Late Paleozoic Basement*, R. R. M. Catalán, R. D. Hatcher, R. Arenas, and F. D. García, Eds., Geological Society of America, Special Paper 364, 2002.

[60] R. Díez Fernández and R. Arenas, "The late Devonian Variscan suture of the Iberian Massif: a correlation of high-pressure belts in NW and SW Iberia," *Tectonophysics*, vol. 654, pp. 96–100, 2015.

[61] R. Díez Fernández, C. Fernández, R. Arenas, and I. Novo-Fernández, "On the rootless nature of a Devonian suture in SW Iberia (Ossa-Morena complex, Variscan Orogen): geometry and kinematics of the Azuaga fault," *Tectonics*, vol. 40, no. 6, article TC006791, 2021.

[62] M. Robardet, "L'originalité du segment hercynien sudibérique au Paléozoïque inférieur: Ordovicien, Silurien et Dévonien dans le nord de la province de Séville (Espagne)," *Comptes Rendus de l'Académie des Sciences de Paris*, vol. 283, pp. 999–1002, 1976.

[63] C. Quesada, O. Apalategui, L. Eguiluz et al., "Ossa-Morena Zone: Stratigraphy," in *Pre-Mesozoic Geology of Iberia*, R. D. Dallmeyer and E. Martínez García, Eds., pp. 252–279, Springer, Berlin, 1990.

[64] J. F. Simancas, I. Expósito, A. Azor, D. Martínez Poyatos, and F. González Lodeiro, "From the Cadomian orogenesis to the early Palaeozoic Variscan rifting in Southwest Iberia," *Journal of Iberian Geology*, vol. 30, pp. 53–71, 2004.

[65] T. Sánchez-García, M. Chichorro, A. R. Solá et al., "The Cambrian-early Ordovician rift stage in the Gondwanan units of the Iberian massif," in *The Geology of Iberia: A Geodynamic Approach, Volume 2: The Variscan Cycle*, Regional Geology Reviews, C. Quesada and J. T. Oliveira, Eds., pp. 27–74, Springer, Regional Geology Reviews, 2019.

[66] F. Sarrionandia, B. Ábalos, J. M. Errandonea et al., "Ediacaran - earliest Cambrian arc-tholeiite and adakite associations of the Malcocinado Formation (Ossa-Morena Zone, SW Spain): juvenile continental crust and deep crustal reworking in northern Gondwana," *Lithos*, vol. 372-373, article 105683, 2020.

[67] H. J. Schäfer, D. Gebauer, T. F. Nägler, and L. Eguiluz, "Conventional and ion-microprobe U-Pb dating of detrital zircons of the Tentudia group (Serie Negra, SW Spain): implications for zircon systematics, stratigraphy, tectonics and the Precambrian/Cambrian boundary," *Contributions to Mineralogy and Petrology*, vol. 113, no. 3, pp. 289–299, 1993.

[68] M. F. Pereira, M. Chichorro, A. R. Solá, J. B. Silva, T. Sánchez-García, and F. Bellido, "Tracing the Cadomian magmatism with detrital/inherited zircon ages by *in- situ* U -Pb SHRIMP geochronology (Ossa-Morena Zone, SW Iberian Massif)," *Lithos*, vol. 123, no. 1-4, pp. 204–217, 2011.

[69] M. E. Sánchez-Lorda, B. Ábalos, S. García de Madinabeitia, L. Eguíluz, J. I. Gil Ibarguchi, and J. L. Paquette, "Radiometric discrimination of pre-Variscan amphibolites in the Ediacaran Serie Negra (Ossa-Morena zone, SW Iberia)," *Tectonophysics*, vol. 681, pp. 31–45, 2016.

[70] T. Sánchez-García, M. F. Pereira, F. Bellido et al., "Early Cambrian granitoids of North Gondwana margin in the transition from a convergent setting to intra-continental rifting (Ossa-Morena Zone, SW Iberia)," *International Journal of Earth Sciences*, vol. 103, no. 5, pp. 1203–1218, 2014.

[71] A. Ochsner, *U-Pb Geochronology of the Upper Proterozoic-Lower Paleozoic Geodynamic Evolution in the Ossa-Morena Zone (SW Iberia): Constraints on the Timing of the Cadomian Orogeny, [Ph. D. thesis]*, ETH, Zurich, 1993.

[72] K. Salman, "The timing of the Cadomian and Variscan cycles in the Ossa-Morena Zone, SW Iberia: granitic magmatism from subduction to extension," *Journal of Iberian Geology*, vol. 30, pp. 119–132, 2004.

[73] M. Robardet and J. C. Gutiérrez-Marco, "Ossa-Morena Zone, stratigraphy, passive margin phase (Ordoician-Silurian-Devonian)," in *Pre-Mesozoic Geology of Iberia*, R. D. Dallmeyer and E. Martínez García, Eds., pp. 267–272, Springer-Verlag, Berlin, 1990.

[74] M. Robardet, J. M. Piçarra, P. Storch, J. C. Gutiérrez-Marco, and G. N. Sarmiento, "Ordovician and Silurian stratigraphy and faunas (graptolites and conodonts) in the Ossa-Morena Zone of the SW Iberian Peninsula (Portugal and Spain)," *Temas Geológico-Mineros*, vol. 23, pp. 289–318, 1998.

[75] M. Robardet and J. C. Gutiérrez Marco, "The Ordovician, Silurian and Devonian sadimentary rocks of the Ossa-Morena Zone (SW Iberian Peninsula, Spain)," *Journal of Iberian Geology*, vol. 30, pp. 73–92, 2004.

[76] M. Van den Boogaard and F. Vázquez Gúzman, "Conodont faunas from Portugal and southwestern Spain. Part 5. Lower carboniferous conodonts at Santa Olalla de Cala (Spain)," *Scripta Geologica*, vol. 61, pp. 1–8, 1981.

[77] U. Giese, R. Walter, and C. Winterfeld, "Geology of the southwestern Iberian Meseta II. The Aracena metamorphic belt between Almonaster La Real and Valdelarco, Huelva Province (SW Spain)," *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen*, vol. 192, pp. 333–360, 1994.

[78] A. Azor, I. Expósito, F. G. Lodeiro, J. F. Simancas, and D. M. Poyatos, "Zona de Ossa-Morena. Estructura y metamorfismo," in *Geología de España*, J. A. Vera, Ed., pp. 173–189, SGE-IGME, Madrid, 2004.

[79] J. M. Piçarra, "Nota sobre a descoberta de graptólitos do Devónico Inferior na Formaçao de Terena, em Barrancos (Zona de Ossa-Morena)," in *Estudos Sobre a Geología Da Zona de Ossa-Morena (Maciço Ibérico).*, Livro de Homenagem Ao Prof. Francisco Gonçalves, 1996.

[80] J. M. Piçarra, J. C. Gutiérrez-Marco, A. C. Lenz, and M. Robardet, "Prídolí graptolites from the Iberian Peninsula: a review of previous data and new records," *Canadian Journal of Earth Sciences*, vol. 35, no. 1, pp. 65–75, 1998.

[81] I. Expósito, *Evolución estructural de la mitad septentrional de la Zona de Ossa Morena, y su relación con el límite Zona de Ossa Morena/Zona Centroibérica, [Ph. D. thesis]*, Universidad de Granada, Spain, 2000.

[82] E. Liñán and J. Fernández-Carrasco, "La Formación Torreárboles y la paleogeografía del límite Precámbrico-Cámbrico en Ossa Morena (flanco norte de la alineación Olivenza-Monesterio)," *Cadernos do Laboratorio Xeolóxico de Laxe*, vol. 8, pp. 315–328, 1984.

[83] E. Liñán, "Las formaciones cámbricas del norte de Córdoba," *Acta Geológica Hispánica*, vol. 9, pp. 15–20, 1974.

[84] E. Liñán, M. E. Dies, J. A. Gámez Vintaned, R. Gozalo, E. Mayoral, and F. Muñiz, "Trilobites et biostratigraphie de l'Ovetien inferieur (Cambrien inferieur) de la Formation Pedroche (Sierra de Cordoba, sud de l'Espagne)," *Geobios*, vol. 38, no. 3, pp. 365–381, 2005.

[85] M. García Hernández, E. Liñán, and J. A. Comba, *Estromatolitos y facies asociadas en la Formación Santo Domingo (Cámbrico inferior de la Sierra de Córdoba)*, Libro Jubilar JM Ríos. Instituto Geológico y Minero de España, Madrid, 1983.

[86] E. Liñán and A. Perejón, "El Cámbrico inferior de la Unidad de Alconera, Badajoz (SW de España)," *Boletín de la Real Sociedad Española de Historia Natural*, vol. 79, pp. 125–148, 1981.

[87] E. Liñán, R. Gozalo, M. E. Dies Álvarez, J. A. Gámez Vintaned, and S. Zamora, "New lower ovetian trilobites (low lower Cambrian) from Sierra Morena (Spain)," *Ameghiniana*, vol. 45, pp. 123–138, 2008.

[88] E. Liñán, J. J. Álvaro, R. Gozalo, J. A. Gámez Vintaned, and T. Palacios, "El Cámbrico Medio de la Sierra de Córdoba (Ossa-Morena, S de España): Trilobites y paleoicnología. Implicaciones bioestratigráficas y paleoambientales," *Revista Española de Paleontología*, vol. 10, pp. 219–238, 1995.

[89] E. Vennin, E. Moreno-Eiris, A. Perejón, and J. J. Álvaro, "Fracturación sinsedimentaria y diagénesis precoz en las bioconstrucciones del Cámbrico Inferior de Alconera (Ossa-Morena)," *Revista de la Sociedad Geológica de España*, vol. 14, pp. 75–88, 2001.

[90] T. Palacios, S. Jensen, J. J. Álvaro et al., "Acritarch-based chronostratigraphic and radiometric calibration of the Cambrian volcanosedimentary Vallehondo and Playón formations in the Cambrian Ossa-Morena rift, Spain," *Palaeogeography, Palaeoclimatology, Palaeoecology*, vol. 565, article 110216, 2021.

[91] T. Sanchez-Garcia, "Volcanismo cámbrico en la unidad de Alconera (sector de Zafra-ZOM-Provincia de Badajoz)," *Boletín Geológico y Minero*, vol. 112, pp. 89–102, 2001.

[92] T. Sanchez-Garcia, F. Bellido, and C. Quesada, "Geodynamic setting and geochemical signatures of Cambrian-Ordovician rift- related igneous rocks (Ossa-Morena Zone, SW Iberia)," *Tectonophysics*, vol. 365, no. 1-4, pp. 233–255, 2003.

[93] M. Chichorro, M. F. Pereira, M. Díaz-Azpiroz et al., "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*, vol. 461, no. 1-4, pp. 91–113, 2008.

[94] T. Sánchez-García, F. Bellido, M. F. Pereira et al., "Rift-related volcanism predating the birth of the Rheic Ocean (Ossa-Morena Zone, SW Iberia)," *Gondwana Research*, vol. 17, no. 2-3, pp. 392–407, 2010.

[95] P. Vermeesch, "IsoplotR: a free and open toolbox for geochronology," *Geoscience Frontiers*, vol. 9, no. 5, pp. 1479–1493, 2018.

[96] P. Vermeesch, "On the visualisation of detrital age distributions," *Chemical Geology*, vol. 312-313, pp. 190–194, 2012.

[97] E. Liñán, *Bioestratigrafía de la Sierra de Córdoba, [Ph. D. thesis]*, Universidad de Granada, Spain, 1978.

[98] A. Perejón, "Bioestratigrafía de los Arqueaciatos en España," *Cuadernos de Geología Ibérica*, vol. 9, pp. 213–316, 1986.

[99] A. Perejón, "Paleogeographic and biostratigraphic distribution of Archaeocyatha in Spain," *Courier Forschungsinstitut Senckenberg*, vol. 172, pp. 341–354, 1994.

[100] C. Accotto, D. Martínez Poyatos, A. Azor et al., "Mixed and recycled detrital zircons in the Paleozoic rocks of the Eastern Moroccan Meseta: Paleogeographic inferences," *Lithos*, vol. 338–339, pp. 73–86, 2019.

[101] C. Accotto, D. Martínez Poyatos, A. Azor et al., "Syn-collisional detrital zircon source evolution in the northern Moroccan Variscides," *Gondwana Research*, vol. 93, pp. 73–88, 2021.

[102] C. Accotto, D. Martínez Poyatos, A. Azor et al., "Systematics of detrital zircon U-Pb ages from Cambrian-Lower Devonian rocks of northern Morocco with implications for the northern Gondwanan passive margin," *Precambrian Research*, vol. 365, p. 106366, 2021.

[103] C. Accotto, D. Martínez Poyatos, A. Azor et al., "Detrital zircon sources in the Ordovician metasedimentary rocks of the Moroccan Meseta: Inferences for northern Gondwanan passive-margin paleogeography," in *New Developments in the Appalachian-Caledonian-Variscan Orogen*, Y. D. Kuiper, J. B. Murphy, R. D. Nance, R. A. Strachan, and M. D. Thompson, Eds., Geological Society of America, special paper 554, 2022.

[104] A. Cambeses, J. H. Scarrow, P. Montero, C. Lázaro, and F. Bea, "Palaeogeography and crustal evolution of the Ossa–Morena Zone, southwest Iberia, and the North Gondwana

margin during the Cambro-Ordovician: a review of isotopic evidence," *International Geology Review*, vol. 59, no. 1, pp. 94–130, 2017.

[105] U. Linnemann, A. Gerdes, M. Hofmann, and L. Marko, "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*, vol. 244, pp. 236–278, 2014.

[106] J. Shaw, G. Gutiérrez-Alonso, S. T. Johnston, and D. Pastor Galán, "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*, vol. 126, no. 5-6, pp. 702–719, 2014.

[107] J. F. Ghienne, A. Benvenuti, M. El Houicha et al., "The impact of the end-Ordovician glaciation on sediment routing systems: a case study from the Meseta (northern Morocco)," *Gondwana Research*, vol. 63, pp. 169–178, 2018.

[108] D. Letsch, M. El Houicha, A. von Quadt, and W. Winkler, "A missing link in the peri-Gondwanan terrane collage: the Precambrian basement of the Moroccan Meseta and its Lower Paleozoic cover," *Canadian Journal of Earth Sciences*, vol. 55, no. 1, pp. 33–51, 2018.

[109] S. Collett, K. Schulmann, P. Štípská, and J. Míková, "Chronological and geochemical constraints on the pre-variscan tectonic history of the Erzgebirge, Saxothuringian Zone," *Gondwana Research*, vol. 79, pp. 27–48, 2020.

[110] B. Solís-Alulima, J. Abati, A. López-Carmona, G. Gutiérrez-Alonso, J. Fernández-Suárez, and D. F. Stockli, "Detrital zircon ages and provenance of a Cambrian succession in the sierra Albarrana domain (SW Iberian massif)," *Lithos*, vol. 408-409, p. 106542, 2022.

[111] R. D. Nance, J. B. Murphy, R. A. Strachan et al., "Neoproterozoic-early Palaeozoic tectonostratigraphy and palaeogeography of the peri-Gondwanan terranes: Amazonian v. West African connections," in *The Boundaries of the West African Craton*, N. Ennih and J. P. Liégeois, Eds., vol. 297, pp. 345–383, Geological Society of London, Special Publication, 2008.

[112] J. C. Gutiérrez-Marco, J. M. Piçarra, C. A. Meireles et al., "Early Ordovician–Devonian Passive Margin Stage in the Gondwanan Units of the Iberian Massif," in *The Geology of Iberia: A Geodynamic Approach, volume 2: the Variscan Cycle, Regional Geology Reviews*, C. Quesada and J. T. Oliveira, Eds., Springer, 2019.

[113] W. Franke, "The Variscan orogen in Central Europe: construction and collapse," in *European Lithosphere Dynamics*, D. G. Gee and R. A. Stephenson, Eds., Geological Society of London, Memoir 32, 2006.

[114] J. R. Martínez Catalán, S. Collett, K. Schulmann, P. Aleksandrowski, and S. Mazur, "Correlation of allochthonous terranes and major tectonostratigraphic domains between NW Iberia and the Bohemian Massif, European Variscan belt," *International Journal of Earth Sciences*, vol. 109, no. 4, pp. 1105–1131, 2020.

[115] C. Guerrot, J. J. Peucat, R. Capdevila, and L. Dosso, "Archean protoliths within early Proterozoic granulitic crust of the west European Hercynian belt: possible relics of the West African Craton," *Geology*, vol. 17, no. 3, pp. 241–244, 1989.

[116] V. Gardien, N. Arnaud, and L. Desmurs, "Petrology and Ar-Ar dating of granulites from the Galicia Bank (Spain): African Craton relics in Western Europe," *Geodinamica Acta*, vol. 13, no. 2–3, pp. 103–117, 2000.

[117] J. Y. Calvez and P. Vidal, "Two billion years old relicts in the Hercynian belt of Western Europe," *Contributions to Mineralogy and Petrology*, vol. 65, no. 4, pp. 395–399, 1978.

[118] S. D. Samson and R. S. D'Lemos, "U–Pb geochronology and Sm–Nd isotopic composition of Proterozoic gneisses, Channel Islands, UK," *Journal of the Geological Society*, vol. 155, no. 4, pp. 609–618, 1998.

[119] J. D. Inglis, S. D. Samson, R. S. D'Lemos, and M. Hamilton, "U-Pb geochronological constraints on the tectonothermal evolution of the Paleoproterozoic basement of Cadomia, La Hague, NW France," *Precambrian Research*, vol. 134, no. 3-4, pp. 293–315, 2004.

[120] J. M. Fuenlabrada, R. Arenas, S. Sánchez Martínez et al., "Geochemical and isotopic (^{Sm}single bondNd) provenance of Ediacaran-Cambrian metasedimentary series from the Iberian Massif. Paleoreconstruction of the North Gondwana margin," *Earth-Science Reviews*, vol. 201, p. 103079, 2020.

[121] E. Rojo-Pérez, J. M. Fuenlabrada, U. Linnemann et al., "Geochemistry and Sm–Nd isotopic sources of Late Ediacaran siliciclastic series in the Ossa–Morena Complex: Iberian–Bohemian correlations," *International Journal of Earth Sciences*, vol. 110, no. 2, pp. 467–485, 2021.

[122] M. F. Pereira and C. Gama, "Revisiting the Intermediate Sediment Repository Concept Applied to the Provenance of Zircon," *Minerals*, vol. 11, p. 233, 2021.

[123] L. Eguíluz, J. I. Gil Ibarguchi, B. Ábalos, and A. Apraiz, "Superposed Hercynian and Cadomian orogenic cycles in the Ossa-Morena zone and related areas of the Iberian Massif," *Geological Society of America Bulletin*, vol. 112, no. 9, pp. 1398–1413, 2000.

[124] H. El Hadi, J. F. Simancas, D. Martínez-Poyatos et al., "Structural and geochronological constraints on the evolution of the Bou Azzer Neoproterozoic ophiolite (Anti-Atlas, Morocco)," *Precambrian Research*, vol. 182, no. 1-2, pp. 1–14, 2010.

[125] J. F. Simancas, "Variscan cycle," in *The Geology of Iberia: A Geodynamic Approach, Volume 2: The Variscan Cycle, Regional Geology Reviews*, C. Quesada and J. T. Oliveira, Eds., pp. 1–25, Springer, 2019.

[126] A. Michard, A. Soulaimani, C. Hoepffner et al., "The South-Western branch of the Variscan belt: evidence from Morocco," *Tectonophysics*, vol. 492, no. 1-4, pp. 1–24, 2010.

[127] J. F. Simancas, A. Azor, D. J. Martínez Poyatos et al., "Relations tectoniques du Sud-Ouest de l'Iberie avec les allochtones du Nord- Ouest iberique et le Maroc varisque," *Comptes Rendus Geoscience*, vol. 341, no. 2-3, pp. 103–113, 2009.

[128] B. Ordóñez Casado, *Geochronological Studies of the Pre-Mesozoic Basement of the Iberian Massif: The Ossa Morena Zone and the Allochthonous Complexes within the Central Iberian Zone, [Ph. D. thesis]*, Swiss Federal Institute of Technology, Zurich, Switzerland, 1998.

[129] H. J. Schäfer, *Geochronological Investigations in the Ossa Morena Zone, SW Spain, [Ph. D. thesis]*, Swiss Federal Institute of Technology, Zurich, Switzerland, 1990.

[130] G. Gutiérrez-Alonso, J. Fernández-Suárez, T. E. Jeffries et al., "Terrane accretion and dispersal in the northern Gondwana margin. An early Paleozoic analogue of a long-lived active margin," *Tectonophysics*, vol. 365, no. 1-4, pp. 221–232, 2003.

[131] C. Talavera, P. Montero, D. Martínez Poyatos, and I. S. Williams, "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*, vol. 22, no. 3-4, pp. 928–942, 2012.

[132] M. Jouhari, F. Chopin, M. El Houicha et al., "U-Pb detrital zircon geochronology and source provenance in the Moroccan Meseta (Variscan belt): a perspective from the Rehamna Massif," *Journal of African Earth Sciences*, vol. 194, article 104611, p. 104610, 2022.

[133] J. Abati, A. Mohsine Aghzer, A. Gerdes, and N. Ennih, "Detrital zircon ages of Neoproterozoic sequences of the Moroccan Anti-Atlas belt," *Precambrian Research*, vol. 181, no. 1-4, pp. 115–128, 2010.

[134] D. Avigad, A. Gerdes, N. Morag, and T. Bechstädt, "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*, vol. 21, no. 2-3, pp. 690–703, 2012.

[135] U. Linnemann, K. Ouzegane, A. Drareni et al., "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-ICP-MS detrital zircon ages," *Lithos*, vol. 123, no. 1-4, pp. 188–203, 2011.

[136] D. Rösel, S. D. Boger, A. Möller et al., "Indo-Antarctic derived detritus on the northern margin of Gondwana: evidence for continental-scale sediment transport," *Terra Nova*, vol. 26, no. 1, pp. 64–71, 2014.