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Provenance of Ediacaran-Ordovician sediments of the Medio Armorican Domain, Brittany, West France: Constraints from U/Pb detrital zircon and Sm–Nd isotope data

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Abstract

The temporal evolution of the sedimentary source areas of the Armorican Massif, involving Ediacaran to Upper Ordovician strata, is investigated to gain insight into the palaeogeographic affinities and changes that occurred as a result of Cadomian orogenesis. Until now, palaeogeographic reconstructions based on geodynamic, stratigraphic and paleontological data have shown geological continuity between the Armorican Massif and the Iberian and Bohemian massifs and have allowed researchers to locate the Armorican Massif near the West African Craton and the Trans-Saharan Belt. This study goes beyond the interpretations based on lithostratigraphic correlation, which may be influenced by allocyclic factors (e.g., sea-level change) or fauna assemblages that have a wide provincial distribution, to provide a correct assessment of sediment flux. To determine the palaeogeographic location more accurately, the provenance of the siliciclastic sediments was examined in this study using U–Pb LA-MC-ICP–MS geochronology on detrital zircons coupled with whole-rock Sm–Nd and zircon Lu–Hf isotope analysis. This work was carried out on the sedimentary succession of the Medio Armorican Domain. The oldest studied sedimentary rocks were shown to belong to the Brioverian succession, which contains mainly 519–

[1] †Deceased

781 Ma old zircons, likely derived from sources that are still present in the Armorican basement. Successively, the lower Paleozoic succession was deposited in the rift stages of the Rheic Ocean, with contributions from a new source of 827–1,120 Ma old zircons.

A comparison of the zircon populations showed an increase in negative $\varepsilon_{Nd(t)}$ and $\varepsilon_{Hf(t)}$ values of the sedimentary supply in the post-Cadomian samples. Moreover, it revealed that the Medio and North Armorican domains had different locations during the Lower Ordovician, and that some areas of the Iberian Massif and the Medio Armorican Domain close to the Sahara Metacraton and Arabian-Nubian Shield were contiguous.

Keywords: North Gondwana; Cadomian Belt; Brioverian; Grès Armoricain Formation; U-Pb geochronology zircon

1. Introduction

The present study aims to analyse the provenance of sediments of the Armorican Massif (West France), from the Ediacaran–early Cambrian (Cadomian cycle) to the Late Ordovician, and to explore the palaeogeographic implications of the results. For this area, palaeogeographic reconstructions have been established on the basis of geodynamic arguments, i.e., the evolution of the Cadomian Belt during the Ediacaran, rifting of the Rheic Ocean in the Cambrian, and the opening in the Early Ordovician (e.g., Chantraine et al., 2001; Linnemann et al., 2014). In addition, and especially for Paleozoic times, stratigraphic and paleontological arguments have been used, e.g., the strong affinities between benthic fauna of the Medio and North Armorican Domain (Armorican Massif) and the Central Iberian Zone (Iberian Massif) (Paris and Robardet, 1977; Young, 1988; Robardet, 2002). These arguments have suggested geological continuity between the Armorican Massif and the Iberian and Bohemian massifs and allowed researchers to locate the Armorican Massif at the periphery of the Gondwana supercontinent close to the West African Craton and Trans-Saharan Belt (e.g., Linnemann et al., 2008; Avigad et al., 2012; Pereira et al., 2012a, b). However, these proxies are not homogeneous and involve very large areas. This is the case with some stratigraphic evolutions that may be controlled by allocyclic factors (e.g., sea-level variations) or with faunal assemblages that have a wide provincial distribution and appear rather homogeneous over vast domains. Other approaches can be used to reconstruct the palaeogeographic position, such as the characterization of source areas of siliciclastic supplies. In particular, detrital zircon age dating is a powerful tool to analyse the provenance of clastic sediments and to understand the paleogeography and tectonic evolution of continental realms. Only limited zircon data are available for the Armorican Massif (i.e., Fernández-Suráez et al., 2002a; Strachan et al., 2014; Gougeon et al., 2018; Ballouard et al. 2018), but there is an abundance of chronological literature concerning the Iberian Massif (e.g., Fernández-Suárez et al., 2000, 2002b; Pereira et al., 2012a, b; Shaw et al., 2014; Talavera et al., 2015), Saxo-Thuringia (Linnemann et al., 2008), and North Africa (e.g., Meinhold et al., 2011; Avigad et al., 2012; Gärtner et al., 2016).

The purpose of the present study is to identify the origin of Ediacaran to Upper Ordovician sediments in the Crozon Peninsula within the Medio Armorican Domain (Fig. 1), in which U–Pb LA-MC-ICP–MS geochronology was applied in the characterization of detrital zircons and coupled with whole-rock Sm–Nd and Lu–Hf on zircon isotope analyses. As a consequence, the affinity between the Iberian and Armorican massifs is considered in order to provide insights into the palaeogeographic location of the Medio Armorican Domain at the North Gondwana margin and its relations with the Iberian Massif.

Fig.1: (A) Schematic palaeogeographical reconstruction of the Gondwana supercontinent around 485 Ma (modified from Linnemann et al., 2008). Terranes that are still recognizable are shown in black. OMZ: Ossa Morena Zone; AM: Armorican Massif; SXZ: Saxo-Thuringian Zone; TBU: Tepla-Barrandian Unit.
(B) Simplified geological map of the Armorican Massif, modified after Chantraine et al. (1996), and location of the studied samples in the Medio Armorican Domain (black stars). Samples from Normandy (white squares: Strachan et al., 2014), North Brittany (grey square: Fernández-Suárez et al., 2002a), Central Brittany (black square; Gougeon et al., 2018); samples NEA, PON, DAO, PLO, and SNC are from Dabard et al. (1996), and samples 7a, 7b, 8, 18, and 26 are from Michard et al. (1985).

2. Geological setting

Late Carboniferous transcurrent shear zones (Jégouzo, 1980; Gapais and Le Corre, 1980) subdivide the Armorican Massif into three domains: the North Armorican Domain (NAD) and the Medio Armorican Domain (MAD), which are grouped together into the Medio-North Armorican Domain (MNAD), and the South Armorican Domain (Fig.1). These serve as records of distinct tectonic and magmatic evolution during Cadomian and Variscan orogenesis.

During the Neoproterozoic, the Armorican Massif experienced a suite of extensive and compressive episodes associated with magmatism that led to the development of the Cadomian Belt (cf. synthesis in Chantraine et al., 2001). The main evidence for the Cadomian orogeny, which is a part of the Pan-African orogeny, is derived from the NAD. In North Brittany, geochemical studies (e.g., Thiéblemont et al., 1999) demonstrated the existence of continental arcs around 750–650 Ma (Eocadomian) that affected the Icartian basement (1.8–2.1 Ga). Subsequently, several episodes of magmatic activity occurred in succession (c. 610–575 Ma and 555–530 Ma). At the same time, a thick siliciclastic succession, called the Brioverian Supergroup, accumulated in extensional basins. They are divided into two groups. The lower Brioverian Group of Ediacaran age is located in the NAD and is made up of sediments containing interbedded graphitic cherts (phtanites: Dabard, 2000) or devoid of cherts. This group was deposited between 624 Ma, the age of the youngest detrital zircon grains in the basal part of the group (e.g., Poudingue de Cesson: Samson et al., 2003), and about 580 Ma, the age of plutonic intrusions into the sedimentary successions (e.g., Coutances quartz diorite: Guerrot and Peucat, 1990; Saint Quay diorite: Nagy et al., 2002). The upper Brioverian Group of late Ediacaran to early Cambrian age (Guerrot et al., 1992; Gougeon et al., 2018) is present in the three domains and is composed of sediments containing chert clasts.

In the MAD, the upper Brioverian sediments consist of several-thousand-meters-thick alternations of wackes and siltstones that were mainly deposited in various sedimentary environments, ranging from submarine fans to continental shelf deposits. The latter are represented by distal to tidal plain facies. These sedimentary strata were, in part, slightly deformed during the

Cadomian orogeny (Le Corre, 1977). The lower Paleozoic deposits consist mainly of siliciclastic lithofacies alternating with some carbonate levels (Paris et al., 1999; Vidal et al., 2011a). The sedimentation of the Brioverian sediments began between the Tremadocian and the Floian (Lower Ordovician) with the Initial Red Beds (Cap de la Chèvre Formation in the Crozon Peninsula) and the Grès Armoricain Formation (Fm), which rest unconformably on the Brioverian strata (Fig. 2). The Initial Red Beds are characterized by lateral facies variations and were deposited in alluvial to deltaic environments (Bonjour, 1988; Suire et al., 1991). The Grès Armoricain Fm was deposited in wave- and tide-dominated nearshore environments (Dabard et al., 2007; Pistis et al., 2016). The significant lateral thickness variations (0–100 m for the Initial Red Beds and 20–700 m for the Grès Armoricain Fm) are related to the extensional event that led to the progressive opening from west to east, in present coordinates, of the Rheic Ocean between southern Avalonia and North Gondwana (Fig. 1a). A model of tilted blocks associated with listric faults was proposed for the Initial Red Beds (Dauteuil et al., 1987; Brun et al., 1991). For the Grès Armoricain Fm, the large thicknesses (several hundreds of meters) of isofacies are explained by high subsidence rates. The lateral variations in thicknesses are linked to tectonically controlled depocenters that are constantly filled in by oversupplied nearshore depositional systems (Dabard et al., 2015). From the Darriwilian (Middle Ordovician), the subsidence rate stabilized around 20 m/my, which is interpreted as post-rift thermal subsidence (Dabard et al., 2015). Up to the end of the Ordovician, the sediments were laid down in a continental shelf whose main architecture was controlled by high glacioeustatic variations under icehouse conditions (Dabard et al., 2015). Until the Sandbian (early Late Ordovician), the sedimentation is represented by silty–clayey lithofacies (Postolonnec Fm on the Crozon Peninsula, 400 m thick, Fig. 2) deposited in a storm-dominated shelf environment (Dabard et al., 2015). After a major sea-level fall, sedimentation continued into the Katian with micaceous sandstones, quartz arenites and mudstones (Kermeur Fm on the Crozon Peninsula, 90–450 m thick, Fig. 2) deposited in bay/lagoon barrier environments evolving toward open shelf settings (Vidal et al., 2011b; Gorini et al., 2008). Sedimentation then continued, without significant interruptions, until the Carboniferous with the development of several-thousand-meter-thick deposits.

The samples for the U–Pb LA-MC-ICP–MS geochronology of detrital zircons were collected from the Crozon Peninsula (western part of the MAD, Figs. 1 and 2) at Trez Bihan (BS and IRBS samples at N 48°13'07.16"; W 4°22'57.36" and coordinate: N 48°13'15.70"; W 4°23'56.25", respectively), Morgat (GAFS sample, N 48°13'18.92"; W 4°29'43.43"), Postolonnec (PFS sample, N 48°14'17.47"; W 4°28'06.24") and Veryarc'h (KFS sample, N 48°15'40.15"; W 4°36'29.19") along beach cliffs. The Brioverian BS sample is a fine quartz wacke with a matrix and was taken about 10 meters below the post-Cadomian angular unconformity surface. The IRBS sample (Cap de la Chèvre Fm) is a subarkose with abundant lithic fragments, collected about 80 meters above the same angular unconformity. The IRBS sample (Cap de la Chèvre Fm) is a subarkose with abundant lithic fragments, collected about 80 meters above the angular discordance. The GAFS sample (Grès Armoricain Fm) is a fine-grained quartz arenite without a matrix of abundant heavy minerals (e.g., rutile, zircon, monazite, tourmaline, ...), collected about 60 meters below the stratigraphic boundary with the overlying Postolonnec Fm. The PFS sample (Postolonnec Fm) is a medium-grained quartz arenite without a matrix, taken at 136 meters from the base of the formation. The KFS sample (Kermeur Fm) is a medium-grained quartz arenite with low matrix content, which was collected at 114 meters from the base of the formation.

Some Sm–Nd whole-rock data of sedimentary rocks are partly provided by published data (for details, see Michard et al., 1985; Dabard et al., 1996). The samples of this study (Fig 1 and 2) are from different localities of the MAD. The sample of Brioverian quartz wacke, 99036, was taken at about 9 km from North Laval (black star in Fig. 1, N 48°09'22.21"; W 0°44'47.92"). The sample of sandy siltstone from the Initial Red Beds, LBG5-8872, was taken at Pont Réan (South of Rennes, black star in Fig. 1, at N 47°59'45.99"; W 1°45'00.26"). The quartz wacke sample 8RL3-8881, also from the Initial Red Beds succession, was taken at Cap de la Chèvre (Crozon Peninsula, black star in Fig. 1, at N 48°10'14.78"; W 4°32'25.62"). Two samples of very fine quartz arenite from the Grès

Armoricain Fm, denoted CFR25-5618 and CFR28-5617, were taken at the old quarry of Camp Français in North Laval (black star in Fig. 1, at N 48°09'17.52"; W 0°44'51.47" and N 48°09'18.99"; W 0°44'59.33", respectively). All samples are poor in heavy mineral content and have a fine phyllosilicate matrix when a matrix is present.

Fig.2: Lithostratigraphic (x-axis represents grain-size from mudstone to conglomerate) context of the Lower Paleozoic succession in the Crozon Peninsula (modified after Vidal et al., 2011a). This figure indicates the stratigraphic positions of the studied samples.

3. Methodology

The Sm and Nd concentrations were obtained by the isotope dilution method using a Cameca TSN 206 mass spectrometer at Rennes University. Total blanks for the chemical separations are estimated to be around 0.1 ng for Nd. Isotopic compositions of Nd were determined using a Finnigan MAT 262 mass spectrometer. Isotopic ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$. The results are reported relative to the La Jolla Nd standard (= 0.511860). The detailed technique for Sm–Nd analysis is reported in Jahn et al. (1980). The precisions of measurements are given at the 95% confidence level. T_{DM} model ages were calculated according to DePaolo (1981).

Zircon concentrates were extracted from 3–4 kg of each rock sample by first crushing and then using conventional magnetic and heavy liquid separation techniques. The samples were not sieved before zircon separation. For each sample, an arbitrary aliquot of this detrital zircon fraction, almost 150 zircon grains per sample, was placed in a glass with ethanol and selected randomly without bias using a pipette under a binocular microscope. This technique avoids bias as the grains are randomly selected without any pre-consideration of size, colour, or shape (Sláma and Košler, 2012). Afterward, the zircon grains were mounted into epoxy blocks and polished to about half-thickness in order to better expose internal surfaces. Then, the blocks were sputtered with carbon and zircon and examined for internal structures (such as magmatic zonation or metamorphic rims) using the FEI Quanta 450 scanning electron microscope at the University of Brasilia.

The U–Pb and Lu–Hf isotopic analyses were performed on zircon using a Thermo Scientific Neptune MC-ICP–MS coupled with a Nd:YAG UP213 NewWave laser ablation system (Laboratory Conditions in Supplementary Materials) installed in the Laboratory of Geochronology and Isotope Geochemistry of Brasilia University.

The U–Pb analyses of zircon grains were carried out using the sample–standard bracketing method (Albarède et al., 2004) using GJ-1 (Jackson et al., 2004) as the first standard zircon in order to quantify the amount of ICP–MS fractionation. Between four and eight (when little fractionation is observed) unknown zircon samples were analysed per two GJ-1 reference material analyses and the $^{206}Pb/^{207}Pb$ and $^{206}Pb/^{238}U$ ratios were time corrected. The raw data were processed offline and reduced using an Excel worksheet (Bühn et al., 2009). Analyses were performed using a spot size of 30 µm in general, and laser-induced fractionation of the $^{206}Pb/^{238}U$ ratio was corrected using the linear regression method (Koşler et al., 2002). During each analytical session, the zircon standard Temora-2 (Black et al., 2004; Temora U/Pb data in Supplementary Material), for which the recommended age is 390–420 Ma, was also analysed as a secondary zircon standard.

Lu–Hf isotopes were analysed in selected zircon grains that had previously been analysed using the U–Pb method. The selection was made on the basis of the highest concordance values (95–105%) and for representativity of all observed U–Pb age groups in a sample's age population. Lu–Hf isotopic analyses were performed following the methodology of Matteini et al. (2010). The $\varepsilon_{Hf}(t)$ values were calculated using the decay constant $\lambda = 1.865 \times 10^{-11}$ yr^{-1} proposed by Scherer et al. (2001) and $^{176}Lu/^{177}Hf$ and $^{176}Hf/^{177}Hf$ CHUR values of 0.0336 and 0.282785 (Bouvier et al., 2008). A two-stage T_{DM} age was calculated from the initial Hf isotopic composition of the zircon using an average crustal Lu/Hf ratio of 0.0113 (Gerdes and Zeh, 2006, 2009; Nebel et al., 2007). This value was selected because it best represents the composition of a hypothetical crust. The initial Hf composition of zircon represents the $^{176}Hf/^{177}Hf$ value calculated at the time of zircon crystallization, given by the U-Pb age previously obtained for the same grain and that, if possible, should be concordant. The two-stage depleted mantle Hf model ages (T_{DM} Hf) were calculated using $^{176}Lu/^{177}Hf$ = 0.0384 and $^{176}Hf/^{177}Hf$ = 0.28325 for the depleted mantle (Chauvel and Blichert-Toft, 2001) and a $^{176}Lu/^{177}Hf$ value of 0.0113 for average crust (Taylor and McLennan, 1985; Wedepohl, 1995).

Before Hf isotope measurements of zircons, replicate analyses of a 200 ppb Hf JMC 475 standard solution doped with Yb (Yb/Hf = 0.02) were carried out with the following result: $^{176}Hf/^{177}Hf$ = 0.282162 ± 13, 2s error, n = 4. During the analytical session replicate analyses of the GJ-1 standard zircon were conducted, which gave an average $^{176}Hf/^{177}Hf$ ratio of 0.282006 ± 16 2s (*n = 25*), in agreement with the reference value for the GJ standard zircon (Morel et al., 2008).

4. Analytical results

4.1. Whole rock Sm–Nd isotopic analyses

The $^{143}Nd/^{144}Nd$ initial ratios and ε_{Nd} were recalculated for each formation taking into account the stratigraphic available age. Samples from the upper Brioverian Group yield negative ε_{Nd} (540) values ranging between −1.4 and −6.3 (Tab. 1, Fig. 3) and Mesoproterozoic Nd model ages ranging between 1.2 and 1.6 Ga. The two IRB samples also have negative ε_{Nd} (480) values of −3.0 and −4.4 and Mesoproterozoic Nd model ages of 1.4 and 1.5 Ga, similar to the data obtained for the Brioverian sediments. For the Grès Armoricain Fm, all analysed samples exhibit large negative ε_{Nd}(470) values between −8.5 and −11.5 and Paleoproterozoic Nd model ages ranging from 1.7 to 2.1 Ga.

Table 1: Whole–rock Sm and Nd concentrations and Nd isotope data of Brioverian and Lower Ordovician sedimentary rocks. Data (1) from Dabard et al. (1996), (2) Michard et al. (1985), and (3) this work (LBG5: Pont Réan, South of Rennes; 8RL3: Crozon Peninsula; 99036, CFR25 and CFR28: North Laval). T_{DM} model ages calculated according to DePaolo (1981).

samples	Ages Ma	Sm	Nd	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ (± 2σ)	$\varepsilon_{Nd(0)}$	$\varepsilon_{Nd(t)}$	T_{DM} (Ga)
Brioverian	540							
NEA (1)		2.96	15.36	0.1164	0.512283(6)	-7.0	-1.4	1.20
PON (1)		5.89	29.04	0.1225	0.512285(5)	-6.9	-1.8	1.28
DAO (1)		3.09	15.64	0.1194	0.512045(6)	-11.6	-6.3	1.64

PLO (1)		2.81	13.95	0.1219	0.512100(7)	-10.5	-5.4	1.60
SNC (1)		4.34	22.62	0.116	0.512227(5)	-8.1	-2.5	1.28
8 (2)		5.95	27.2	0.1323	0.512266(28)	-7.3	-2.9	1.48
26 (2)		8.33	39.91	0.1263	0.512180(34)	-9.0	-4.1	1.50
99036 (3)		4.81	24.19	0.1201	0.512237(5)	-7.9	-2.6	1.33
Initial Red Beds	480							
LBG5-8872 (3)		6.07	29.28	0.1254	0.512191(3)	-8.8	-4.4	1.48
8RL3-8881 (3)		2.58	12.26	0.127	0.512269(3)	-7.2	-3.0	1.39
Grès Armoricain Fm	470							
7b (2)		9.57	45.99	0.1259	0.511988(29)	-12.7	-8.5	1.84
7a (2)		1.85	10.09	0.1109	0.511788(35)	-16.6	-11.5	1.87
18 (2)		3.76	22.43	0.1014	0.511755(33)	-17.3	-11.5	1.73
CFR25-5618 (3)		7.56	44.65	0.1023	0.511837(3)	-15.7	-10.0	1.65
CFR28-5617 (3)		18.13	85.24	0.1285	0.511885(3)	-14.7	-10.6	2.07

Fig.3: Age (Ga) versus $\varepsilon_{Nd(t)}$ diagram for the Brioverian (red triangles), Initial Red Beds (IRB) (blue circles) and Grès Armoricain (yellow squares) samples.

4.2. Detrital zircon ages

Generally, the zircon grain sizes of the analysed samples did not exceed 260 µm, with the most frequently observed size being around 100 µm. The zircon grains of the GAFS (Grès Armoricain Fm) sample are very well sorted and, on average, smaller than those of the other samples. The zircon grains are generally colourless or weakly coloured and have euhedral shapes with rare rounded grains. An exception is the GAFS sample and, to a lesser degree, the samples from overlying strata, where the observation of numerous coloured and rounded grains are testament to long transport processes or multiple deposition/alteration/transport cycles.

From the Brioverian sample (BS), 68 detrital zircon grains were analysed and 49 gave concordant data (Fig. 4 and U/Pb data in Supplementary Material). The most abundant age population (67%) is Ediacaran to Tonian <800 Ma in age (33 zircon grains). The Kernel probability plot shows two Ediacaran major peaks (587 Ma and 620 Ma) and two minor Cryogenian (666 Ma) and Tonian (724 Ma) peaks. There is a prominent age gap between 781 Ma and 1.93 Ga (Orosirian), with the exception of a single zircon grain with an age of 988 Ma. Ten zircon grains yield Paleoproterozoic ages, with a peak at 2.02 Ga, and four grains yield Archean ages.

In the Lower Ordovician sample (IRBS), 55 detrital zircon grains give concordant results, out of 69 analysed grains. The ages for the most abundant zircon population (38 zircon grains) are from Furongian (latest Cambrian) to Tonian <800 Ma, with 24 zircon grains being Ediacaran in age. The Kernel probability plot shows two Ediacaran major peaks (568 and 622 Ma) and two minor peaks at 490 Ma (late Cambrian) and 694 Ma (Cryogenian). There is a prominent age gap between the Tonian <800 Ma and the Orosirian, with exception of two zircon grains with ages of 901 and 998 Ma. The other zircon grains are Paleoproterozoic (8 zircon grains, minor peak at 1.96 Ga) and Archean (7 zircon grains, 2.53–3.48 Ga) in age.

In the Floian sample (GAFS), 51 zircon grains are concordant (69 analysed grains). The Kernel plot shows numerous age peaks between the Cambrian and Stenian with major peaks located at 537, 616, 720, 899, and 980 Ma. Grains with Ediacaran and Tonian ages are abundant (16 and 19 zircon grains, respectively), whilst only one grain yields a Stenian age. The youngest concordant zircon grains are Fortunian in age (528–535 Ma), and the data reveal that the oldest grains are Paleoproterozoic and Neoarchean, with ages between 1.88 and 2.69 Ga.

The PFS+KFS sample combines two samples from the Postolonnec (PFS) and the Kermeur (KFS) formations (Middle and Upper Ordovician, respectively). Seventy zircon grains are concordant out of an analysed population of 134 grains. The Kernel probability plot shows two main populations: an Ediacaran to Tonian <800 Ma population with ages of 584 to 785 Ma for 36 zircon grains and major peaks at 640 and 697 Ma, and another population of Tonian (>800 Ma) to Stenian age, with several minor peaks at 855 Ma, 945 Ma, and as high as 1.05 Ga (17 zircon grains). The age distribution shows a gap at 800 Ma in the age diagram between these two age populations. The ages of the other zircon grains are widely dispersed over the Calymmian (early Mesoproterozoic), Orosirian (Paleoproterozoic), and Neoarchean.

Fig.4: U–Pb ages of detrital zircon grains from the studied samples: frequency and Kernel density estimate (KDE) distribution plots. The $^{207}Pb/^{206}Pb$ and the $^{206}Pb/^{238}U$ ages have been used for zircon grains older and younger than 1 Ga, respectively. The vertical orange bands shown in the figure

represent the main range of ages for magmatic rocks. Magmatic rock ages are from (1) Auvray et al. (1980), Inglis et al. (2004), Samson and D'Lemos (1998), Vidal (1980), Martin et al. (2018); (2) Samson et al. (2003), Egal et al. (1996); (3) Samson et al. (2003), Guerrot and Peucat (1990), Graviou et al. (1988), Nagy et al. (2002); (4) Vidal (1980), Chantraine et al. (1999, 2001), Egal et al. (1996), Inglis et al. (2005), Cocherie et al. (2001), Guerrot and Peucat (1990), Peucat et al. (1981), Vidal et al. (1974), Strachan et al. (1996), Miller et al. (2001), Cocherie et al., 2001; (5) Auvray (1979), Graviou et al. (1988), Egal et al. (1996), Guerrot et al. (1992), Pasteel and Doré (1982), Peucat (1986), Chantraine et al. (2001), Hebert et al. (1993), Guerrot and Peucat (1990), Marcoux et al. (2009); (6), Guerrot et al. (1992), Auvray et al. (1980), Bonjour et al. (1988), Miller et al. (2001), Ballouard et al. (2018).

As there is a low total number of studied zircon grains with concordant ages per sample, data from a recent compilation (Ballouard et al., 2018) for the same locations as those in this study were compared with the present results . This can make up for the loss of underrepresented zircon age populations (Fig. 5). In this work, a Brioverian and Silurian sample from the Crozon Peninsula in the Medio Armorican Domain were analysed. For our Brioverian sample, the probability curve (BS in Fig. 4.) and the sample studied by Ballouard et al. (2018) in Fig. 5 are very similar. For the Ordovician samples, it is not possible to make a direct comparison, as these materials are not represented in the work by Ballouard et al. (2018). Nevertheless, it is possible to observe a coincidence between our data and the main populations of the Silurian sample from Crozon (213 zircons analysed), in which there is also an evident gap in the age diagram that separates the two main age populations for the lower Cambrian to Tonian <800 Ma and for Tonian >800 Ma to Stenian ages.

Fig. 5: U–Pb ages of detrital zircon grains for samples from the Crozon Peninsula (Medio Armorican Domain). Histogram and Kernel density estimate (KDE) modified after Ballouard et al. (2018).

4.3. Lu-Hf on detrital zircons

In order to characterize the recognized zircon populations with Lu–Hf isotope ratios, nineteen zircons of the main populations were selected from the Brioverian (BS) (Lu/Hf data in the Supplementary Materials). The results show variable $\varepsilon_{Hf(t)}$ values ranging from −30 to +4, suggesting the involvement of Ediacaran-Cryogenian magma and Paleoproterozoic juvenile input (at 2.1 and 2.7 Ga).

Fig. 6: U/Pb age (Ga) versus ε_{Hf} for selected zircon grains from this study. DM indicates depleted mantle and CHUR is chondritic uniform reservoir; grey domains represent the $\varepsilon_{Hf(t)}$ bulk rock evolution trends for terranes of different ages that could be recognized from the studied samples, calculated using $^{176}Lu/^{177}Hf$ of 0.0113 (Taylor and McLennan, 1985; Wedepohl, 1995). Numbers indicate magmatic ages, whose references are listed in Fig. 4 caption.

The fourteen representative zircons from the Lower Ordovician sample (IRBS) vary in $\varepsilon_{Hf(t)}$ values from −11 to +4, suggesting both the supply of juvenile material mainly in the Cryogenian and reworking of the older pre-existing crust.

Twenty representative zircon crystals from the Ordovician (Floian) sample (GAFS) gave $\varepsilon_{Hf(t)}$ values between −32 and +7, which indicates a juvenile contribution for the zircon grains of Tonian age and, for the remaining grains, recycling of the oldest Paleoproterozoic and Archean crust.

The five representative zircon crystals of sample PFS+KFS gave $\varepsilon_{Hf(t)}$ values ranging from −14 to +3, suggesting a juvenile contribution for the Stenian zircons and reworking of Paleoproterozoic crust for the Cryogenian population.

The obtained Hf data allow for the following magmatic chronological evolution to be deduced:

- The Archean population involves zircon grains from the Neoarchean and Mesoarchean. The Neoarchean population, represented by zircon grains from the BS, IRBS, and GAFS samples, shows negative and positive $\varepsilon_{Hf(t)}$ values (between −9.52 and +4.04). The T_{DM} model ages indicate reworking of Paleoarchean (3.5 Ga) to Mesoarchean crusts (2.92 Ga). The Mesoarchean population, represented by zircon grains from the BS and IRBS samples, shows negative $\varepsilon_{Hf(t)}$ values between −7.37 and −3.18. The T_{DM} model ages indicate reworking of Eoarchean (3.84 Ga) to Paleoarchean crusts (3.44 Ga).

- Paleoproterozoic magma input provided zircon grains from the Rhyacian and Orosirian periods. The Rhyacian population from the BS, IRBS, and GAFS samples gave negative to positive $\varepsilon_{Hf(t)}$ values ranging between −5.44 and + 2.88, with a T_{DM} indicating reworking of Mesoarchean (2.95 Ga) to Siderian (2.47 Ga) crusts. The Orosirian population, represented by zircons from BS and GAFS, yields negative $\varepsilon_{Hf(t)}$ values ranging between −18.89 and −3.44, and the T_{DM} values of Orosirian zircon indicate reworking of Eoarchean (3.61 Ga) and Mesoarchean (2.76 Ga) crusts.
- A Mesoproterozic population is only present in the PFS+KFS and GAFS samples. The analysed zircon crystals from the PFS+KFS sample gave a positive $\varepsilon_{Hf(t)}$ value of ca. +3.0 and a T_{DM} model age of 1.66 Ga. This suggests reworking of Mesoproterozoic crust. The Stenian zircon in the GAFS sample is characterized by a negative $\varepsilon_{Hf(t)}$ value of −2.5 and a T_{DM} of 1.97, which suggests reworking of Orosirian crust.
- Neoproterozoic input was evidenced for all the studied samples (37 zircon grains analysed). The Cryogenian–Ediacarian is represented by zircon grains from the BS, IRBS, GAFS, and PFS+KPS samples. The Cryogenian zircon grains have negative to positive $\varepsilon_{Hf(t)}$ values (−10.52 to +4.57), which indicates that Rhyacian (2.20 Ga) to Stenian (1.20 Ga) crust was involved. The Tonian population (which is only missing from the zircon population of the PFS+KFS sample) gave mainly negative $\varepsilon_{Hf(t)}$ values and indicates that Paleo- and Mesoproterozoic crust was involved in the generation of these zircon grains. Only one Neoarchean zircon (2.72 Ga) is observed. The Ediacaran zircon grains with highly negative to slightly positive $\varepsilon_{Hf(t)}$ values (varying from −32.31 to +2.13) have a T_{DM} that indicates reworking of Mesoarchean (3.12 Ga) to Ectasian (1.27 Ga) crust.
- Finally, the selected Cambrian to Ordovician zircons display negative $\varepsilon_{Hf(t)}$ values of −1.70 and −0.18, showing that Mesoproterozoic crust was involved in the recycling.

5. Discussion

5.1. General remarks

Although the number of zircon grains per sample analysed in this study is lower than desirable, the reliability of the presented results is verified through comparison with provenance data recently compiled by Ballouard et al. (2018). They analysed a comparatively larger number of zircon grains but obtained a very similar distribution of population ages (Fig. 5) and also documented the Tonian gap in the data. These data would appear to be indicative of age gaps, but a more robust dataset may eventually clarify whether this is the case.

The sedimentary zircon grains from the Brioverian sample (BS) are mainly of local origin, as deduced from the perfect coincidence of provenance ages with those of magmatic rocks outcropping in the Armorican Massif (denoted 1–6 in Figures 4 and 5). The Lu–Hf isotopic data for the other Ordovician samples analysed here show zircon grains with different ages, but they also show ages similar to those of the locally occurring magmatic rocks. However, the $\varepsilon_{Hf(t)}$ values obtained from the zircon grains of the BS and IRBS samples, which have an Armorican source area, are mostly positive, whereas the younger samples (GAFS and PFS+KFS) yield, on average, negative values (Fig. 6).

A comparison of $\varepsilon_{Hf(t)}$ values from zircon in Cadomian (BS) and post-Cadomian (IRBS, GAFS and PFS+KFS) samples shows a progressive increase in the proportion of negative-value zircon grains in the post-Cadomian samples, and the younger the sample, the greater the negative-value zircon fraction. This progression is less evident in the IRBS sample, which contains local Cadomian contributions (pre-rift deposits), whereas the more recent samples (GAFS and PFS+KFS) show this trend strongly (syn-rift and post-rift deposits). This suggests that other source areas in the sediment flux became gradually involved and added to the earlier Cadomian sources.

This observation is in agreement with the results obtained by whole-rock Sm–Nd isotopic analysis (Fig. 3). In particular, the Tonian >800Ma and Stenian populations gave mostly negative $\varepsilon_{Hf(t)}$ values that indicate the recycling of older Orosirian crust (Fig. 6). It should be noted that the lack of zircons in the Brioverian sample (BS) is evidence for recycling of Orosirian crust. Furthermore, the U–Pb and Hf isotope results for zircon grains from the Armorican Massif suggest the importance of recycling of older crust, which is characteristic of the majority of the analysed samples.

5.2. Upper Brioverian and Cap de la Chêvre Fm

The zircon populations of the Brioverian sample (BS) from West Brittany (this study, 1 in Fig. 7) and others from other Armorican areas (Fig. 7), i.e. Central Brittany (21: Gougeon et al., 2018) , North Brittany (3: Fernández-Suárez et al., 2002a) and Normandy (Samson et al., 2005; 2: Strachan et al., 2014), show strong similarities, i.e., in the prevalence of Neoproterozoic zircon grains, especially those of Ediacaran and Cryogenian ages, and the lack of Mesoproterozoic ones. The main differences between samples are the total lack of Tonian zircon grains in Normandy and Central Brittany and for the latter region, the lack of Paleoproterozoic and Archean zircon grains and the occurrence of Cambrian zircon grains. Additionally, in the Brioverian (BS) sample, there is a younger age of 519 Ma that may suggest the possibility of an extension of the Brioverian age until the early Cambrian. This possibility cannot be ruled out but must be confirmed further as it has only been detected for a single zircon grain.

In the palaeogeographic and orogenic contexts of the Armorican Massif, the potential source areas for the Brioverian sediments include the Cadomian and Pan-African orogenic belts. The Tonian <800 Ma to Ediacaran ages are consistent with the age of the Cadomian magmatism in the Armorican Massif, from the Eocadomian (750–650 Ma: 2 and 3 in Fig. 4; e.g., Port Morvan orthogneiss, boulders in Cesson conglomerate: Guerrot and Peucat, 1990; Egal et al., 1996; Samson et al., 2003) and Cadomian (620–575 Ma; 4 in Fig. 4; e.g., North Trégor Batholith, Lanvollon, Erquy, Lézardrieu, and Paimpol formations: Graviou et al., 1988; Egal et al., 1996; Chantraine et al., 1999; Chantraine et al., 2001; Cocherie et al., 2001; Nagy et al., 2002) episodes, right up to the crustal melting phase around 540 Ma (5 in Fig. 4; e.g., Mancellian Batholith, Vires, and Carolles granites: Graviou et al., 1988; Pasteel and Doré, 1982). The Paleoproterozoic ages are consistent with the ages found for the Icartian orthogneissic basement in the region (1 in Fig. 4; e.g., Port Béni, Trébeurden, and La Hague orthogneiss: Auvray et al., 1980; Inglis et al., 2004; Martin et al., 2018). Archean rocks have not been documented in the Armorican Massif, but they could represent the paragneisses associated with the Icartian complex (e.g., Trebeurden micaschist: Auvray et al., 1980).

Fig. 7: Map with detrital zircon age spectra for Neoproterozoic (*) and Cambrian (**) samples. Zircon age population diagrams are limited to the sectors with the most significant ages, and the oldest Mesoproterozoic ages have been excluded (1600 Ma). Age spectrum 1 (upper left) represents the present work (Fig. 4), whereas the other diagrams are extracted from the literature, as mentioned in the text.

Detrital zircon ages in the upper Brioverian sediments of the Medio Armorican Domain (MAD) suggest source areas mainly located in the North Armorican Cadomian Belt, although a Gondwana source contribution cannot be completely excluded, especially for the Archean zircon population. This hypothesis, already suggested by Denis and Dabard (1988) and Dabard (1990), is in agreement with the increased maturity of sediments located southward in the Medio-North Armorican Domain (MNAD) (Chantraine et al., 1983; Denis and Dabard, 1988) and with the occurrence of chert fragments provided from the lower Brioverian Group of the North Armorican Domain (NAD). The MAD, thus, could constitute a retro-arc basin of the Cadomian Belt that was mainly fed by its own erosion products.

A comparison with the Iberian Massif (Fig. 7) shows that the zircon grain distribution in the MAD presents similarities to those observed for samples from the Ossa Morena Zone, with a low abundance of Tonian >800 Ma ages and a lack of Stenian ages (4: Fernández-Suárez et al., 2002a; 14: Linnemann et al., 2008; 22: Pereira et al., 2012b). By contrast, in the Central Iberian, West Asturian and Cantabrian zones these populations are abundant (5: Fernández-Suárez et al., 2000; 7: Pereira et al., 2012a; 17, 18: Fernández-Suárez et al., 2014; 15: Talavera et al., 2015).

The detrital zircon age population for the Lower Ordovician sample IRBS (Fig.4) is very similar to that of BS, with a prevalence of Cryogenian and Ediacaran ages and the occurrence of some Paleoproterozoic and Archean grains. Moreover, the whole-rock Sm–Nd isotopic signatures of samples from the Initial Red Beds gave $\varepsilon_{Nd(T)}$ values and model ages (−4.4 to −3.0 and 1.4to −1.5 Ga, respectively; Table 1) that fall within the range of the Brioverian sedimentary rocks (−1.4–−6.2 and 1.2–1.6 Ga, respectively). All these data are in agreement with local sources from the Armorican basement, i.e., Cadomian magmatic rocks and Brioverian sediments. The origin of Furongian (latest Cambrian) and Tremadocian (earliest Ordovician) zircon grains may be related to the volcanism associated with episodes of continental rifting (Guerrot et al., 1992; Auvray et al., 1980; Bonjour et al., 1988; Miller et al., 2001; Ballouard et al., 2018).

5.3. Grès Armoricain and overlying formations

There is a marked change in zircon populations from the Grès Armoricain Fm. (GAFS, 1a,b in Fig. 8) onwards. This is testified by the emergence of Stenian to Tonian >800 Ma grains (Fig. 4) whose $\varepsilon_{Hf(t)}$ values range from −20 to 8 with a predominance of zircon grains with negative $\varepsilon_{Hf(t)}$ values (Fig. 6). Moreover, the $\varepsilon_{Hf(t)}$ values of zircon with Tonian <800 Ma to Ediacaran ages are mostly negative (about −10 to −20) with Orosirian T_{DM} model ages, whereas the $\varepsilon_{Hf(t)}$ values of the underlying sediments are mostly positive with Ectasian and Stenian model ages. The whole-rock Sm–Nd isotopic signatures (Fig. 3) support the assumption of a significant change in source areas; old model ages (1.7–2.1 Ga versus 1.2–1.6 Ga) attest to a supply of recycled crustal material.

The zircon grain age distribution is similar in the Middle–Upper Ordovician sample (PFS+KFS), with the only difference from GAFS observed in the amplitudes of the major peaks, with a relative decrease in the abundance of Tonian >800 Ma and Ediacaran ages and an increase in grains with Cryogenian ages (main peak at 640 Ma). Detrital zircon grains of Tonian >800 Ma ages also appear in Normandy (2: Strachan et al., 2014, in Fig. 8) but are less abundant, and no Stenian zircon grains were reported from there.

Since the detrital zircon grains of the Brioverian sample (BS) are of local origin (Fig. 6) and represent a provenance older than the Cadomian orogenesis, our U-Pb-Hf isotopic results are relevant for the evolution of the Armorican crust in pre-Cadomian times. The Ordovician samples show the evolution of the sedimentary flux from respective source areas in more recent times, during the rifting that led to the opening of the Rheic Ocean. In Ordovician samples, the sedimentary contribution changed as a result of Cadomian orogenesis. The new palaeogeographic context provides, on the one hand, new populations (e.g., Stenian and Tonian >800 Ma) and, on the other, a contribution of zircons that have the same age population as the Brioverian sample (BS) but with different $\varepsilon_{Hf(t)}$ values. In fact, we note that the $\varepsilon_{Hf(t)}$ values of the zircon grains of the BS and IRBS samples, which have relatively proximal source areas, are mostly positive, while the younger samples (GAFS and PFS+KFS) have zircons with mostly negative values (Fig. 6).

Fig. 8: Map with detrital zircon age spectra for Ordovician samples. Zircon population diagrams are limited to the most significant age ranges, and the oldest Mesoproterozoic ages have been excluded (>1600 Ma). Age spectra 1a and 1b are from this work (Fig. 4), while the other diagrams are extracted from the literature, as noted in the text.

Although the contribution from the Cadomian basement in the Armorican Massif cannot be totally excluded for the Grès Armoricain Fm and overlying formations, external contributions must be considered. Between the sedimentation of the Initial Red Beds and the sedimentation of the Upper Ordovician formations, the environmental context of the MAD evolved from small isolated basins developed above tilted blocks related to the Rheic opening, with local inputs, to a wide passive margin setting along the northern Gondwana margin (Dauteuil et al., 1987; Brun et al., 1991). This resulted in significant supply from terrigenous sediments overlying the Cadomian/Pan-African basement or the Cambrian formations. According to the palaeocurrents, the origin of these sediments could be found in the Gondwana hinterland (Beuf et al., 1971; Noblet and Lefort, 1990; Ghienne et al., 2007; Avigad et al., 2012). The source areas of the new zircon populations identified in the Grès Armoricain Fm and overlying formations of the MAD must then be investigated Gondwana-wide. Within this continent, there are many known Neoproterozoic ages from many areas (e.g., Tuareg Shield, Mauritanide fold belt, East African Orogen) related to the Pan-African orogenic cycle, from about 850 to 550 Ma (Liégeois et al., 1994, 2003; Abdelsalam et al., 2002; Küster et al., 2008). Several areas experienced magmatic events between the late Mesoproterozoic and early Neoproterozoic times (cf. maps and compilations in Linnemann et al., 2004, 2011; Pereira et al., 2012b; Fernández-Suárez et al., 2014; Shaw et al., 2014), e.g., the Sunsas Belt and Arequipa Massif in the southern Amazonian Craton, the Irumide and Kibaran belts (to the south and west of the Tanzania Craton), the Namaqua–Natal belt (southern Kaapvaal craton), and the Arabian–Nubian Shield. The palaeogeographic affinities of the MAD can be found in these geological domains that in the Ordovician time were supplied with a similar sedimentary flux in the Ordovician time, with zircon grains of Stenian and Tonian >800 Ma ages.

The high textural and mineralogical maturity of the sedimentary rocks of the Grès Armoricain Fm (Dabard et al., 2007; Pistis et al., 2016) and the abraded and rounded forms of the majority of zircon grains in this formation are not in agreement with the rift context, in which this formation was laid down. These petrographic characteristics can be explained by the reworking of sandy sources that were already mature and available on the Gondwana continent. A compilation of detrital zircon ages for North Africa and Western Europe was undertaken (Figs. 7 and 8). This shows that, in North Africa, Stenian and Tonian >800 Ma ages are known from Neoproterozoic and Cambrian sedimentary rocks (Fig. 7) in the Arabian–Nubian Shield (Avigad et al., 2003; 12: Avigad et al., 2007; 13: Morag et al., 2012; 24: Be'eri-Shlevin et al., 2009), the Saharan Metacraton

(11: Meinhold et al., 2011; 29: Le Heron et al., 2009), and some Cambrian samples of the West African Craton (Bradley et al., 2015; 25: Gärtner et al., 2017; 28: Avigad et al., 2012). Moreover, studies of some Neoproterozoic and Cambrian samples from the West African Craton have shown a total absence of Tonian and Stenian zircons (19: Abati et al., 2010; 20: Avigad et al., 2012).

Regarding Ordovician sediments (Fig. 8), these ages are present in the eastern zone, i.e., the Arabian–Nubian Shield and Sahara Metacraton (23: Kolodner et al., 2006; 12: Avigad et al., 2007; 11: Meinhold et al., 2011). By contrast, only rare Tonian >800 Ma zircon grains occur in the western zone, i.e., the Tuareg Shield and West African Craton (16: Linnemann et al., 2011; 26: Gärtner et al., 2017). In Western Europe, Stenian and Tonian >800 Ma grains are not ubiquitous in Ordovician sediments. In the Iberian Massif, they are present with variable abundances in the West Asturian, Cantabrian, and Central Iberian Zones (5: Fernández Suárez et al., 2000; 6: Fernández Suárez et al., 2002b; 7: Pereira et al., 2012a; 8, 9, 10: Shaw et al., 2014). In the Ossa Morena Zone (Iberian Massif; 14; Linnemann et al., 2008) and Saxo-Thuringia (27: Linnemann et al., 2008), only a few Tonian >800 Ma zircon grains have been noted.

Thus, the comparison of detrital zircon populations between the Armorican Massif and other areas along the North Gondwana margin shows similarities between, on the one hand, the MAD and the Central Iberian, West Asturian and Cantabrian Zones, the Saharan Metacraton and the Arabian–Nubian Shield, and on the other hand, Normandy (2: NAD; Strachan et al., 2014), the Ossa Morena Zone, Saxo-Thuringia, the West African Craton, and the Tuareg Shield.

In palaeogeographic reconstructions, the Armorican Massif is often located to the north of the West African Craton (e.g., Linnemann et al., 2008; Avigad et al., 2012; Stephan et al., 2019). However, the occurrence of zircon populations of Stenian and late Tonian ages in the Grès Armoricain Fm in the MAD excludes derivation from this basement. Moreover, available data on zircon populations of sediments laid down during the Ordovician time in the Tuareg Shield (Linnemann et al., 2011) and on the West Africa Craton (Gärtner et al., 2016) emphasize the lack of zircon grains with Stenian and late Tonian ages. These features exclude the possibility that these zones and the MAD were in close proximity. By contrast, the similarities between detrital zircon populations from the MAD and those from the Arabian–Nubian Shield and Saharan Metacraton suggest possible relationships between these areas.

The generally juvenile character of the magmatism in the Arabian–Nubian Shield, demonstrated by εNd(t) and εHf(t) values (Hargrove et al., 2006; Morag et al., 2011), excludes this basement as the main source area for the zircon population with Stenian and Tonian >800 Ma ages. Considering that the sedimentary rocks of the Grès Armoricain Fm. are characterized by negative isotopic Sm–Nd signatures (Morag et al., 2011), they are possibly derived from reworking of the Cambro–Ordovician sedimentary cover of the Arabian–Nubian Shield or from the same source area that fed it. In this regard, some authors (Squire et al., 2006; Meinhold et al., 2013) proposed that the Cambrian–Ordovician sediments (e.g., Libya: Meinhold et al., 2011; Jordan: Kolodner et al., 2006) constituted a super-fan system, fed by the erosion of the East African Orogen (also often referred to as the Transgondwanan Supermountain). These sediments have probability density plots for age distribution that are similar to those of the Armorican sedimentary rocks (two main zircon populations, one Pan-African and the other Stenian to late Tonian in age, separated by a gap of around 800 Ma; cf. compilation in Meinhold et al., 2013, and Figs. 7 and 8).

This hypothesis implies that the MAD should be positioned further east along the Gondwana margin, likely to the north of the Saharan Metacraton and the Arabian–Nubian Shield. In the same way, the analysis of zircon grain populations of some areas of the Iberian Massif (NW Iberia, Central Iberian Zone) has already led some authors (Fernández-Suárez et al., 2014; Meinhold et al., 2013; Shaw et al., 2014; Stephan et al., 2019) to propose a location to the north of the Sahara Metacraton. By contrast, the Ordovician sample from Normandy (NAD), characterized by a lack of Stenian detrital zircon and a paucity of Tonian grains (Strachan et al., 2014), yields a zircon population close to those of Saxo-Thuringia and in the Ossa Morena zone (Fig. 8). These findings attest to distinct source areas for the North and Medio Armorican Domains and demonstrate that these areas had to be distant from each other during the Lower Ordovician, and that they moved closer to each other until becoming fully connected in more recent times, probably during the Variscan orogenesis.

6. Conclusion

Detrital zircon age analysis of sedimentary rocks from the Medio Armorican Domain reveals a variation in source areas for the terrigenous flux between the Ediacaran and Upper Ordovician times, highlighted by the addition of new populations of zircon ages to the populations of the comparatively older strata. Cryogenian and Ediacaran ages are dominant in the zircon populations of Brioverian sedimentary rocks that were mainly fed by the erosion of the Cadomian Belt. The first Paleozoic sedimentary strata (Initial Red Beds) have the same zircon populations provided by the erosion of the Brioverian rocks. In the Grès Armoricain Fm, zircon grains with Stenian and Tonian >800 Ma ages appear, and whole-rock Sm–Nd and zircon Hf isotopic signatures attest to a greater contribution of recycled crustal material and to a renewal of source areas. These sediments were laid down in a rift setting with high subsidence rates (the environment remained in tidal facies over several hundred meters in thickness), which is in contrast to their high compositional and textural maturity. This paradox—isofacies deposition versus sediment maturity—can be explained by a sedimentary flux from a faraway origin. In the Cambro–Ordovician sediments of North Africa, zircon grains of Stenian and late Tonian ages are rare in the western part but are ubiquitous in the eastern part (Saharan Metacraton, Arabian–Nubian Shield). Here, whole-rock Sm–Nd and zircon Hf isotopic signatures also attest to a supply of recycled crustal material. These sediments, which according to Squire et al. (2006) and Meinhold et al. (2013), constitute a super-fan system, could be the source of the Ordovician sediments of the MAD. In this case, the MAD had to be positioned toward the Saharan Metacraton and the Arabian–Nubian Shield. The lack of Stenian and late Tonian ages in the zircon populations of Ordovician sediments of the NAD implies distinct source areas that were probably located further to the west.

On the basis of the presence or lack of Stenian and Tonian >800 Ma ages, the comparison of detrital zircon populations with the Iberian Massif shows, for the Brioverian sediments, similarities to the Ossa Morena Zone, and for the Ordovician sediments, similarities to the Central Iberian, West Asturian and Cantabrian zones. In contrast to the Armorican Massif, Stenian and Tonian >800 Ma zircon populations were present in these Iberian zones from the Ediacaran until the Ordovician. During the Neoproterozoic, some inputs to the NW Iberian Massif came from the Arabian–Nubian Shield (Fernández-Suárez et al., 2014), whereas in the Armorican Massif, the sources were constrained to the Cadomian basement. After the closure of the back-arc basin that limited the Armorican Massif and the Gondwana continent, the source area of the Ordovician sediments of the MAD would have been a super-fan system that developed in eastern Gondwana, from where Stenian and Tonian >800 Ma zircon populations are known.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Supplementary data
Supplementary material 1
Supplementary material 2
Supplementary material 3
Supplementary material 4

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Highlights:

- Medio Armorican Domain positioned near Saharan Metacraton and Arabian-Nubian Shield
- Ordovician deposits show senile renewed source area with Tonian and Stenian zircon ages
- Ordovician of North and Medio Armorican Domains have different sedimentary supplies