

# Terrane accretion and dispersal in the northern Gondwana margin. An Early Paleozoic analogue of a long-lived active margin

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## Abstract

If reconstruction of major events in ancient orogenic belts is achieved in sufficient detail, the tectonic evolution of these belts can offer valuable information to widen our perspective of processes currently at work in modern orogens. Here, we illustrate this possibility taking the western European Cadomian–Avalonian belt as an example. This research is based mainly on the study and interpretation of U–Pb ages of more than 300 detrital zircons from Neoproterozoic and Early Paleozoic sedimentary rocks from Iberia and Brittany. Analyses have been performed using the laser ablation–ICP–MS technique. The U–Pb data record contrasting detrital zircon age spectra for various terranes of western Europe. The differences provide information on the processes involved in the genesis of the western European Precambrian terranes along the northern margin of Neoproterozoic Gondwana during arc construction and subduction, and their dispersal and re-amalgamation along the margin to form the Avalonia and Armorica microcontinents. The U–Pb ages reported here also support the alleged change from subduction to transform activity that led to the final break-up of the margin, the birth of the Rheic Ocean and the drift of Avalonia. We contend that the active northern margin of Gondwana evolved through several stages that match the different types of active margins recognised in modern settings.

**Keywords:** U–Pb dating; Laser ablation–ICP–MS; Detrital zircon; Cadomia; Iberia; Gondwanan margin

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## 1. Introduction

The creation, dispersal, amalgamation and destruction of peripheral microcontinents, magmatic arcs and

oceans are involved in the formation of most orogenic belts and the origin of continental crust. The study of these fundamental processes in ancient orogens is often hindered by their involvement in subsequent tectonic events and plate reorganisations. Here, we address the Neoproterozoic–Early Paleozoic paleogeographic and tectonic evolution of western Europe based on a laser ablation–ICP–MS study of U–Pb ages of more than 300 detrital zircons from Neo-

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proterozoic and Early Paleozoic sedimentary rocks in Iberia and Brittany. Detrital zircons are a powerful tool in the investigation of sediment source areas and in providing paleogeographic constraints, particularly in cases where no paleontological record exists and/or paleomagnetic data are not available. This study is aimed at obtaining first order constraints on the genesis and location of the western European terranes along the active margin of north Gondwana, the formation of the Armorica and Avalonia microcontinents, their dispersal and subsequent opening of the Early Paleozoic Rheic Ocean.

In this paper, we present new data from Neoproterozoic rocks of Central and Northern Iberia (samples ZD-1 to ZD-4) together with an overview of previous work on detrital zircons from related Neoproterozoic–Early Paleozoic rocks of Iberia and Brittany (Fernández-Suárez et al., 2000, 2002; Gutiérrez-Alonso et al., 2001). This contribution is an update aimed at giving a more comprehensive hypothesis for the evolution of the northern margin of Gondwana. The approach used here, based on the study of detrital zircon ages in key sedimentary formations, provides information that other types of geological evidence may fail to detect or constrain.

In our view, this example is of general relevance in the understanding of the nature, evolution and time-scales of processes operating in long-lived subduction-related orogenic belts with complex history and geometry including large, margin-parallel terrane transfer.

## 2. Geological and paleogeographic setting

The Late Paleozoic Variscan belt of western Europe involves several crustal units with Precambrian basement (Fig. 1) that originally formed part of the Neoproterozoic assemblage of terranes that made up the peri-Gondwanan Cadomian–Avalonian arc (e.g. Nance and Murphy, 1994; Unrug, 1997; Murphy et al., 2000). There is general agreement that these terranes formed as a result of Neoproterozoic subduction along the northern Gondwanan margin, and were subsequently dispersed as subduction was replaced by transform activity and the opening of the Early Paleozoic Rheic Ocean (Murphy and Nance, 1989; Murphy et al., 2000; von Raumer et

al., 2002). Subsequent Paleozoic plate tectonic motions that culminated in Appalachian (Alleghenian)–Variscan orogenesis further re-shuffled these terranes to their present arrangement in western Europe and Atlantic North America. Reconstructing the tectonic evolution of these terranes and their location along the Cadomian–Avalonian orogen is fundamental to the study of the implications of Neoproterozoic tectonic events.

Paleomagnetic studies and geological correlation based on stratigraphy and the paleontological record have provided a wealth of information on Neoproterozoic–Early Paleozoic continental reconstructions (e.g. Dalziel, 1997; Tait et al., 1997; Robardet, 2000). Yet tighter constraints are needed in order to obtain a more detailed picture of the geography and tectonic settings of the northern Gondwana margin and adjacent regions. Tracing the ancestry and evolution of the peri-Gondwanan terranes is further hindered by the absence of exposed pre-Neoproterozoic basement throughout most of the Cadomian–Avalonian belt. In these circumstances, the approach of comparing U–Pb ages of detrital zircons in coeval sedimentary rocks from separate terranes can yield valuable information on first order tectonic events and constraints on the nature and age of the basement source rocks and, therefore, on the contemporary paleogeography.

The above issues are explored herein through a study of detrital zircon U–Pb ages in the following sedimentary formations of the variscan belt of western Europe (Fig. 1).

(A) Neoproterozoic greywackes in the Ossa Morena Zone (SW Iberia) and the north Armorican domain (samples ZD-6 and ZD-9, respectively, in Fig. 1; Gutiérrez-Alonso et al., 2001). Sample ZD-6 is a coarse greywacke from the upper part of the Serie Negra, in the core of the Olivenza–Monesterio antiform, and sample ZD-9 is a medium-grained greywacke from the Brioverian sediments in the Binic Formation (north of the town of Binic, Brittany). Both formations are considered to have a latest Neoproterozoic stratigraphic age (e.g. Nagy et al., 2002). The correlation of the SW Iberian (Ossa Morena) and North Armorican domains, based on shared Neoproterozoic–Lower Paleozoic stratigraphy, and the abundance of igneous rocks of Cadomian age is highlighted by restoration of the Late Paleozoic Iber-

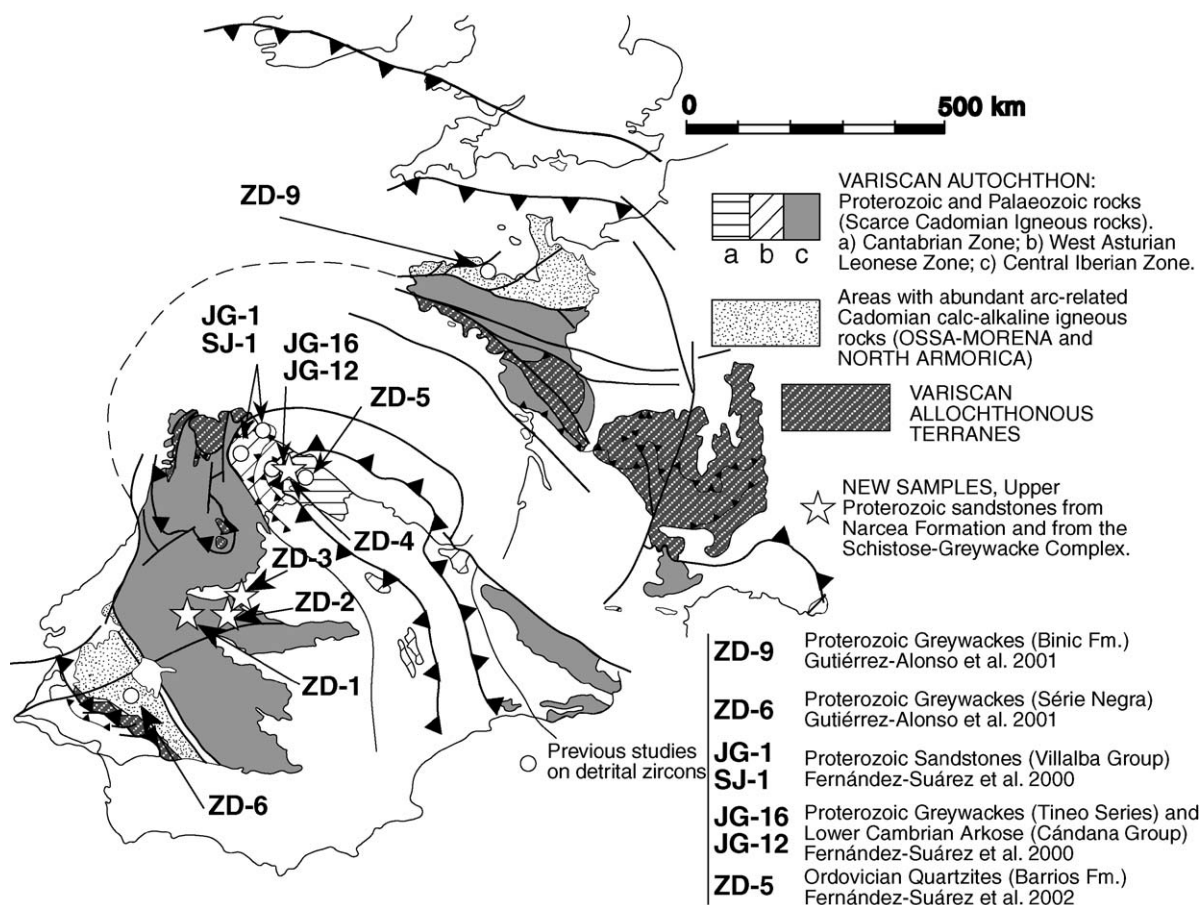


Fig. 1. Simplified geological map of Iberia and Cadomia showing the main geological units cited in the text and sample locations (see text for geographic coordinates).

ian– Armorican arc (Fig. 1). Both domains record widespread Cadomian deformation and both are, respectively, juxtaposed against the Central Iberian and South Armorican domains along major strike-slip faults with movement histories that may predate the earliest recognised Variscan deformation (Eguiluz et al., 2000; Simancas et al., 2001).

(B) Neoproterozoic and Paleozoic formations from the NW Iberian realm. Seven Neoproterozoic, one Cambrian and one Ordovician samples were studied. These samples cover the three main paleogeographic domains of the NW Iberian autochthonous terrane (Central Iberian, Westasturian– Leonese and Cantabrian Zones; Fig. 1).

Sample JG-12 (Fernández-Suárez et al., 2000) is a Neoproterozoic, medium-grained feldspathic greywacke from the Tineo Series (eastern part of the WALZ). Samples JG-1 and SJ-1 are Neoproterozoic, medium-grained feldspathic greywackes from Lower and Upper Villalba Series, respectively (western part of the WALZ) (Fernández-Suárez et al., 2000).

Sample JG-16 (Fernández-Suárez et al., 2000) is a Cambrian, medium-grained sub-arkose from the lower part of the Cándana Formation (eastern part of the WALZ). The sampling spot is located approximately 10 m above the unconformity with the Neoproterozoic Tineo–Narcea Series.

Sample ZD-5 (Fernández-Suárez et al., 2002a) is an extremely pure, unmetamorphosed white quartzite from the Barrios Quartzite Formation (local name for the Ordovician (Arenigian) Armorican quartzite in the Cantabrian Zone of NW Iberia).

Four new samples were collected for this study. Sample ZD-3 (43°N15'30" -6°W28'12") is a coarse-grained arkose from the Narcea Slates Formation (the only Neoproterozoic outcrop in the Cantabrian Zone; Fig. 1). The other three samples (ZD-1, ZD-2 and ZD-

4) are representative of the Neoproterozoic Schistose–

Greywacke Complex in the Central Iberian Zone (Fig. 1). These samples were collected in the Monterrubio Formation (ZD-1: 40°N35'48" -5°W38'00"), the Lower Series (ZD-2: 40°N25'43" -6°W16'17" and the Aldeatejada Formation (ZD-4: 40°N54'36" -5°W42'34").

### 3. Analytical techniques

U–Pb dating of individual zircon grains was performed using a laser ablation quadrupole ICP–MS at Memorial University of Newfoundland (Fernández-Suárez et al., 2000; Kosler et al., 2002) and The Natural History Museum (London) (Jeffries, 2001). Zircons were separated using conventional techniques, and 50–90 grains per sample, representing all types and morphologies, were selected by hand-picking under a binocular microscope. Zircons were set in synthetic resin mounts, polished and cleaned in a warm HNO<sub>3</sub> ultrasonic bath. Cathodoluminescence (CL) and back-scattered electron (BSE) imaging were performed and in view of the relatively large ablation pit size (c. 50–70 µm in diameter), only zircons considered to be homogeneous on the basis of their CL/BSE images, or large cores, were analysed. Analyses were performed using 213 and 266 nm Nd:YAG laser ablation systems coupled to quadrupole based ICP–mass spectrometers. To reduce the effects of inter-element laser-induced fractionation, the zircons were ablated at the lowest power density required to couple to the sample (pulse energy = 0.15 mJ/pulse). During ablation, the sample was moved relative to the beam along raster or line patterns, appropriate to its size. For each determination, time-resolved signals were carefully studied to select stable, non-fractionated intervals, ensuring that inclusions, zonation or

core-rim features were always excluded from age calculations.

Full details of analytical methods and equipment are given elsewhere (Fernández-Suárez et al., 2000; Horn et al., 2000; Jeffries, 2001; Kosler et al., 2002).

### 4. Detrital zircon ages

The results of the new single grain analyses are shown in the concordia diagrams of Fig. 2 (ZD-3 and ZD-1, ZD-2, ZD-4) and Table 1 and the results of the whole dataset (ca. 300 analyses) are presented in the histograms of Fig. 3A. Although the analytical methodology and data reduction approach ensure that only isotopically homogeneous domains were ablated, analyses with >20% discordancy (calculated from  $[^{206}\text{Pb}/^{238}\text{U}]/[^{207}\text{Pb}/^{206}\text{Pb}]$  age) were rejected.

All Neoproterozoic samples from NW Iberia contain zircon populations with similar morphological features, suggesting limited transport, and all yielded U–Pb age groups that are analytically equivalent. The same similarity of features and U–Pb age groups was found in the Neoproterozoic samples from Ossa Morena (SW Iberia) and Brittany.

#### 4.1. Ossa Morena and Brittany

Samples ZD-6 (Ossa Morena, SW Iberia) and ZD-9 (Brittany) (Fig. 3A) (Fernández-Suárez et al., 2002b) show the same U–Pb age groups with a predominance of zircons in the age range 550–680 Ma (Fig. 3A), which corresponds to Cadomian–Avalonian–Pan-African events. Fewer zircons yielded older Neoproterozoic ages (ca. 680–840 Ma), which may correspond either to Early Cadomian–Avalonian arc construction (Fernández-Suárez et al., 2000; Murphy et al., 2000) or to other events recorded along the Gondwanan margin of NW Africa (Unrug, 1997) and South America (Hartmann, 2001). The second group in abundance consists of Paleoproterozoic zircons (ca. 1850–2300 Ma), which could correspond to events in NW Africa (Eburnian), South America (Trans-Amazonian) and western Europe (Icartian). A few zircons with Archean ages (2500–3300 Ma) were also found.

The above age groups are consistent with U–Pb IDTIMS single grain ages obtained from zircons in the stratigraphically equivalent Jersey Shale Forma-

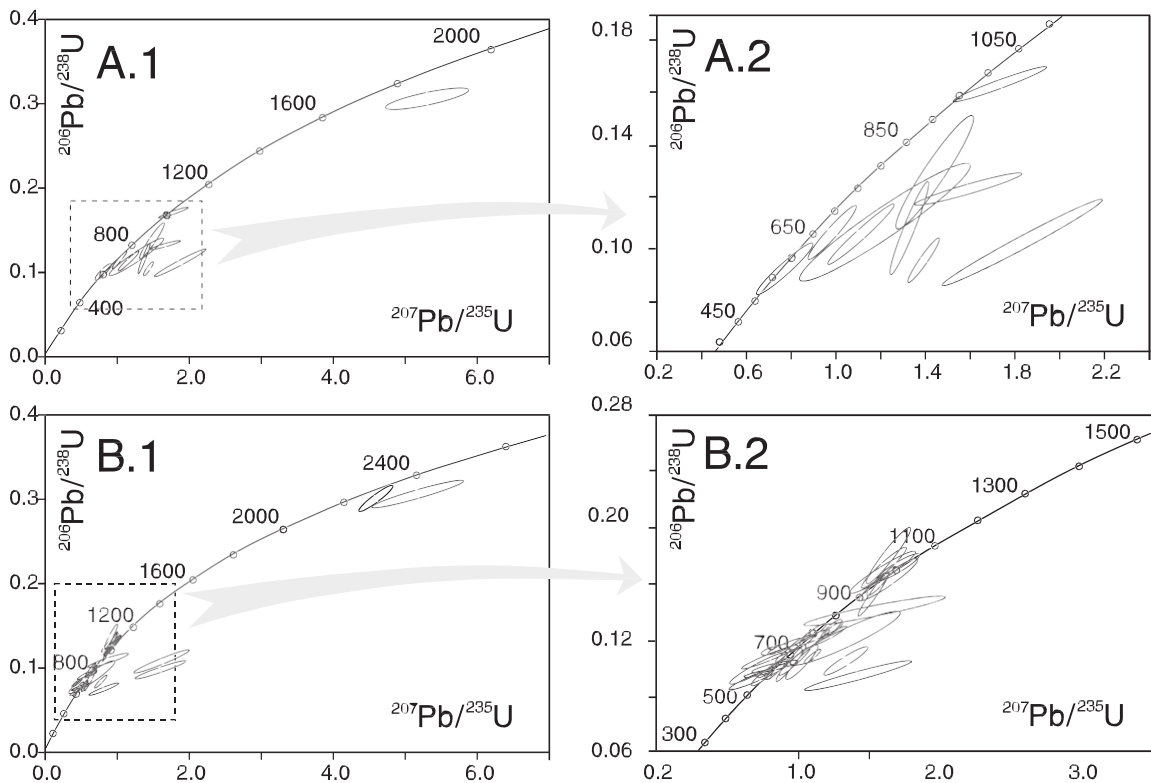


Fig. 2. Concordia plots of U–Pb analytical data of detrital zircons. (A.1 and A.2) Sample ZD-3 (Uppermost Neoproterozoic Narcea Slates Fm.). (B.1 and B.2) Combined data from samples ZD-1, ZD-2 and ZD-4 (Schistose-Greywacke Complex, Central Iberian Zone). Ellipses represent  $2\sigma$  uncertainties.

tion of the Brioverian Supergroup (Miller et al., 2001) and with the main Neoproterozoic magmatic events identified in SW Iberia by SHRIMP U–Pb dating (Ordoñez, 1998).

#### 4.2. NW Iberia

The Neoproterozoic greywackes in NW Iberia are dominated by zircons belonging to two age groups: Neoproterozoic zircons with ages between ca. 620 and 780 Ma and Late Mesoproterozoic zircons (950–1300 Ma). Fewer zircons yielded Paleoproterozoic (ca. 1800–2300 Ma) and Archean (2500–2700 Ma) ages (Figs. 2 and 3).

Zircons from the Cambrian arkose yielded Late Proterozoic ages mainly between 540 and 640 Ma, these are significantly younger than those found in the Neoproterozoic greywackes (Fig. 3B). Besides this dominant group, Late Mesoproterozoic (1000–1200

Ma), Paleoproterozoic and Archean zircons were also found.

#### 4.3. The Armorican quartzite of NW Iberia

The U–Pb ages indicate a predominance of zircons in the range 550–800 Ma, which corresponds to the Cadomian–Avalonian–Pan-African events (ca. 32% of analyses; Fig. 3A). The second group in abundance consists of Mesoproterozoic (Grenvillian) zircons in the age range 900–1300 Ma (ca. 26% of analyses), which might correspond to the Sunsas and Oaxacan events in Central and South America (Hartmann, 2001; Keppie et al., 2001). Older zircons have Paleoproterozoic ages (1800–2300 Ma) (12 zircons, ca. 13%), which might correspond to events in NW Africa (Eburnian), Amazonian Craton (Trans-Amazonian) and western Europe (Icartian), and Archean ages (2.5–3.0 Ga) (16 analyses, ca. 18%). It is also

Table 1  
Analytical data for samples ZD-1, ZD-2, ZD-3 and ZD-4

	Measured ratios						Apparent ages					
	207/235 2σ		206/238 2σ		207/206 2σ		207/235	±	206/238	±	207/206	±
ZD-1												
1	1.55615	0.12762	0.16783	0.01237	0.06890	0.00196	953	51	1000	68	896	59
3	0.83254	0.11700	0.10963	0.00481	0.07352	0.00219	615	65	671	28	1028	60
5	0.83239	0.04639	0.10218	0.00443	0.06389	0.00122	615	26	627	26	738	40
9	1.18905	0.06765	0.12070	0.00487	0.07131	0.00110	796	31	735	28	966	31
11	2.85574	0.58408	0.13410	0.01619	0.16116	0.00889	1370	154	811	92	2468	93
12	1.51353	0.06594	0.15625	0.00743	0.07880	0.00169	936	27	936	41	1167	43
13	1.04804	0.07124	0.11887	0.00506	0.06938	0.00145	728	35	724	29	910	43
14	1.37407	0.31069	0.08724	0.00867	0.14778	0.00987	878	133	539	51	2320	115
15	0.85476	0.19970	0.09709	0.00608	0.07576	0.00221	627	109	597	36	1089	59
16	1.02019	0.11074	0.11032	0.00455	0.08150	0.00202	714	56	675	26	1233	49
17	1.18994	0.05822	0.12249	0.00565	0.07256	0.00142	796	27	745	32	1002	40
18	1.02976	0.14678	0.11297	0.00510	0.08363	0.00288	719	73	690	30	1284	67
20	0.93272	0.05834	0.10444	0.00462	0.06140	0.00138	669	31	640	27	653	48
21	1.09611	0.08965	0.11794	0.00492	0.06968	0.00101	751	43	719	28	919	30
22	9.66636	0.98108	0.41926	0.01972	0.14039	0.00194	2404	93	2257	90	2232	24
ZD-2												
2	1.04579	0.05379	0.10163	0.00426	0.07181	0.00126	727	27	624	25	980	36
4	1.28609	0.12664	0.09898	0.00844	0.1758	0.00171	840	59	608	50	2614	16
5	1.46205	0.07579	0.14531	0.01025	0.0897	0.00276	915	45	875	58	1420	59
6	0.91920	0.09619	0.09711	0.00989	0.0659	0.00162	662	51	597	58	803	52
7	0.80363	0.06724	0.09503	0.00873	0.0580	0.00143	599	38	585	51	628	54
8	1.48987	0.41084	0.13545	0.00897	0.11598	0.00841	926	167	819	50	1895	130
9	1.57419	0.13782	0.17548	0.01864	0.13742	0.00818	960	87	1042	102	2195	103
12	2.90206	0.53167	0.11862	0.01290	0.18099	0.00801	1382	138	723	74	2662	73
ZD-4												
1	0.87116	0.06699	0.09511	0.00989	0.06154	0.00119	636	36	586	58	658	41
2	0.87607	0.09454	0.09769	0.00917	0.06576	0.00120	639	51	601	54	799	38
3	0.97328	0.09149	0.09716	0.01073	0.06803	0.00346	690	47	598	63	870	106
4	0.84551	0.04243	0.09424	0.00567	0.06042	0.00111	622	23	581	33	619	40
6	1.18205	0.09503	0.11795	0.00536	0.07727	0.00187	792	44	719	31	1128	48
8	8.57014	0.36581	0.41433	0.01814	0.14342	0.00205	2293	39	2235	83	2269	25
ZD-3												
1	5.25246	0.47621	0.30445	0.01111	0.16589	0.01081	1861	77	1713	55	2517	110
2	1.18854	0.30983	0.10753	0.01932	0.07097	0.00349	795	144	658	112	957	101
3	1.40790	0.14388	0.12790	0.01842	0.07194	0.00211	892	61	776	105	984	60
4	1.80694	0.29046	0.09980	0.01418	0.12882	0.00389	1048	105	613	83	2082	53
5	1.71424	0.16848	0.16356	0.00604	0.08914	0.00204	1014	63	977	33	1407	44
6	1.30041	0.06973	0.10523	0.01517	0.12192	0.00409	846	38	645	88	1985	60
7	1.56266	0.19400	0.12126	0.00523	0.12334	0.00421	956	77	738	30	2005	61
8	1.36410	0.05441	0.09232	0.00721	0.15795	0.00859	874	25	569	43	2434	92
9	0.94982	0.08674	0.10324	0.00863	0.06447	0.00143	678	45	633	50	757	47
11	1.08311	0.11990	0.10286	0.00993	0.07124	0.00194	745	58	631	58	964	56
12	0.73375	0.10161	0.08882	0.00818	0.06297	0.00118	559	60	549	48	707	40

Errors are expressed as  $2\sigma$ .



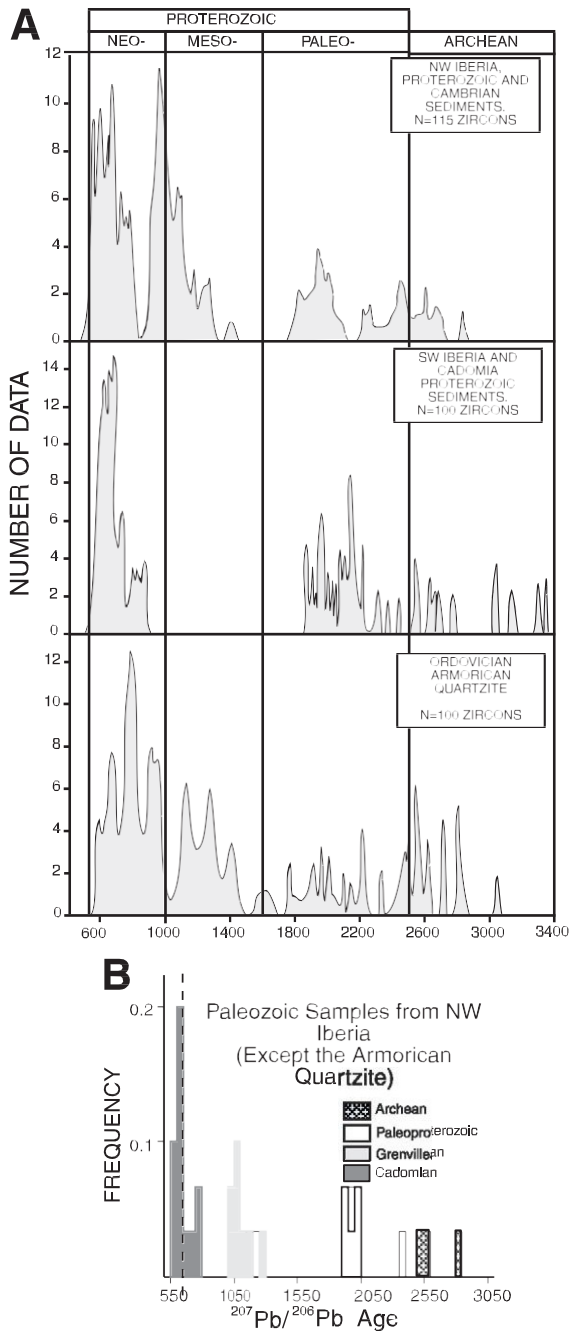


Fig. 3. (A) Histograms of U–Pb ages of detrital zircons from Proterozoic formations of NW Iberia, SW Iberia and Brittany, and U–Pb ages of detrital zircons from the Armorican Quartzite. (B) Histogram of U–Pb ages of detrital zircons from Paleozoic rocks of NW Iberia (excluding the Armorican Quartzite, modified after Fernández-Suárez et al., 2000).

important to note that the relative amount of Paleoproterozoic and Archean zircons is higher in the Armorican quartzite (ca. 25–30%) than in Neoproterozoic and Early Cambrian greywackes and arkoses from neighbouring areas of NW Iberia (10–15%; Fig. 3A) suggesting a higher sedimentary input from a cratonic source area.

## 5. Sm–Nd data

Sm–Nd isotopic features of sedimentary rocks are of major importance in provenance studies and, combined with detrital zircon U–Pb ages, constitute a powerful tool in continental reconstructions (e.g. Nance and Murphy, 1994; Murphy et al., 2000). Sm–Nd analyses carried out on some of the sedimentary

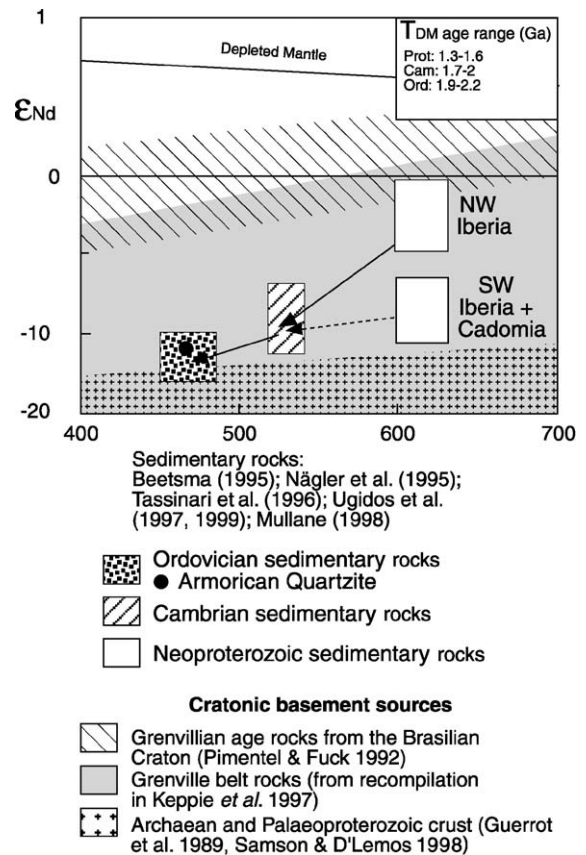


Fig. 4. Plot of initial  $\epsilon_{Nd}$  vs. stratigraphic age for Neoproterozoic and Early Paleozoic rocks from Iberia.

formations considered in this study (e.g. Nägler et al., 1995; Ugidos et al., 1997; Mullane, 1998) are in agreement with findings revealed by detrital zircon U–Pb ages. Fig. 4 illustrates this and presents initial  $\epsilon_{\text{Nd}}$  values vs. stratigraphic age for Neoproterozoic and Early Paleozoic formations of Iberia. The main feature of this diagram is the sharp contrast in initial  $\epsilon_{\text{Nd}}$  values shown by Neoproterozoic greywackes of NW Iberia (Central Iberian Zone) and SW Iberia (Ossa Morena zone), suggesting a different source area for both units, in agreement with their contrasting detrital zircon populations. Taken at face value, these data suggest that NW Iberian greywackes recycled a higher proportion of detritus of juvenile crustal material than did greywackes of SW Iberia. This could reflect that NW Iberia incorporated Late Mesoproterozoic (juvenile?) detritus and Early Cadomian–Avalonian juvenile arc material (e.g. Fernández-Suárez et al., 2000), whereas SW Iberia did not receive Late Mesoproterozoic detritus and received a smaller proportion of juvenile Cadomian–Avalonian arc material (as reflected by the scarcity of zircons in the age span ca. 640–760 Ma, which are dominant in NW Iberian Neoproterozoic greywackes). In the Early Paleozoic, this contrasting Sm–Nd isotopic feature is not observable, suggesting homogenization of the source and a significant dwindling of the contribution of juvenile material.

## 6. Discussion

The following sections are aimed at discussing the above data within the framework of major events that shaped the northern margin of Gondwana in the Neoproterozoic–Early Paleozoic (i.e. between ca. 600 and 480 Ma). The discussion is followed by a few thoughts concerning what the study of ancient orogens may offer to aid the interpretation and understanding of their modern counterparts.

### *6.1. First order constraints on the Neoproterozoic–Early Paleozoic evolution of the northern Gondwana margin*

The Cadomian–Avalonian terranes of western Europe and Atlantic North America were developed upon, and recycled material from, a pre-Neoproterozoic cratonic basement whose age and composition

varied along the northern Gondwana margin. This basement, with the exception of Paleoproterozoic Icarian gneisses in Brittany and the Channel Islands, is not exposed, and insights into its age and composition have to be gained indirectly through U–Pb and Sm–Nd isotopic studies of Neoproterozoic and Early Paleozoic rocks. These studies have allowed the distinction of two main signatures: terranes with West African craton affinity and terranes with South American (Amazonia) craton affinities. The main difference between these signatures being the presence of ca. 1600–900 Ma zircons in the latter, which is generally coupled with higher initial  $\epsilon_{\text{Nd}}$  values (e.g. Nance and Murphy, 1994).

The most significant feature of the age populations of detrital zircons in Neoproterozoic greywackes of SW Iberia and Brittany is the lack of Mesoproterozoic zircons (Fig. 3A), in contrast with similar-aged sedimentary rocks of NW Iberia (Figs. 2 and 3A) and other areas of the central European Variscides (NE Bohemia and Moravo–Silesian Zone; Friedl et al., 2000; Hegner and Kröner, 2000) and with those reported from West Avalonia (compilation in Nance and Murphy, 1994; Keppie et al., 1998).

The lack of Mesoproterozoic zircons in Neoproterozoic–Early Cambrian sedimentary formations from SW Iberia and Brittany (Fig. 3A) suggests that these fragments of the Cadomian–Avalonian orogen along with parts of the Bohemian Massif of central Europe (Gebauer et al., 1989; Friedl et al., 2000; Tichomirova et al., 2001) were deposited in a realm that had no access to exposures of basement rocks containing Mesoproterozoic zircons. The absence of high-grade Mesoproterozoic events in the West African craton may suggest that SW Iberia, Cadomia and most of the Bohemian Massif developed adjacent to this cratonic area, whereas NW Iberia (Fig. 3), NE Bohemia and Moravo–Silesia (all containing Mesoproterozoic zircons) were situated along the periphery of the South American craton (Fig. 5A). Sm–Nd isotope features also reflect this contrasting signature as sedimentary rocks with West African affinities show much lower initial  $\epsilon_{\text{Nd}}$  values than those with South American provenance. A good example is found in the Neoproterozoic greywackes from NW Iberia with initial  $q_{\text{Nd}}$  mostly comprised between 0 and –7.5 (Nägler et al., 1995; Ugidos et al., 1997) and greywackes of equivalent age in SW Iberia (Fig. 4) with initial  $\epsilon_{\text{Nd}}$  values between –9 and –12 (Mullane, 1998).



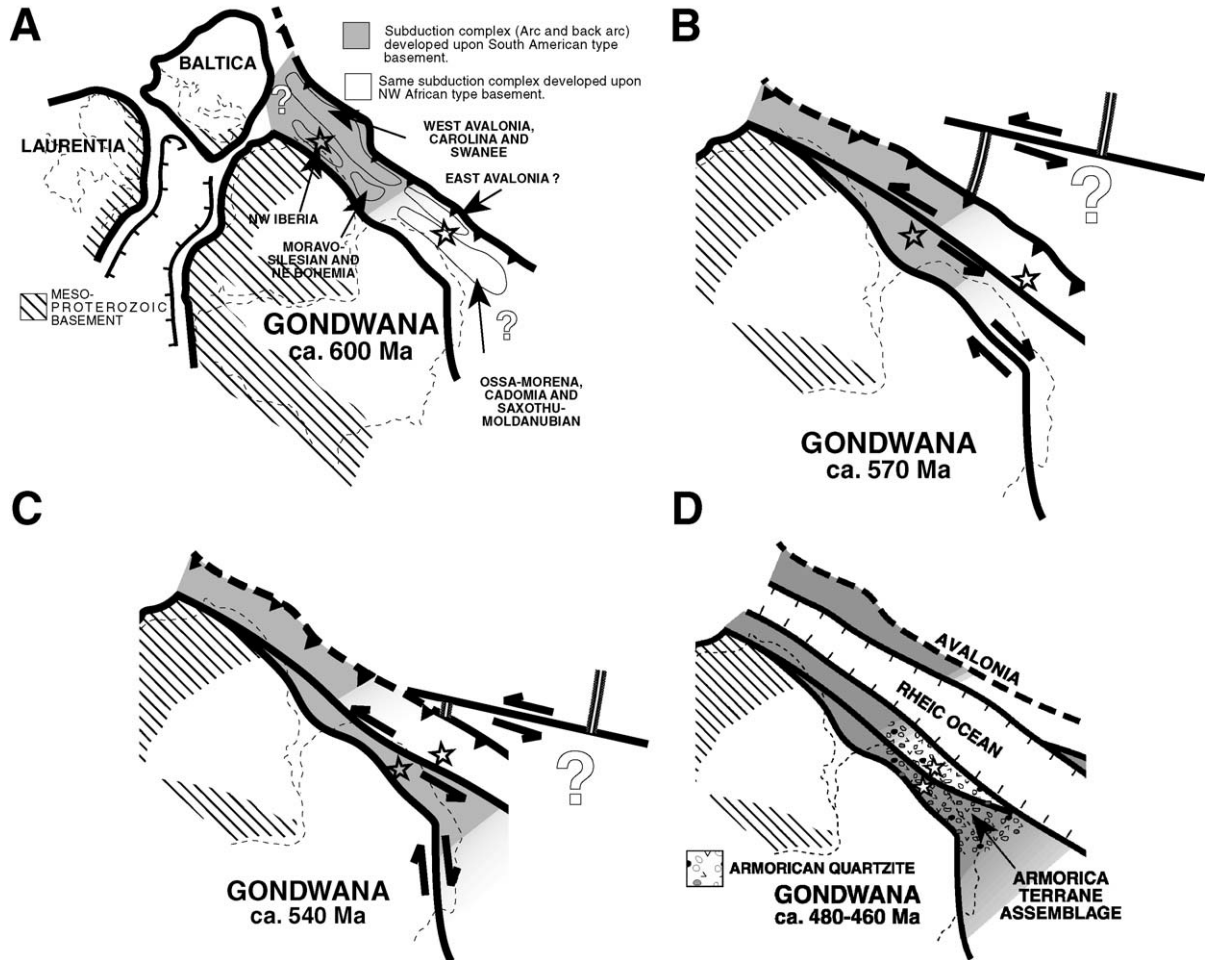


Fig. 5. Proposed Neoproterozoic terrane distribution (A – B) and Early Paleozoic tectonic evolution (C – D) along the northern Gondwanan margin (see text for details). Stars represent the hypothetical location of NW and SW Iberia/North Armorica. (A) modified after Nance and Murphy (1994) and Fernández-Suárez et al. (2000, 2002b).

All these terranes formed part of the active northern margin of Gondwana (Fig. 5A) that featured both a magmatic arc and a variety of back-arc basins (e.g. Murphy et al., 2000). It has been proposed that NW Iberia (Fernández-Suárez et al., 2000) and NE Bohemia (Hegner and Kröner, 2000) were part of the back-arc environment and were closer to the Gondwana margin than the more outboard West Avalonian terranes, which would represent the main magmatic edifice around the South American segment of Gondwana (Fig. 5A).

Subduction along the margin proceeded until either ridge-trench collision (Murphy et al., 2000) or a change in subduction regime (Fernández-Suárez et

al., 2000) caused progressive transition to a transform regime (Fig. 5B– D). The arrest of subduction is considered to have been diachronous along the margin (e.g. Murphy et al., 2000 and references therein). This is consistent with the contrasting evolution of SW Iberia and Brittany with respect to NW Iberia and the predominance of younger Cadomian detrital zircons (550–640 Ma) in rocks from Brittany and SW Iberia in relation to those from NW Iberia (Fig. 3A).

In the western European Variscan belt, terranes with differing (Amazonian vs. West African) basement signatures were juxtaposed prior to the deposition of the Armorican quartzite. This is the case for

NW and SW Iberia (Fig. 1) and the different domains that make up the Bohemian Massif, and implies that crustal units separated by hundreds or thousands of kilometers in the Neoproterozoic had been amalgamated before middle Ordovician times. This is supported by faunal, paleomagnetic and geologic evidence indicating that NW and SW Iberia, Cadomia and Bohemia had all been assembled adjacent to NW Africa to form the Armorica realm (or Armorican Terrane Assemblage) by that time (Tait et al., 1997 and references therein; Robardet, 2000; Franke, 2000; von Raumer et al., 2002).

If the Armorican quartzite was deposited upon an extensive NW African continental platform (e.g. Paris and Robardet, 1990; McKerrow and Scotese, 1990), then the abundance of Mesoproterozoic zircons in this formation (Fig. 3A) suggests that the source for these zircons had been transferred tectonically from a South American realm before its deposition. Alternative possibilities, such as recycling of zircons from West African basement cannot account for the presence of Mesoproterozoic zircons in the Armorican quartzite as there are no significant high-grade events of this age in the West African section of northern Gondwana.

We therefore propose that pre-Ordovician NW Iberia drifted along the Gondwana margin from a South American realm towards the African margin, as might have been the case for the rest of the South America-derived terranes that formed part of the Armorica Terrane Assemblage. Later erosion of these tectonically transported crustal fragments produced detritus containing Mesoproterozoic zircons that was incorporated into the Armorican quartzite.

We further suggest that this dispersal took place along major transform faults that roughly paralleled the Gondwana margin (Fig. 5B), and proceeded until the South America-derived terranes had docked against those that had occupied a peri-NW African location since the Neoproterozoic (Fig. 5C). This would explain why peri-Gondwanan terranes with differing basement signatures are juxtaposed in present-day exposures of the western European Variscan belt. This tectonic amalgamation gave birth to the Armorica Terrane Assemblage, which evolved as a single unit until its involvement in the Variscan–Appalachian collision and subsequent dispersal during the opening of the Atlantic ocean. Geological evidence for this docking may be recorded in the tectonic

contact between the NW and SW Iberian terranes (Eguiluz et al., 2000; Simancas et al., 2001), which we interpret as a reactivated Early Paleozoic terrane boundary between both units. Deposition of the Armorican quartzite at ca. 465 Ma (Bonjour et al., 1988) provides a minimum age for this docking.

Shortly following (and/or partially overlapping) this dispersal of terranes along the Gondwanan margin, a change in tectonic regime gave rise to extension on the margin and the birth of the Rheic Ocean. Rifting occurred between Armorica (an inboard terrane assemblage) and the more outboard Avalonia (Fig. 5D), which progressively separated from Gondwana until its docking to Laurentia–Baltica in the Silurian. The scarcity of zircons recording the early stages of arc construction (ca. 620–780 Ma) in the Cambrian arkose (Fig. 3B) may suggest that the outboard terranes (main magmatic arc) had begun to drift away from the margin during the Cambrian. Therefore, the opening of the Rheic Ocean might have taken place between ca. 520–530 Ma (age of the youngest detrital zircon in the Cambrian arkose) and 470–460 Ma (depositional age of the Armorican quartzite).

In conclusion, detrital zircon ages in Neoproterozoic and Early Paleozoic rocks from western Europe provide a record of the geography and tectonic evolution along the northern Gondwanan margin from ca. 600 to 480 Ma. Such studies provide major constraints on the histories of terrane dispersal and accretion, particularly in those cases where the geological record has been obscured by major orogenic events and plate reorganization. In addition, the approach used herein provides evidence in an ancient orogenic belt supporting observations in modern active margins (e.g. East Pacific margin; Monger, 1984) in which the processes that take place in the late stages of subduction, particularly the processes triggered by ridge subduction, are thought to cause a switch from orthogonal to lateral terrane accretion.

## 6.2. Ancient orogens: a window to modern ones?

Modern subduction environments are considered to fit into three broad types: Andean, Western Pacific and Cordilleran. There is, in our view, a certain penchant to interpret ancient active margins as a motionless picture of their modern counterparts and thus a tendency to

make them match the overall features of one of the above types. Our contention here is that studies of modern orogens are to some extent hindered by the fact that they have not reached the final status of their evolution, a circumstance absent in the study of ancient orogens. This contribution and many others devoted to the study of the Neoproterozoic–Early Paleozoic northern margin of Gondwana (see references) suggest that this margin was active during ca. 250–300 Ma from its early stages after the break-up of Rodinia (ca. 800 Ma ago) (although the position of West Africa and South America with respect to Rodinia is uncertain; Pisarevsky and Natapov, 2001) to the birth of the Rheic Ocean and drift of Avalonia in the Early Paleozoic. During this protracted period of activity, the margin evolved through a primitive stage where the proto-Avalonian–Cadomian terranes were generated (Murphy et al., 2000) (western Pacific stage), followed by a phase of main arc construction and accretion of terranes to the margin (Andean stage). This phase of subduction-arc construction was replaced by oblique subduction and terrane dispersal-accretion along the margin dominated by transform activity (Cordilleran stage). Finally, extension on the margin gave rise to the opening of the Rheic Ocean and the drift of outboard Avalonian terranes, this final stage being possibly a far-field response to global tectonic events at the end of the Neoproterozoic.

The above is an invitation to view modern arcs as representing a fleeting episode in their evolution towards the closing of a cycle rather than regarding them as stationary snapshots of one model or other. We could then bridge the gap backwards and apply our knowledge of ancient orogens to the study of their modern counterparts. In other words, one must consider that while observations in modern orogenic belts have much use in the interpretation of ancient ones, the flow of knowledge should go in both directions as the geological evolution of ancient orogens, when confidently understood in sufficient detail, can also afford valuable clues to direct studies of modern orogens.

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