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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 discuss paleogeographic affinities and changes that occurred as a result of the Cadomian orogenesis. Until now, paleogeographic reconstructions based on geodynamic, stratigraphic and palaeontological data show a geological continuity between the Armorican Massif and the Iberian and Bohemian massifs, and allow 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 the allocyclic factors (e.g., sea level change) or fauna assemblages that have a wide provincial distribution, in order to provide a correct assessment of sediment flux. In order to provide a more accurate paleogeographic location, the provenance of the siliciclastic sediments has been studied 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 done on the sedimentary succession of the Crozon Peninsula (Medio Armorican Domain) that shows the tectonic evolution of northern Gondwana from Neoproterozoic to Palaeozoic times. The oldest studied sedimentary rocks belong to the Brioverian succession that contains mainly 519 to 781 Ma old zircons, likely derived from sources still present

in the Armorican basement. Subsequently, in the rift stages of the Rheic Ocean, the lower Palaeozoic succession was deposited, with contributions from, a new source of 827 to 1,120 Ma old zircons.

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

Key words: 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 discuss the palaeogeographic implications of the results. For this area, palaeogeographic reconstructions have been established on geodynamic arguments, i.e. evolution of the Cadomian Belt during the Ediacaran and rifting of the Rheic Ocean in the Cambrian and opening in the Early Ordovician (e.g. Chantraine et al., 2001; Linnemann et al., 2014). In addition, and especially for the Palaeozoic times, stratigraphic and palaeontological 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 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 they do 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. To reconstruct the palaeogeographic position, other approaches can be used 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 discuss palaeogeography and tectonic evolution of continental realms. Only few detrital 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 abundant 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), with the application of U-Pb LA-MC-ICP-MS geochronology on detrital zircons coupled with whole-rock Sm-Nd and Lu-Hf on zircon isotope analyses. As a consequence, the affinity between the Iberian and Armorican massifs will be considered in order to discuss the palaeogeographic location of the Medio Armorican Domain at the North Gondwana margin and its relations with the Iberian Massif.

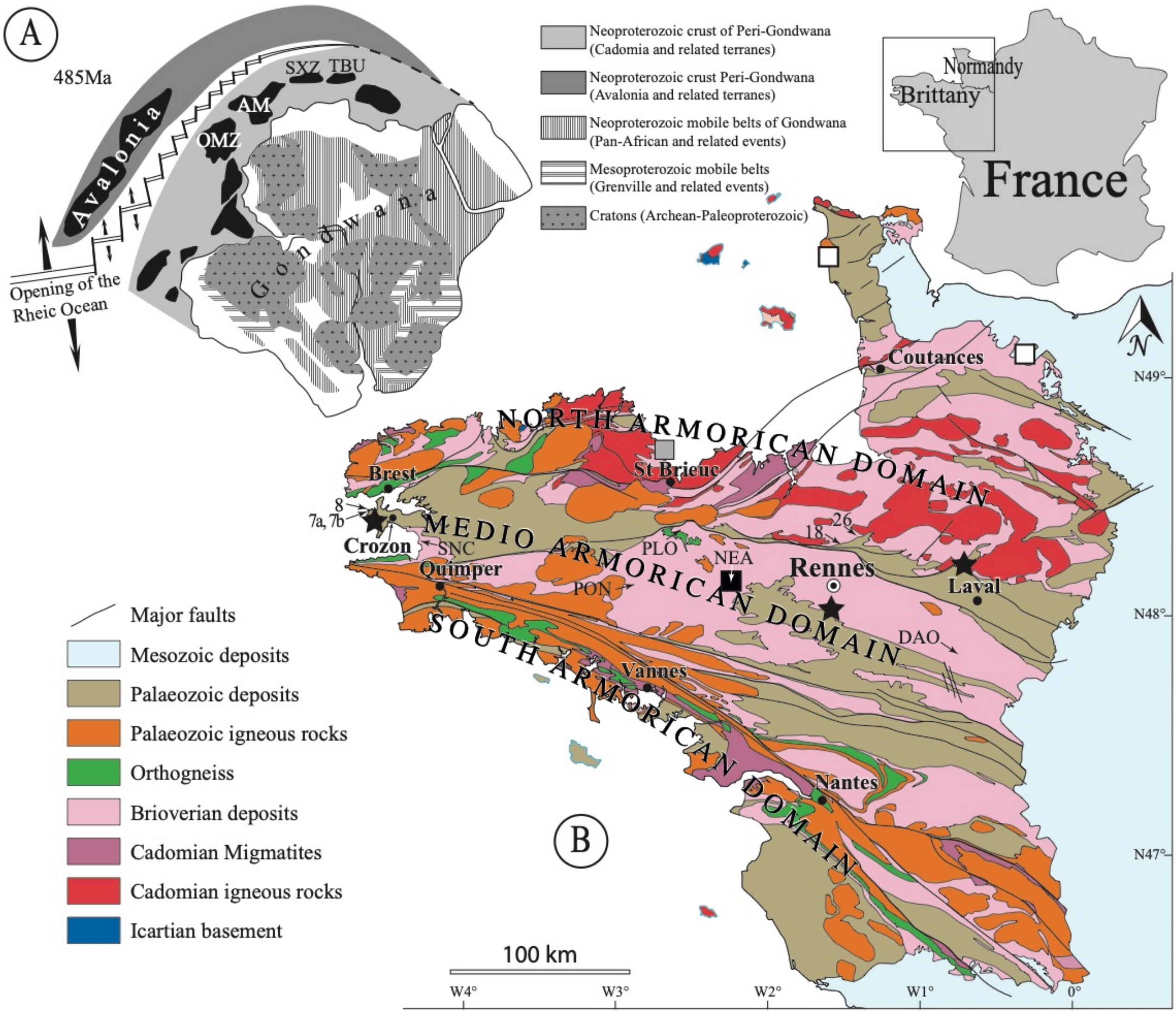

Fig.1: (A) Schematic palaeogeographical reconstruction of the Gondwana supercontinent around 485 Ma (modified from Linnemann et al., 2008). In black are still recognisable terranes OMZ: Ossa Morena Zone; AM: Armorican Massif; SXZ: Saxo-Thuringian Zone; TBU: Tepla-Barrandian Unit. (B) Simplified geological 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, SNC from Dabard et al. (1996) and samples 7a, 7b, 8, 18 and 26 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) that are grouped together into the Medio-North Armorican Domain (MNAD), and the South Armorican Domain (Fig.1). These domains record distinct tectonic and magmatic evolutions during the Cadomian and Variscan orogenesis.

During the Neoproterozoic, the Armorican Massif has 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, derives 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 to 2.1 Ga). Subsequently, several episodes of magmatic activity succeeded each other (ca. 620 - 575 Ma and ca. 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 metre 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 facies until tidal plain facies. These sedimentary strata were in part slightly deformed during the Cadomian orogeny (Le Corre, 1977). The lower Palaeozoic 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 uncomformably 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 to 100 m for the Initial Red Beds and 20 to 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 high thicknesses of several hundreds of metres in iso-facies are explained by high subsidence rates. The lateral variations of thicknesses are linked to tectonically-controlled depocenters 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 glacio-eustatic 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, the sedimentation continued into the Katian with micaceous sandstones, quartzarenites and mudstones (Kermeur Fm on the Crozon Peninsula, 90 to 450 m thick, Fig. 2) deposited in bay/lagoon-barrier environments evolving towards open shelf settings (Vidal et al., 2011b; Gorini et al., 2008). Then sedimentation continued, without significant interruptions, until the Carboniferous with development of several thousand metre thick deposits.

The samples for the U-Pb LA-MC-ICP-MS geochronology of detrital zircons were collected on 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 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 matrix with 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 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 from published data (for details see Michard et al., 1985; Dabard et al., 1996). The samples of this study (Fig 1 and Fig 2) come 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, if any, have a fine phyllosilicate matrix.

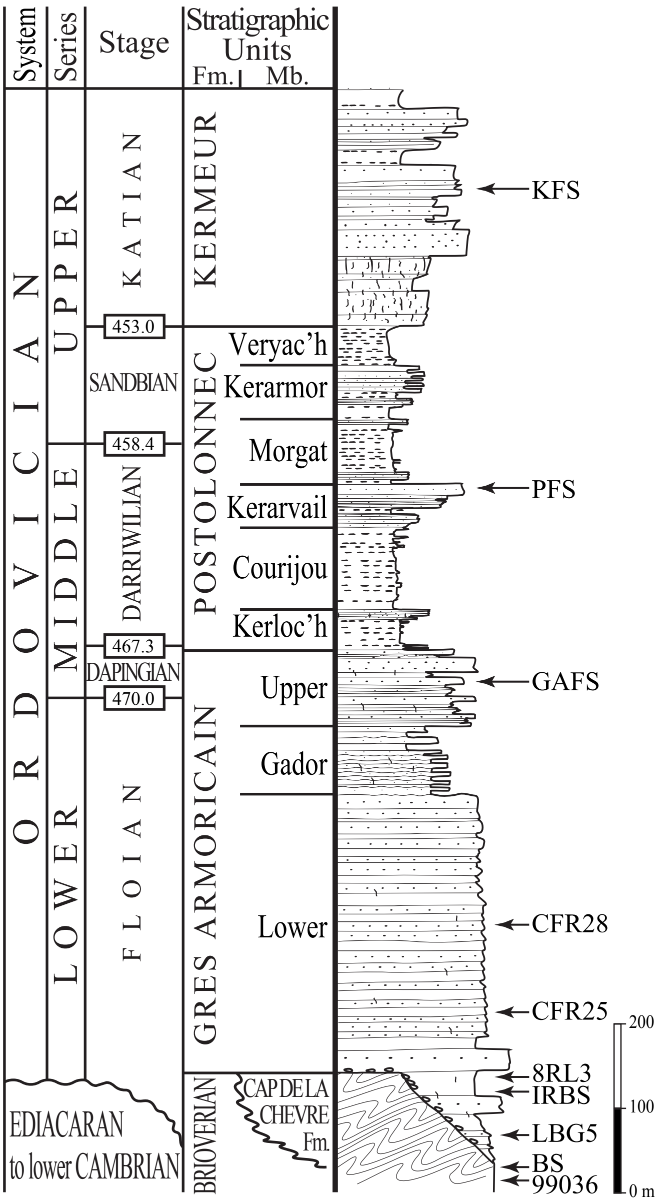

Fig.2: Lithostratigraphic (x-axis represents grain-size from mudstone to conglomerate) context of the Lower Palaeozoic succession in the Crozon Peninsula (modified after Vidal et al., 2011a). This figure indicates the stratigraphic positions of the studied samples.

3. Methodology

The Sm and Nd concentrations were obtained by the isotope dilution method, using on a Cameca TSN 206 mass spectrometer at Rennes University. Total blanks for the chemical separations are estimated around 0.1 ng for the Nd. Isotopic compositions of the Nd have been determined using a Finnigan MAT 262 mass spectrometer. Isotopic ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$. The results are reported to the La Jolla Nd standard (= 0.511860). The detailed technique on Sm-Nd is reported in Jahn et al. (1980). Precisions of the 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 first by 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, were put in a glass with ethanol and picked randomly with a pipette under a binocular microscope, without introducing any bias. This technique avoids any bias because the grains are randomly selected without any pre-consideration of size, color or shape (Sláma and Košler, 2012). Afterwards, 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 were examined for internal structures (such as magmatic zonation or metamorphic rims) using the FEI Quanta 450 scanning electron microscopy at the University of Brasilia.

The U–Pb and Lu–Hf isotopic analyses were performed on zircon using a Thermo-Fisher 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 the Brasilia University.

The U-Pb analyses on zircon grains were carried out using the standard-sample bracketing method (Albarède et al., 2004) using the GJ-1 (Jackson et al., 2004) as 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 between each two GJ-1 reference material analyses $^{206}Pb/^{207}Pb$ and $^{206}Pb/^{238}U$ ratios have been time corrected. The raw data were processed off-line and reduced using an Excel worksheet (Bühn et al., 2009). Analyses were performed using generally a spot size of 30 μm, 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 previously analysed with the U–Pb method. The selection was made on the basis of 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 $\lambda = 1.865*10^{-11}$ yr^{-1} proposed by Scherer et al. (2001) and the $^{176}Lu/^{177}Hf$ 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 represents best the composition of a hypothetic 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 on the same grain and that, if possible, should be concordant. The two-stage depleted mantle Hf model ages (T_{DM} Hf) are 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 on zircons, replicate analyses of a 200 ppb Hf JMC 475 standard solution doped with Yb (Yb/Hf=0.02) were carried out with this 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 made, 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 between -1.4 and -6.3 (Tab. 1, Fig. 3) and Mesoproterozoic Nd model ages ranging between 1.2 and 1.6 Ga, respectively. The two IRB samples have also negative ε_{Nd} (480) values of -3.0 and -4.4 and Mesoproterozoic Nd model ages of 1.4 and 1.5 Ga, similar with the obtained data for the Brioverian sediments. For the Grès Armoricain Fm, all analyzed samples exhibit much negative ε_{Nd}(470) values between -8.5 and -11.5 and Paleoproterozoic Nd model ages ranging from 1.7 to 2.1 Ga, respectively.

samples	Ages Ma	Sm	Nd	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ ($\pm 2\sigma$)	$\varepsilon_{Nd(0)}$	$\varepsilon_{Nd(t)}$	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

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).

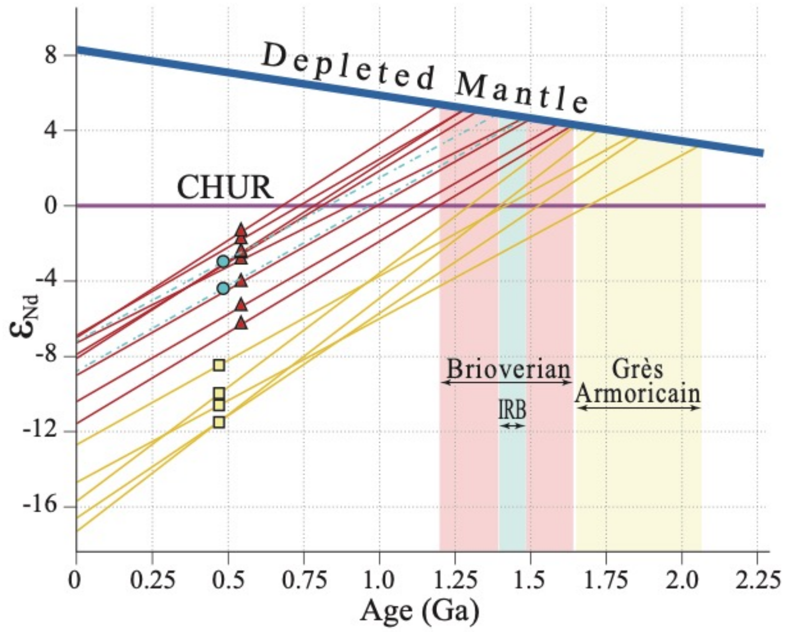

Fig.3: Age (Ga) versus $\varepsilon_{Nd(t)}$ diagram for the Brioverian (red triangles), Initial Red Beds (IRB) (blue circles) and Grès Armoricain (yellow squares) samples.

4.2. Detrital zircon ages

Generally, the sizes of the zircon grains of the analysed samples are not larger than 260 µm and the most frequent size is 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 minor degree, the samples from overlying strata, where many coloured and rounded grains are observed that testify 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 of 988 Ma age. Ten zircon grains yielded Paleoproterozoic ages, giving a peak at 2.02 Ga, and four grains yielded Archean ages.

In the Lower Ordovician sample (IRBS), 55 detrital zircon grains gave concordant results, out of 69 analysed grains. The ages for most abundant zircon population (38 zircon grains) gave ages 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 Ma 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. Abundant grains have Ediacaran and Tonian ages are abundant (16 and 19 zircon grains, respectively), whilst only one grain yielded a Stenian age . The youngest concordant zircon grains are Fortunian in age (528-535 Ma), and the oldest data 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 one with 584 to 785 Ma ages for 36 zircon grains and major peaks at 640 and 697 Ma; and another of Tonian (>800 Ma) to Stenian age, with several minor peaks at 855, 945 Ma, and up to 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.

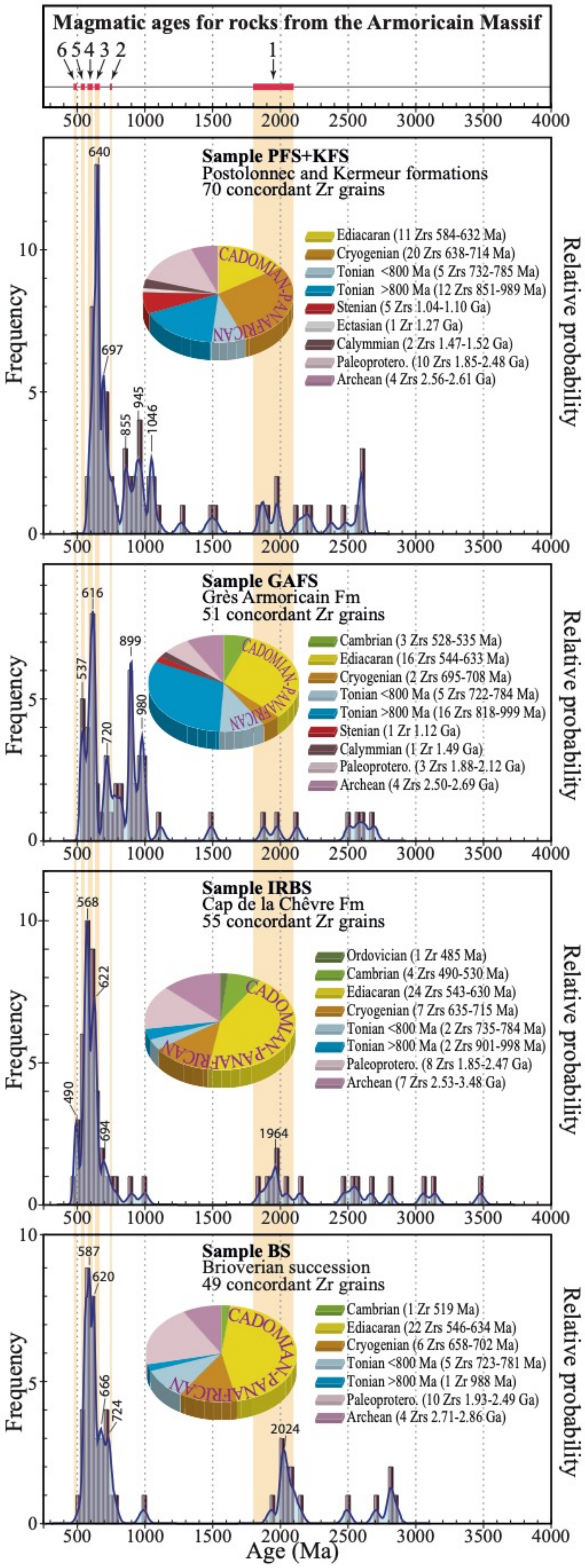

Fig.4: U-Pb ages of detrital zircon grains from the studied samples: frequency and Kernel density estimate (KDE) distribution plots. The $^{207}Pb/^{206}Pb$ and the $^{206}Pb/^{238}U$ ages have been used for zircon grains older and younger than 1 Ga, respectively. The vertical orange bands shown in the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

represent the main range 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 the total number of studied zircon grains with concordant ages per sample is low, comparison with data from a recent compilation made for the same locations of this study (Ballouard et al., 2018) is made. This allows to make up for the loss of underrepresented zircon age populations (Fig. 5). In this work, a Brioverian and a Silurian sample from the Crozon Peninsula in the Medio Armorican Domain have been analyzed. 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). Nnevertheless it is possible to observe a coincidence of our data with the main populations of the Silurian sample from Crozon (213 zircons analyzed), in which the gap in the age diagram that separates the two main age populations for the lower Cambrian to Tonian <800 Ma and the for Tonian >800 Ma to Stenian ages, is also evident.

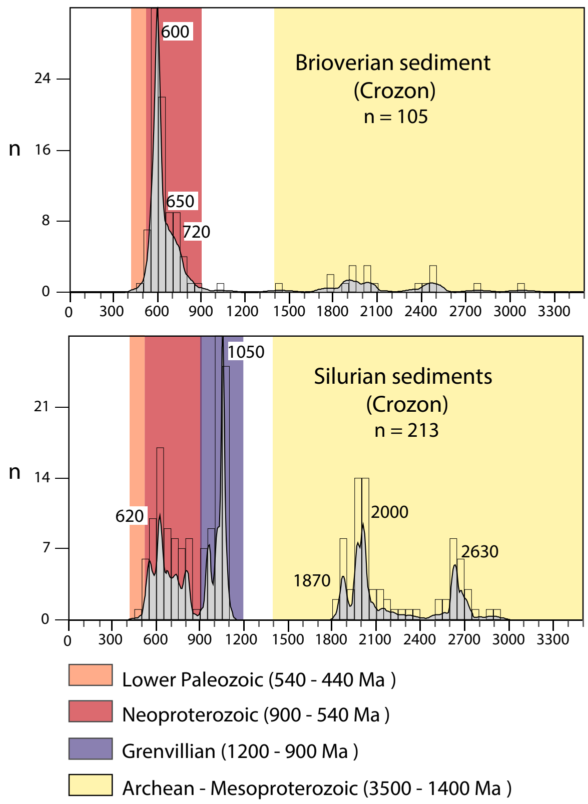

Fig. 5: U-Pb ages of detrital zircon grains for samples from the Crozon Peninsula (Medio Armorican Domain). Histogram and Kernel Density Estimate (KDE) modified after Ballouard et al. (2018).

4.3. Lu-Hf on detrital zircons

In order to characterize by Lu-Hf isotope 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).

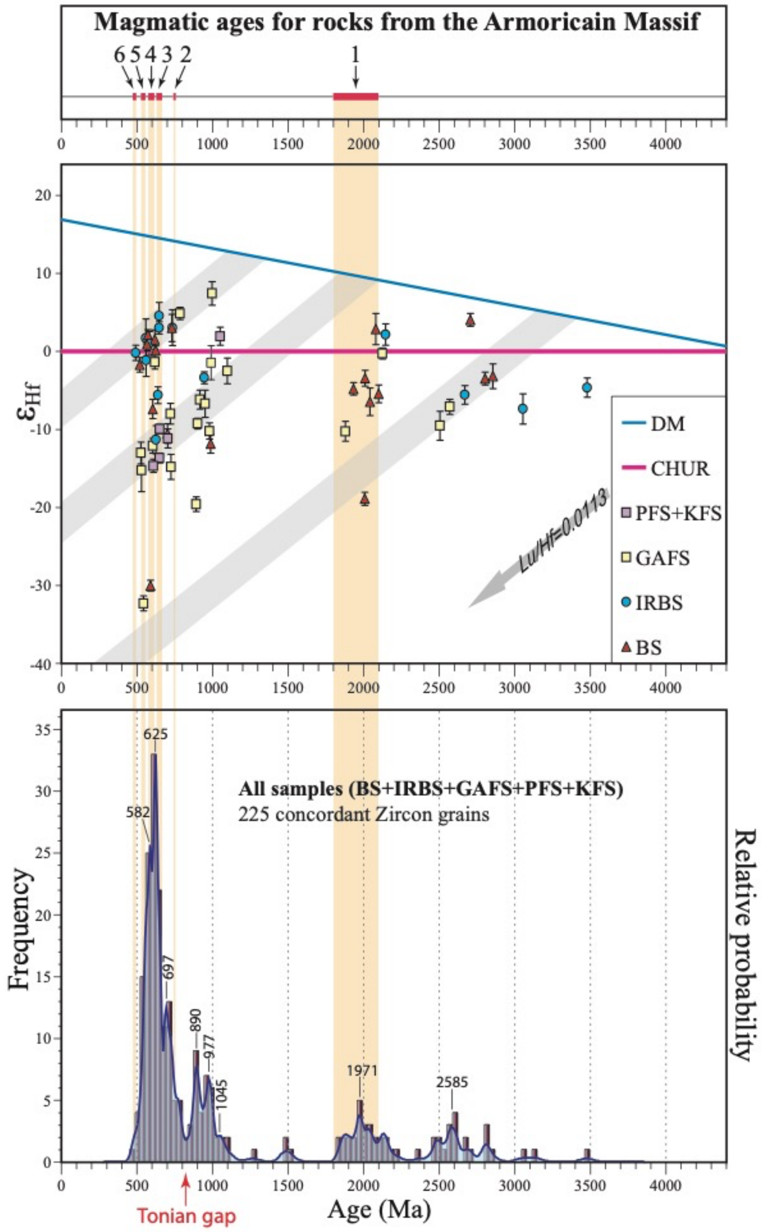

Fig. 6: U/Pb Age (Ga) versus ε_{Hf} for selected zircon grains from this study. DM indicates Depleted Mantle and CHUR is Chondritic Uniform Reservoir; Grey domains represents the $\varepsilon_{Hf(t)}$ bulk-rock evolution trends for terranes of different ages that could be recognized by the studied samples, 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 Hf data obtained allow to draw the following magmatic chronological evolution:

- 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 crust (2.92 Ga). The Mesoarchean population, represented by zircon grains from the BS and IRBS samples, show 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 between -5.44 and + 2.88, with a T_{DM} indicating reworking of Mesoarchean (2.95 Ga) to Siderian (2.47 Ga) crust. The Orosirian population, represented by zircons from BS and GAFS yielded negative $\varepsilon_{Hf(t)}$ values 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 ~ +3.0 and T_{DM} model ages of 1.66 Ga. This suggests reworking of Mesoproterozoic crust. The Stenian zircon in the GAFS

sample are 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 is 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 Palaeo- and Mesoproterozoic crust was involved in the generation of these zircon grains. Only one Neoarchean zircon (2.72 Ga) was 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} indicating reworking of Mesoarchean (3.12 Ga) to Ectasian (1.27 Ga) crust.
- Finally, the selected Cambrian to Ordovician zircons displayed 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 by the comparison of provenance data compiled recently by Ballouard et al. (2018). They analyzed 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.

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 also similar to the ages 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) yielded,I 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 of the proportion of negative values zircon grains in the post-Cadomian samples the younger the sample, the more abundant the negative values 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 (sin-Rift and post-Rift deposits). This suggests a gradual involvement of other source areas in the sediment flux that became 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 an older Orosirian crust (Fig. 6). It should be noted that no zircon from the Brioverian sample (BS) showed evidence for recycling of Orosirian crust.

Furthermore, the U-Pb and Hf isotope results on zircon grains from the Armorican Massif suggest the importance of recycling of older crust – which is characteristic for 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) and North Brittany (3: Fernández-Suárez et al., 2002a) and Normady (Samson et al., 2005; 2: Strachan et al., 2014), show strong similarities: prevalence of Neoproterozoic zircon grains, especially of Ediacaran and Cryogenian ages, and lack of Mesoproterozoic ones. The main differences between samples are the total lack of Tonian zircon grains in Normandy and Central Brittany, and for this latter region, the lack of Paleoproterozoic and Archean zircon grains and the occurrence of Cambrian zircon grains. Also, 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 on 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. Trébeurden micaschist: Auvray et al., 1980).

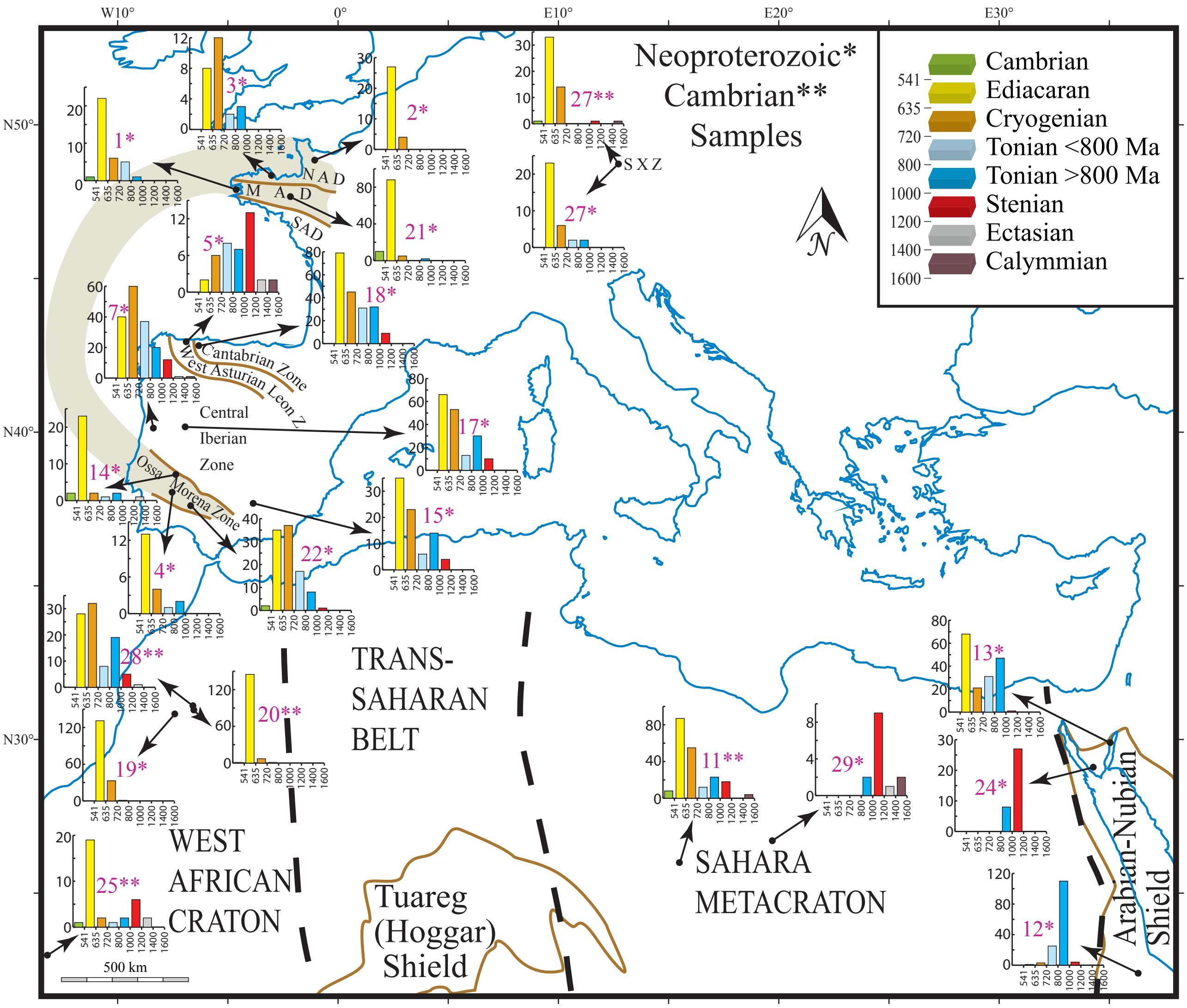

Fig. 7: Map with detrital zircon age spectra for Neoproterozoic (*) and Cambrian (**) samples. Zircon age population diagrams are limited to the sectors with the most significant ages, and the oldest Mesoproterozoic ages have been excluded (1600 Ma). Age spectrum 1 (upper left) represents the present 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 maturity increase of sediments southward in the Medio-North Armorican Domain (MNAD) (Chantraine et al., 1983; Denis and Dabard, 1988), and with the occurrence of chert fragments providing from the lower Brioverian Group of the North Armorican Domain (NAD). The MAD, thus, could constitute the 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 with that observed for samples from the Ossa Morena Zone, with a low abundance of Tonian >800 Ma ages and the lack of Stenian ages (4: Fernández-Suárez et al., 2002a; 14: Linnemann et al., 2008; 22: Pereira et al., 2012b). In contrast, in the Central Iberian, West Asturian and Cantabrian zones these populations are significantly present (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 occurrence of some Paleoproterozoic and Archean grains. Moreover, the whole-rock Sm-Nd isotopic signatures of samples from the Initial Red Beds give $\varepsilon_{Nd(T)}$ values and model ages (-4.4 – -3.0 and 1.4 – 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 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 of 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 $\varepsilon_{Hf(t)}$ 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 to 2.1 Ga versus 1.2 to 1.6 Ga) attest to supply of recycled crustal material.

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

Since the detrital zircon grains of the Brioverian sample (BS) are of local origin (Fig. 6) 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 due to Cadomian orogenesis. The new paleogeographic context provides, on the one hand, new populations (e.g., Stenian and Tonian >800Ma) and, on the other, a contribution of zircons that have the 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 mostly zircon with negative values (Fig. 6).

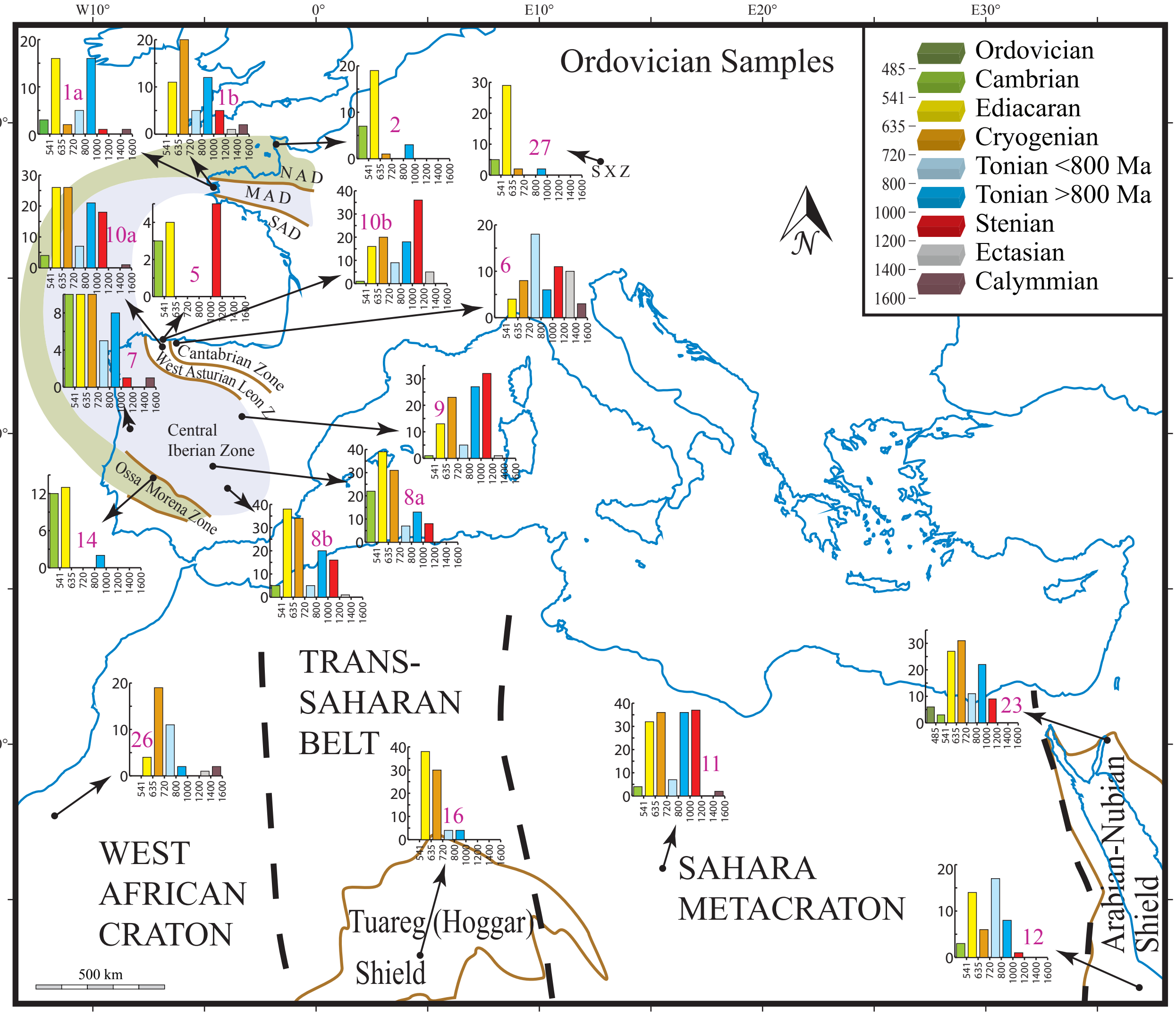

Fig. 8: Map with detrital zircon age spectra for Ordovician samples. Zircon population diagrams are limited to the most significant age ranges, and the oldest Mesoproterozoic ages have been excluded (>1600 Ma). Age spectra 1a and 1b are from this work (Fig. 4), the other diagrams were extracted from the literature, as mentioned 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, Neoproterozoic ages are known 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 late Mesoproterozoic and the 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 at 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, with zircon grains of Stenian Tonian >800 Ma and age.

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, 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). It 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 from 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., Arabian-Nubian Shield and Sahara Metacraton (23: Kolodner et al., 2006; 12: Avigad et al., 2007; 11: Meinhold et al., 2011). In 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 the MAD and the Central Iberian, West Asturian and Cantabrian Zones, the Saharan Metacraton and the Arabian-Nubian Shield, on the one hand, and Normandy (2: NAD; Strachan et al., 2014), the Ossa Morena Zone, Saxo-Thuringia, the West African Craton, and the Tuareg Shield, on the other.

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 age in the Grès Armoricain Fm in the MAD excludes derivation from this basement. Moreover, available data on zircon populations of sediments laid down during 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 whit Stenian and late Tonian ages. These features exclude 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 possibly are 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 erosion of the East African Orogen (also often referred as the Transgondwanan Supermountain). These sediments have age probability density distribution plots similar to those for the Armorican sedimentary rocks (two main zircon populations, one Pan-African and the other Stenian to late Tonian in age, separated by a gap 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), yielded a zircon population close to that 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 until they were 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 of source areas for the terrigenous flux between the Ediacaran and the 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 Palaeozoic sedimentary strata (Initial Red Beds) have the same zircon populations provided from 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 thickness) that 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 they are ubiquitous in the eastern part (Saharan Metacraton, Arabian-Nubian Shield). Here, whole-rock Sm-Nd and zircon Hf isotopic signatures also attest to supply of recycled crustal material. These sediments, which according to Squire et al. (2006) and Meinhold et al. (2013) constituted a super-fan system, could be the source of the Ordovician sediments of the MAD. In this case, the MAD had to be positioned towards 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 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 with the Ossa Morena Zone and, for the Ordovician sediments, similarities with the Central Iberian, West Asturian and Cantabrian zones. In contrast with 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, in the NW Iberian Massif some inputs 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 limiting the Armorican Massif and the Gondwana continent, the source area of the Ordovician sediments of the MAD would have been the super-fan system developed in eastern Gondwana, from where Stenian and Tonian >800 Ma zircon populations are known.

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References

Abati, J., Aghzer, M.A., Gerdes, A., Ennih, N., 2010. Detrital zircon ages of Neoproterozoic sequences of the Moroccan Anti-Atlas belt. Precambrian Research 181, 115-128.

Abdelsalam, M.G., Liégeois, J.P., Stern, R.J., 2002. The Saharan Metacraton. Journal of African Earth Sciences 34, 119–136.

Albarède, F., Telouk, P., Blichert-Toft, J., Boyet, M., Agranier, A., Nelson, B., 2004. Precise and accurate isotopic measurements using multiple-collectorICPMS. Geochimica et Cosmochimica Acta 68, 2725–2744.

Auvray, B., 1979. Genèse et évolution de la croûte continentale dans le Nord du Massif Armoricain. Thèse d’Etat, Université Rennes, 680 pp.

Auvray, B., Charlot, R., Vidal, P., 1980. Données nouvelles sur le Protérozoïque inférieur du domaine Nord-Armoricain (France): âge et signification. Canadian Journal of Earth Sciences 17, 532-538.

Avigad, D., Kolodner, K., McWilliams, M., Persing, H., Weissbrod, T., 2003. Origin of northern Gondwana Cambrian sandstones revealed by detrital zircon SHRIMP dating. Geology 31, 3, 227-230.

Avigad, D., Stern, R.J., Beyth, M., Miller, N., McWillians, M.O., 2007. Detrital zircon U–Pb geochronology of Cryogenian diamictites and Lower Paleozoic sandstone in Ethiopia (Tigrai): Age constraints on Neoproterozoic glaciation and crustal evolution of the southern Arabian–Nubian Shield. Precambrian Research 154, 88-106.

Avigad, D., Gerdes, A., Morag, N., Bechstädt, T., 2012. Coupled U–Pb–Hf of detrital zircons of Cambrian sandstones from Morocco and Sardinia: Implications for provenance and Precambrian crustal evolution of North Africa. Gondwana Research 21, 690-703.

Ballouard, C., Poujol, M., Zeh, A., 2018. Multiple crust reworking in the French Armorican Variscan belt: implication for the genesis of uranium-fertile leucogranites. International Journal of Earth Sciences 107, 2317–2336.

Be'eri-Shlevin, Y., Katzir, Y., Whitehouse, M.J., Kleinhanns, I.C., 2009. Contribution of pre Pan-African crust to formation of the Arabian Nubian Shield: New secondary ionization mass spectrometry U-Pb and O studies of zircon. Geology 37, 10, 899-902.

Beuf, S., Biju-Duval, B., de Charpal, 0., Rognon, P., Gariel, 0., and Benacef, A., 1971. Les grès du Paléozoïque inferieur au Sahara. Sédimentation et discontinuités. Evolution structurale d'un craton: Institut Français du Pétrole, Science et technique du Pétrole 18, 464 pp.

Black, L. P., Calver, C. R., Seymour, D. B., & Reed, A., 2004. SHRIMP U–Pb detrital zircon ages from Proterozoic and Early Palaeozoic sandstones and their bearing on the early geological evolution of Tasmania. Australian Journal of Earth Sciences, 51, 6, 885-900.

Bonjour, J.-L., Peucat, J.-J., Chauvel, J.-J., Paris, F., Cornichet, J., 1988. U–Pb zircon dating of the Early Paleozoic (Arenigian) transgression in Western Brittany (France): anew constraint for the Lower Paleozoic time-scale. Chemical Geology 72, 329–336.

Bonjour, J.L., 1988. Sédimentation paléozoïque initiale dans le Domaine Centre Armoricain. Unpublished PhD Thesis, Université de Rennes I, France 257pp.

Bouvier, A., Vervoort, J.D., Patchett, P.J., 2008. The Lu–Hf and Sm–Nd isotopic composition of CHUR: constraints from unequilibrated chondrites and implication for the bulk composition of terrestrial planets. Earth and Planetary Science Letters 273, 48–57.

Bradley, D.C., O'Sullivan, P., Cosca, M.A., Motts, H.A., Horton, J.D., Taylor, C.D., Beaudoin, G., Lee, G.K., Ramezani, J., Bradley, D.B., Jones, J.V., Bowring, S., 2015. Synthesis of geological, structural, and geochronologic data (Phase V, Deliverable 53). Chapter A of Taylor C.D. (ed.), Second Projet de Renforcement Institutionnel du Secteur Minier de la République Islamique de Mauritanie (PRISM-II). U.S. Geological Survey Open-File Report 2013- 12080-A, 328p. doi:10.3133/ofr20131280.

Brun, J.P., Ballard, J.F., Le Corre, C., 1991. Identification of Ordovician block-tilting in the Hercynian fold-belt of Central Brittany (France): field evidence and computer models. Jornal of Structural Geology 13, 419–429.

Bühn, B., Pimentel, M.M., Matteini, M., Dantas, E.L., 2009. High spatial resolution analysis of Pb and U isotopes for geochronology by laser ablation multi-collector inductively coupled plasa ass spectroetry (L-C-ICPMS). Anais da Academia Brasileira de Ciências 81, 99-114.

Chantraine, J., Chauvel, J.J., Dupret, L., Gatinot, F., Icart, J.C., Le Corre, C., Rabu, D., Sauvan, P. and Villey, M., 1983. Inventaire lithologique et structural du Briovérien (Protérozoïque) de la Bretagne Centrale et du Bocage normand pour la recherche de guides métalloggniques. Documents du Bureau de Recherches Géologiques et Minières 67, 185 pp.

Chantraine, J., Autran, A., Cavelier, C., 1996. Carte géologique de la France, 1/1 000 000. BRGM, Orléans, France.

Chantraine, J., Houlgatte, E., Chauris, L., Coussement, C., Le Goff, E., Barrière, M., Larsonneur, C., Garreau, J., 1999. Carte Géologique de France (1/50 000), feuille Lannion (203), BRGM, Orléans. Explanatory notes by Chantraine et al., 144 pp.

Chantraine, J., Egal, E., Thiéblemont, D., Le Goff, E., Guerrot, C., Ballèvre, M., Guennoc, P., 2001. The Cadomian active margin (North Armorican Massif, France): a segment of the North Atlantic Panafrican belt. Tectonophysics 331, 1-18.

Chauvel, C., Blichert-Toft, J., 2001. A hafnium isotope and trace element perspective on melting of the depleted mantle. Earth and Planetary Science Letters 190, 137–151, doi:10.1016/S0012-821X(01)00379-X.

Cocherie, A., Chantraine, J., Mark Fanning, C., Dabard, M.P., Paris, F., Le Hérissé, A., Egal, E., 2001. Datation U/Pb: âge Briovérien de la série d'Erquy (Massif armoricain, France). Comptes Rendus de l'Académie des Sciences, Paris 333, 427-434.

Dabard, M.P., 1990. Lower Brioverian formations (Upper Proterozoic) of the Armorican Massif (France): geodynamic evolution of source areas revealed by sandstone petrography and geochemistry. Sedimentary Geology 69, 45-58.

Dabard, M.P., Loi, A., Peucat, J.J., 1996. Zircon typology combined with Sm-Nd whole-rock isotope analysis to study Brioverian sediments from the Armorican Massif. Sedimentary Geology 101, 243-260.

Dabard, M.P, 2000. Petrogenesis of graphitic cherts in the Armorican segment of the Cadomian orogenic belt (NW France). Sedimentology 47, 787-800.

Dabard, M.P., Loi, A., Paris, F., 2007. Relationship between phosphogenesis and sequence architecture: sequence stratigraphy and biostratigraphy in the Middle Ordovician of the Armorican Massif (France). Palaeogeography, Palaeoclimatology, Palaeoecology 248, 339-356.

Dabard, M.P., Loi, A., Paris, F., Ghienne, J.F., Pistis, M., Vidal, M., 2015. Sea-level curve for the Middle to early Late Ordovician in the Armorican Massif (western France): Icehouse third-order glacio-eustatic cycles. Palaeogeography, Palaeoclimatology, Palaeoecology 436, 96-111.

Dauteuil O., Durand J., Brun J.-P., 1987. Arguments en faveur de décrochements synchrones du dépôt des séries rouges d'Erquy-Fréhel. Comptes Rendus de l'Académie des Sciences, Paris, II-304, 83-88.

Denis, E., Dabard, M.P., 1988. Sandstone petrography and geochemistry of Late Proterozoic sediments of the Armorican Massif (France) – A key to basin development during the Cadomian orogeny. Precambrian Research 42, 189-206.

DePaolo, D.J., 1981. Neodymium isotopes in the Colorado Front Range and crust-mantle evolution in the Proterozoic. Nature 291, 193–196.

Egal, E., Guerrot, C., Le Goff E., Thiéblenont, D., Chantraine, J., 1996. The Cadomian orogeny revisited in northern Brittany (France). Geological Society of America Special Paper 304, 281-318.

Fernández-Suárez, J., Gutiérrez Alonso, G., Jenner, G.A., Tubrett, M.N., 2000. New ideas on the Proterozoic-Early Palaeozoic evolution of NW Iberia: insights from U-Pb detrital zircon ages. Precambrian Research 102, 185-206.

Fernández-Suárez, J., Gutiérrez Alonso, G., Jeffries, T.E., 2002a. 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 204, 75-88.

Fernández-Suárez, J., Gutiérrez Alonso, G., Cox, R., Jenner, G.A., 2002b. Assembly of the Armorica Microplate: A Strike-Slip Terrane Delivery? Evidence from U-Pb Ages of Detrital Zircons. The Journal of Geology 110, 619–626.

Fernández-Suárez, J., Gutiérrez Alonso, G., Pastor-Galán, D., Hofmann, M., Murphy, J.B., Linnemann, U., 2014. The Ediacaran-Early Cambrian detrital zircon record of NW Iberia: possible sources and paleogeographic constraints. International Journal of Earth Sciences 103, 1335-1357.

Gapais, D., Le Corre, C., 1980. Is the Hercynian belt of Brittany a major shear zone. Nature 288, 574-576.

Gärtner, A., Villeneuve, M., Linnemann, U., Gerdes, A., Youbi, N., & Hofmann, M., 2016. Similar crustal evolution in the western units of the Adrar Souttouf Massif (Moroccan Sahara) and the Avalonian terranes: Insights from Hf isotope data. Tectonophysics 681, 305-317.

Gärtner, A., Youbi, N., Villeneuve, M., Sagawe, A., Hofmann, M., Mahmoudi, A., Boumehdi, M. A., Linnemann, U., 2017. The zircon evidence of temporally changing sediment transport-the NW Gondwana margin during Cambrian to Devonian time (Aoucert and Smara areas, Moroccan Sahara). International Journal of Earth Sciences (Geol Rundsch) doi: 10.1007/s00531-017-1457-x

Gerdes A., Zeh A., 2006. Combined U-Pb and Hf isotope LA-(MC)-ICP-MS analyses of detrital zircons: comparison with SHRIMP and new constraints for the provenance and age of an Armorican metasediment in Central Germany. Earth and Planetary Science Letters 249, 47-61.

Gerdes A., Zeh A., 2009. Zircon formation *versus* zircon alteration - New insights from combined U-Pb and Lu-Hf *in-situ* LA-ICP-MS analyses, and consequences for the interpretation of Archean zircon from the Central Zone of the Limpopo Belt. Chemical Geology 261, 230-243.

Ghienne, J.-F., Boumendjel, K., Paris, F., Videt, B., Racheboeuf, P., Ait Salem, H., 2007. The Cambrian–Ordovician succession in the Ougarta Range (western Algeria, North Africa) and interference of the Late

Ordovician glaciation on the development of the Lower Palaeozoic transgression on northern Gondwana. Bulletin of Geosciences 82, 3, 183–214.

Gorini, A., Vidal, M., Loi, A., Paris F., 2008. Evoluzione stratigrafica pre-hirnantiana della Formazione di Kermeur (Massiccio Armoricano). Rendiconti Online Societa Geologica Italiana 3, 2, 451-452.

Gougeon, R., Néraudeau, D., Dabard, M.P., Pierson-Wieckmann, A.C., Polette, F., Poujol, M., Saint-Martin, J.P., 2018. Trace Fossils from the Brioverian (Ediacaran–Fortunian) in Brittany (NW France). Ichnos 25, 1, 11-24. doi: 10.1080/10420940.2017.1308865.

Graviou, P., Peucat, J.J., Auvray, B., Vidal, P., 1988. The Cadomian orogeny in the northern Armorican Massif. Petrological and geochronological constraints on a geodynamic model. Hercynica IV, 1, 1-13.

Guerrot, C., Peucat, J.J., 1990. U-Pb geochronology of the late Proterozoic Cadomian Orogeny in the Northern Armorican Massif, France. In: RS. D'Lemos, R.A. Strachan and C.G. Topley (Editors), The Cadomian Orogeny. Geological Society of London, Special Publication 51, 13-26.

Guerrot, C., Calvez, J.Y., Bonjour, J.L., Chantraine, J., Chauvel, J.J., Dupret, L., Rabu, D., 1992. Le Briovérien de Bretagne centrale et occidentale : nouvelles données radiométriques. Comptes Rendus de l'Académie des Sciences 315, 1741-1746.

Hargrove, U.S., Stern, R.J., Kimura, J.-I., Manton, W.I., Johnson, P.R., 2006. How juvenile is the Arabian–Nubian Shield? Evidence from Nd isotopes and pre-Neoproterozoic inherited zircon in the Bi'r Umq suture zone, Saudi Arabia. Earth and Planetary Science Letters 252, 308–326.

Hebert, R., Hallot, E., Guerrot, C., Chantraine, J., 1993. New structural, petrological and radiometric constraints within the Cadomian belt: chronology of events in the baie de Saint Brieuc, Northern Armorican Massif (France). Comptes Rendus de l'Académie des Sciences, Paris 316, II, 395-401.

Horstwood, M.S., Košler, J., Gehrels, G., Jackson, S.E., McLean, N.M., Paton, C., ..., Bowring, J.F., 2016. Community-derived standards for LA-ICP-MS U-(Th-) Pb geochronology–Uncertainty propagation, age interpretation and data reporting. Geostandards and Geoanalytical Research, 40, 3, 311-332.

Inglis, J.D., Samson, S.D., D'Lemos, R.S., Hamilton, M., 2004. U–Pb geochronological constraints on the tectonothermal evolution of the Paleoproterozoic basement of Cadomia, La Hague, NW France. Precambrian Research 134, 293-315.

Inglis, J.D., Samson, S.D., D'Lemos, R.S., Miller, B.V., 2005. Timing of Cadomian deformation and magmatism within La Hague, NW France. Journal of the Geological Society, London 162, 389–400.

Jackson, S.E., Pearson, N.J., Griffin, W.L., Belousova, E.A., 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U-Pb zircon geo- chronology. Chemical Geology 211, 47–69.

Jahn, B.M., Bernard-Griffiths, J., Chariot, R., Cornichet, J., Vidal, P., 1980. Nd and Sr isotopic compositions and REE abundances of Cretaceous MORB (Holes 417D and 418A, Legs 51, 52 and 53). Earth and Planetary Science Letters 48, 103-124.

Jégouzo, P., 1980. The South Armorican Shear Zone. Journal of Structural Geology 2, 1-2, 39-47.

Kolodner, K., Avigad, D., McWilliams, M., Wooden, J.L., Weissbrod, T., Feinstein, S., 2006. Provenance of north Gondwana Cambrian-Ordovician sandstone: U-Pb SHRIMP dating of detrital zircons from Israel and Jordan. Geological Magazine 143, 367-391.

Kosler, J., Fonneland, H., Sylvester, P., Tubrett, M., Pedersen, RB., 2002. U-Pb dating of detrital zircons for sediment provenance studies - a comparison of laser ablation ICMPS and SIMS techniques. Chemical Geology 182, 605-618.

Küster, D., Liégeois, J.P., Matukov, D. Sergeev, S., Lucassen, F., 2008. Zircon geochronology and Sr, Nd, Pb isotope geochemistry of granitoids from Bayuda Desert and Sabaloka (Sudan): Evidence for a Bayudian event (920–900 Ma) preceding the Pan-African orogenic cycle (860–590 Ma) at the eastern boundary of the Saharan Metacraton. Precambrian Research 164, 16–39.

Le Corre, C., 1977. Le Briovérien de Bretagne centrale: essai de synthèse lithologique et structurale. Bulletin du Bureau de Recherche Géologique et Minière I, 3, 219-254.

Le Heron, D.P., Howard, J.P., Alhassi, A.M., Anderson, L.M., Morton, A.C., Fanning, C.M., 2009. Field-based investigations of an 'Infracambrian' clastic succession in SE Libya and its bearing on the evolution of the Al Kufrah Basin. In: Craig, J., Thurow, J., Thusu, B., Whitham, A.G., Abutarruma, Y. (Eds.), Global Neoproterozoic Petroleum Systems: The Emerging Potential in North Africa: Geological Soiety of London, Special Publication 326, 193–210.

Liégeois, J.P., Black, R., Navez, J., Latouche, L., 1994. Early and late Pan-African orogenies in the Aïr assembly of terranes (Tuareg shield, Niger). Precambrian Research 67, 1-2, 59-88.

Liégeois, J.P., Latouche, L., Boughara, M., Navez, J., Guirad, M., 2003. The LATEA metacraton (Central Hoggar, Tuareg shield, Algeria): behaviour of an old passive margin during the Pan-African orogeny. Journal of African Earth Sciences 37, 161–190.

Linnemann, U., McNaughton, N.J., Romer, R.L., Gehmlich, M., Drost, K., Tonk, C., 2004. West African provenance for Saxo-Thuringia (Bohemian Massif): Did Armorica ever leave pre-Pangean Gondwana? - U/Pb-SHRIMP zircon evidence and the Nd-isotopic record. International Journal of Earth Sciences 93, 5, 683-705.

Linnemann, U., Pereira, M.F., Jeffries, T., Drost, K., Gerdes, A., 2008. Cadomian Orogeny and the opening of the Rheic Ocean: new insights in 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 461, 21–43.

Linnemann, U., Ouzegane, K., Drareni, A., Hofmann, M., Becker, S., Gärtner, A., Sagawe, A., 2011. Sands of West Gondwana: An archive of secular magmatism and plate interactions-A case study from the Cambro-Ordovician section of the Tassili Ouan Ahaggar (Algerian Sahara) using U-Pb-La-ICP-MS detrital zircon ages. Lithos 123, 188-203.

Linnemann, U., Gerdes, A., Hofmann, M., Marko, L., 2014. The Cadomian Orogen: Neoproterozoic to Early Cambrian crustal growth and orogenic zoning along the periphery of the West African Craton-Constraints from U-Pb zircon ages and Hf isotopes. Precambrian Research 244, 236-278.

Marcoux, E., Cocherie, A., Ruffet, G., Darboux, J.R., Guerrot, C., 2009. Géochronologie revisitée du dôme du Léon (Massif armoricain, France). Géolologie de la France 1, 19-40.

Martin, E., François, C., Paquette, J.L., Capdevila, R., Lejeune, A.M., 2018. Petro-geochemistry and zircon U-Pb dating of the late Variscan Flamanville granodiorite and its Paleoproterozoic basement (Normandy, France). Géologie de la France 1, 34-48.

Matteini, M., Dantas, E., Pimentel, M., Bühn, B., 2010. Combined U-Pb and Lu-Hf isotope analyses by laser ablation MC-ICP-MS: methodology and applications. Annals of the Brazilian Academy of Science 82(2), 479-491.

Meinhold, G., Morton, A.C., Fanning, C.M., Frei, D., Howard, J.P., Phillips, R.J., Strogen, D., Whitham, A.G., 2011. Evidence from detrital zircons for recycling of Mesoproterozoic and Neoproterozoic crust recorded in Paleozoic and Mesozoic sandstones of southern Libya. Earth and Planetary Science Letters 312, 164-175.

Meinhold, G., Morton, A.C., Avigad, D., 2013. New insights into peri-Gondwana paleogeography and the Gondwana super-fan system from detrital zircon U–Pb ages. Gondwana Research 23, 661-665.

Michard, A, Gurriet, P., Soudant, M., Albarede, F., 1985. Nd isotopes in French Phanerozoic shales: external vs. internal aspects of crustaI evolution. Geochimica Cosmochimica Acta 49, 601-610.

Miller, B.V., Samson, S.D., D'Lemos, R.S., 2001. U-Pb geochronological constraints on the timing of plutonism, volcanism and sedimentation, Jersey, Channel Island, UK. Journal of the Geological Society, London 158, 243-252.

Morag, N., Avigad, D., Gerdes, A., Belousova, E., Harlavan, Y., 2011. Detrital zircon Hf isotopic composition indicates long-distance transport of North Gondwana Cambrian-Ordovician sandstones. Geology 39, 10, 955-958.

Morag, N., Avigad, D., Gerdes, A., Harlavand, Y., 2012. 1000–580 Ma crustal evolution in the northern Arabian-Nubian Shield revealed by U–Pb–Hf of detrital zircons from late Neoproterozoic sediments (Elat area, Israel). Precambrian Research 208–211, 197–212. doi.org/10.1016/j.precamres.2012.04.009.

Morel, M.L.A., Nebel, O., Nebel-Jacobsen, Y.J., Miller, J.S., Vroon, P.Z., 2008. Hafnium isotope characterization of the GJ-1 zircon reference material by solution and laser-ablation MC-ICPMS. Chemical geology 255, 1-2, 231-235.

Nagy, E., Samson, S.D., D'Lemos, R.S., 2002. U–Pb geochronological constraints on the timing of Brioverian sedimentation and regional deformation in the St. Brieuc region of the Neoproterozoic Cadomian orogen, northern France. Precambrian Research 116, 1–17

Nebel, O., Nebel-Jacobsen, Y., Mezger, K., Berndt, J., 2007. Initial Hf isotope compositions in magmatic zircon from early Proterozoic rocks from the Gawler Craton, Australia: A test for zircon model ages. Chemical Geology 241, 23-37.

Noblet, C., Lefort, J.P., 1990. Sedimentological evidence for a limited separation between Armorica and Gondwana during the Early Ordovician. Geology 18, 303-306.

Paris, F., Robardet, M., 1977. Paléogéographie et relations Ibéro-Armoricaines au PaléozoÏQUE ante Carbonifère. Bulletin de la Société Géologique de France 7, 19, 1121-1126.

Paris, F., Robardet, M., Dabard, M.P., Feist, R., Ghienne, J.F., Guillocheau, F., Le Hérissé, A., Loi, A., Mélou, M., Servais, T., Shergold, J., Vidal, M., Vizcaïno, D., 1999. Ordovician sedimentary rocks of France. Acta Universitatis Carolinae-Geologica 43, 1/2, 85-88.

Pasteel, P., Doré, F., 1982. Age of the Vire-Carolles granite. In: G.S. Odin (Edit), Numerical dating in stratigraphy.Vol. II, NDS 212, 784-790.

Pereira, M.F., Linnemann, U., Hofmann, M., Chichorro, M., Solád, A.R., Medina, J., Silva, J.B., 2012a. The provenance of Late Ediacaran and Early Ordovician siliciclastic rocks in the Southwest Central Iberian Zone: Constraints from detrital zircon data on northern Gondwana margin evolution during the late Neoproterozoic. Precambrian Research 192– 195, 166– 189.

Pereira, M.F., Solád, A.R., Chichorro, Lopes, L.n Gerdes, A., Silva, J.B., 2012b. North-Gondwana assembly, break-up and paleogeography: U–Pb isotope evidence from detrital and igneous zircons of Ediacaran and Cambrian rocks of SW Iberia. Gondwana Research 22, 3-4, 866–881.

Peucat, J.J., Hirbec, Y., Auvray, B., Cogné, J., Cornichet, J., 1981. Late Proterozoic age from a basic-ultrabasic volcanic complex: a possible Cadomian orogenic complex in the Hercynian belt of western Europe. Geology 9, 169-173.

Peucat, J.J., 1986. Behaviour of Rb-Sr whole-rock and U-Pb zircon systems during partial melting as shown in migmatitic gneisses from the St-Malo massif, NE Brittany, France. Journal of the Geological Society 143, 875-886.

Pistis, M., Loi, A., Dabard, M.P., 2016. Influence of relative sea-level variations on the genesis of palaeoplacers, the examples of Sarrabus (Sardinia, Italy) and the Armorican Massif (Western France). Comptes Rendus Geoscience 348, 150–157. doi 10.1016/j.crte.2015.09.006

Robardet, M., 2002. Alternative approach to the Variscan Belt in southwestern Europe: Preorogenic paleobiogeographical constraints. In: Martinez Catalan, J.R., Hatcher, R.D., Arenas, R., Diaz Garcia, F. (Eds.), Variscan-Appalachian Dynamics: The Building of the Late Paleozoic Basement. Geological Society of America Special Paper 364, 1-15.

Samson, S.D., D'Lemos, R.S., 1998. U-Pb geochronology and Sm-Nd isotopic composition of Proterozoic gneisses, Channel Islands, UK. Journal of the Geological Society, London 155, 609-618.

Samson, S.D., D'Lemos, R., Blichert-Toft, J., Vervoort, J., 2003. U-Pb geochronology and Hf-Nd isotope compositions of the oldest Neoproterozoic crust within the Cadomian orogen: new evidence for a unique juvenile terrane. Earth and Planetary Science Letters 208, 165-180.

Samson, S.D., D'Lemos, R., Miller, B.V., Hamilton, M.A., 2005. Neoproterozoic palaeogeography of the Cadomia and Avalon terranes: constraints from detrital zircon U–Pb ages. Journal of the Geological Society, London 162, 65–71.

Scherer, E., Münker, C., Mezger, K., (2001). Calibration of the lutetium-hafnium clock. Science 293, 5530, 683-687.

Shaw, J., Gutiérrez-Alonso, G., Johnston, S.T., Pastor Galán, D., 2014. Provenance variability along the Early Ordovician north Gondwana margin: Paleogeographic and tectonic implications of U-Pb detrital zircon ages from the Armorican Quartzite of the Iberian Variscan belt. Geological Society of America Bulletin 126, 5/6, 702–719, doi:10.1130/B30935.1.

Sláma, J., Košler, J., 2012. Effects of sampling and mineral separation on accuracy of detrital zircon studies. Geochemistry, Geophysics, Geosystems 13, 5, 17pp.

Squire, R.J., Campbell, I.H., Allen, C.M., Wilson, C.J.L., 2006. Did the Transgondwanan Supermountain trigger the explosive radiation of animals on Earth? Earth and Planetary Science Letters 250, 116–133.

Stephan, T., Kroner, U., Romer, R.L., 2019. The pre-orogenic detrital zircon record of the Peri-Gondwanan crust. Geological Magazine 156, 281–307.

Strachan, R.A., D'Lemos, R.S., Dallmeyer, R.D., 1996. Neoproterozoic evolution of an active plate margin: North Armorican Massif, France. In: Nance RD, Thompson MD (eds) Avalonian and Related Peri-Gondwanan Terranes of the Circum-Atlantic. Geological Society of America, Special Paper 304, 319-332.

Strachan, R.A., Linnemann, U., Jeffries, T., Drost, K., Ulrich, J., 2014. Armorican provenance for the mélange deposits below the Lizard ophiolite (Cornwall, UK): evidence for Devonian obduction of Cadomian and Lower Palaeozoic crust onto the southern margin of Avalonia. International Journal of Earth Sciences (Geol Rundsch) 103, 1359-1383, Doi 10.1007/s00531-013-0961-x.

Suire, P., Dabard, M.P., Chauvel, J.J., 1991. Nouvelles données sur les séries rouges nord-armoricaines : étude du bassin ordovicien de Bréhec. Comptes Rendus de l'Académie des Sciences, Paris 312, II, 721-727.

Talavera, C., Martínez Poyatos, D., González Lodeiro, F., 2015. SHRIMP U–Pb geochronological constraints on the timing of the intra-Alcudian (Cadomian) angular unconformity in the Central Iberian Zone (Iberian Massif, Spain). International Journal of Earth Sciences (Geol Rundsch) 104, 1739-1757, doi 10.1007/s00531-015-1171-5.

Taylor, S.R., Mclennan, S.M., 1985. The Continental Crust: its Composition and Evolution. Oxford: Black-well, 312 pp.

Thiéblemont, D., Egal, E. Guerrot, C., Chantraine, J., 1999. Témoins d'une subduction « éocadomienne » (665-655 Ma) en Bretagne nord: arguments géochimiques. Géologie de la France 1, 3-11.

Vidal P., Deutsch S., Martineau F., Cogné J., 1974. Nouvelles données radiométriques en Baie de Saint-Brieuc. Le problème d'un socle antécadomien nord-armoricain. Comptes Rendus de l'Académie des Sciences, Paris, 279, 631-634.

Vidal, P., 1980. L'évolution polyorogénique du Massif armoricain : apport de la géochronologie et de la géochimie isotopique du strontium. Mémoire de la Société Géologique et Minéralogique de Bretagne 21, 162 pp.

Vidal, M., Dabard, M.P., Gourvennec, R., Le Hérissé, A., Loi, A., Paris, F., Plusquellec, Y., Racheboeuf, P., 2011a. Le Paléozoïque de la presqu'île de Crozon (France). Géologie de la France 1, 3–45.

Vidal, M., Loi, A., Dabard, M.P., Botquelen, A., 2011b. A Palaeozoic open shelf benthic assemblage in a protected marine environment. Palaeogeography, Palaeoclimatology, Palaeoecology 306, 27-40.

Wedepohl, K.H., 1995. The compositions of the continental crust. Geochimica et Cosmochimica Acta 59, 1217-1232.

Young, T.P., 1988. The lithostratigraphy of the upper Ordovician of central Portugal. Journal of the Geological Society of London 145, 3, 377-392. doi.org/10.1144/gsjgs.145.3.0377.