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The importance of along-margin terrane transport in northern Gondwana: insights from detrital zircon parentage in Neoproterozoic rocks from Iberia and Brittany

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Abstract

Detrital zircons from late Neoproterozoic rocks of the peri-Gondwanan Cadomian belt of SW Iberia and north Armorican Domain of Brittany record Neoproterozoic (ca. 860–550 Ma), Palaeoproterozoic (ca. 2300–1800) and Archaean (ca 3300–2600 Ma) U–Pb ages. The absence of Mesoproterozoic zircons suggests that these terranes evolved in a peri-W African realm. This is in contrast to other western European terranes that preserve Mesoproterozoic zircons and are likely to have evolved in a peri-Amazonian realm. Such a contrast in detrital zircon populations, coupled with the presence of Mesoproterozoic zircons in the Ordovician Armorican quartzite, deposited in a peri-African platform, is interpreted to record along-margin terrane transport. The change in provenance suggests that subduction was replaced by transform faults that juxtaposed Amazonia-derived terranes against W Africa-derived terranes to form the Avalonia and Armorica microcontinents. Subsequent extension along the margin resulted in the birth of the Rheic Ocean and the outboard drift of Avalonia.

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1. Introduction

Orogenic processes in active continental margins involve major tectonic and thermal events leading to the creation, destruction and recycling of continental and oceanic crust, and the accretion, amalgamation and dispersal of crustal frag-

ments on different scales of space and time. Plate reorganisation at continental margins is often accompanied by substantial erosion and concomitant deposition of voluminous clastic sediments containing crucial information on the nature of the crustal elements in the provenance area.

The nature of plate processes and their importance in ancient orogens is commonly obscured by their involvement in subsequent tectonic events that destroy previous plate configurations. Overcoming this difficulty is particularly challenging in orogenic belts that have undergone more than one

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episode of dispersal and accretion. This is the case for the Neoproterozoic Avalonian–Cadomian orogenic belt [1] that was dismembered in Cambro–Ordovician times with the opening of the Rheic Ocean. Subsequently, it became involved in the late Palaeozoic Variscan–Alleghanian orogeny, and finally, was dispersed again to its present-day arrangement in western Europe and eastern North America after the opening of the Atlantic Ocean.

Fundamental to our understanding and interpretation of these issues is the extent to which transform continental margins influence major crustal growth episodes and orogenic events [2]. Present-day tectonic settings such as the continental margin of western North America show the importance of along-margin terrane transport [2]. This has far-reaching implications for palaeogeographic and plate reconstructions of ancient orogenic belts. In the case of early Palaeozoic and Precambrian orogenic belts, evidence for these processes is hard to find in the geological record. Even palaeomagnetic studies may fail to provide evidence for such processes as they may operate at scales of hundreds to a few thousands of km.

Nevertheless, valuable information concerning major tectonic events and former plate configurations, as well as constraints on the nature and age of basement source rocks, can be obtained by comparing U–Pb detrital zircon ages and/or Sm–Nd isotope signatures in coeval sedimentary rocks from separate terranes [3–10]. Here we use this approach to address first-order Neoproterozoic–early Palaeozoic tectonic events along the margin of north Gondwana taking key Cadomian–Avalonian terranes of the western European Variscan Belt as a case study.

1.1. *Geology and palaeogeographic background*

The late Palaeozoic Variscan collision belt of western Europe contains a mixture of crustal blocks with Neoproterozoic basement that originally formed part of an assemblage of terranes along the peri-Gondwanan Cadomian–Avalonian arc [1,10]. It is generally agreed that these terranes formed as a result of Neoproterozoic subduction

and arc construction along the northern Gondwanan margin and that they were subsequently dispersed by the opening of the early Palaeozoic Rheic Ocean as subduction was replaced by transform/extensional activity [11,12]. Subsequent Palaeozoic plate tectonic motions that culminated in Appalachian–Variscan collisional orogenesis further redistributed these terranes toward 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 our understanding of major Neoproterozoic and early Palaeozoic tectonic events.

Palaeomagnetic studies, in addition to stratigraphic and palaeontological data, have provided a wealth of information on Neoproterozoic–early Palaeozoic continental reconstructions [13–15]. Yet, tighter constraints are needed in order to obtain a more detailed picture of the geography and tectonic setting of the northern Gondwanan 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.

This study is focused on the Cadomian–Avalonian terranes presently exposed within the western European Variscan Belt (Fig. 1). Of particular interest are terranes such as Iberia and the Armorican Massif which feature major structural contacts between different tectonostratigraphic domains (Fig. 1). The origin and possible significance of these tectonic boundaries in the pre-Variscan evolution of these terranes are still poorly understood.

Restoration of the late Palaeozoic Iberian–Armorican Arc (Fig. 1) highlights the correlation of the Ossa Morena (SW Iberia) and the North Armorican (Brittany) domains based on shared Neoproterozoic–Lower Palaeozoic stratigraphy and abundance of igneous rocks formed during the time period ca 650–540 Ma [16]. Both domains record widespread Cadomian deformation and both are juxtaposed against the Central Iberian and South Armorican domains, respectively (Fig. 1). This juxtaposition occurs along major strike-slip faults with movement histories that

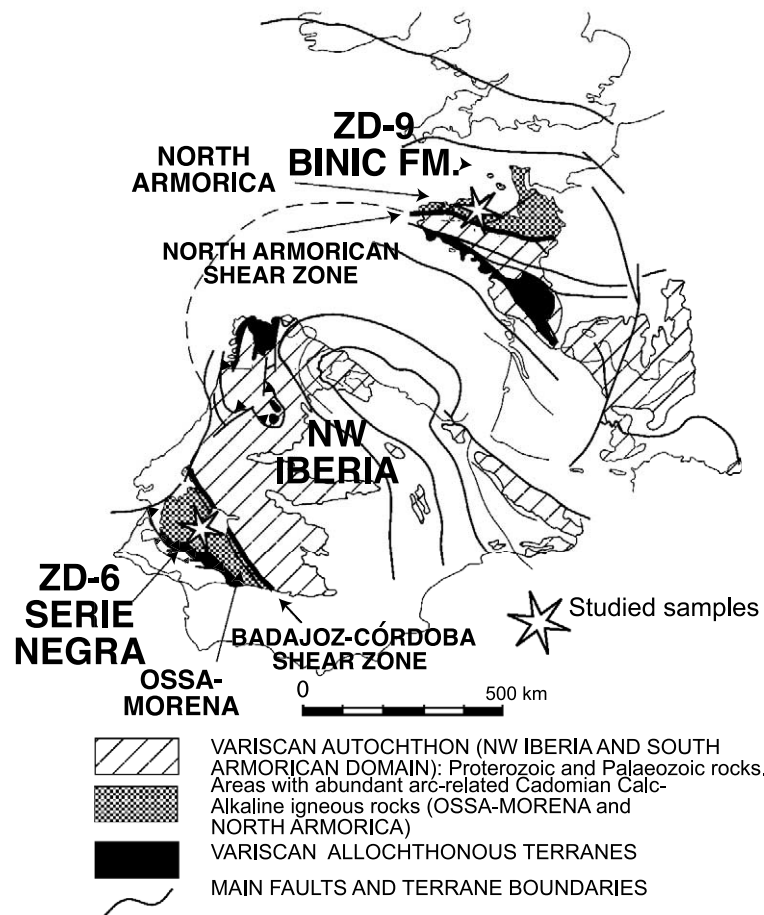


Fig. 1. Simplified geological map of Iberia and Cadomia showing location of samples ZD-6 (Ossa Morena, SW Spain) and ZD-9 (Brittany, NW France).

may predate the earliest recognised Variscan deformation [16]. To test this correlation, two samples were collected from low-grade greywackes in both domains (Fig. 1) in order to compare the age populations of their detrital zircons with those in the NW Iberian Domain [6,17]. Sample ZD-6 was collected in the Ossa Morena Zone (Province of Badajoz, SW Spain), in the upper part of the Serie Negra, in the core of the Olivenza–Monesterio antiform (Fig. 1). Sample ZD-9 was collected from Brioverian sediments of the Binic Formation, north of the town of Binic (Brittany, NW France). Both formations are considered to be of late Neoproterozoic depositional age [18].

Sample ZD-6 is a coarse-grained heterometric lithic greywacke containing clasts of quartz, igne-

ous rocks, micas and plagioclase in a matrix of fine-grained phyllosilicates with a coarse cleavage (pressure–solution seams). Sample ZD-9 is a medium-grained arkosic greywacke containing quartz, plagioclase and scarce igneous rock fragments in a matrix of recrystallised phyllosilicates that display a poorly developed cleavage.

2. U–Pb analytical methods

Mineral separation was performed at UCM (Madrid). The samples were crushed using a jaw crusher and pulverised with a disc mill. Heavy fraction enrichment on a Wilfley table, magnetic separation using a Frantz isodynamic separator

and density separation using di-iodomethane (CH_2I_2) were employed to separate the zircons. The zircons were hand-picked in alcohol under a binocular microscope and grains chosen to represent all types found in the samples with regard to size, length-to-breadth ratio, roundness, colour, and other salient morphological features. Zircons selected for LA-ICP-MS analyses were set in synthetic resin (SpeciFix-20TM) mounts, polished to approximately half their thickness, and cleaned in a warm HNO_3 ultrasonic bath. Prior to analysis, cathodoluminescence (CL) and backscattered electron (BSE) imaging was performed to ensure that analyses did not straddle different domains as indicated by the structure revealed by BSE and CL imaging.

U–Pb dating of individual zircon grains was performed using 213 nm laser ablation ICP-MS at The Natural History Museum (London). The 213 nm laser system had not been used previously to determine U–Pb isotopic ratios in zircons, and prior to its application to the unknown samples, the technique was validated and refined using zircon standards and igneous zircons previously dated by IDTIMS. The main advantages of the 213 nm laser over the more widely used 266 nm laser are a slower, more stable ablation rate and the production of consistently small, readily transported ablated particles. This results in increased signal stability and precision in the analyses. More detailed information on the features of ablation using a 213 nm laser is given in [19,20]. In view of the relatively large ablation pit size (typically 50–60 μm), only zircons considered to be homogeneous on the basis of their CL/BSE images, or large cores, were analysed.

The instrumentation used consisted of a frequency quintupled Nd:YAG laser ablation system, $\lambda=213$ nm (New Wave Research, USA) coupled to a quadrupole based ICP-MS (Plasma-Quad 3, Thermo Elemental, UK) with an enhanced sensitivity (S-option) interface. In this study, analyses were performed using argon as carrier gas. It is worth noting that a work in progress by the authors shows that the use of helium carrier gas greatly improves sample transport efficiency, which reduces elemental fractionation and results in more concordant analyses. It

has no effect on the precision of measured $^{207}\text{Pb}/^{206}\text{Pb}$ ratios.

To reduce the extent 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 per pulse). During ablation, the sample was moved relative to the beam along raster or line patterns, using a computer-controlled motorised stage.

Each analytical ‘run’ consisted of 20 analyses in the following order: four analyses of standard reference zircon 91500 [21], 12 analyses of the sample zircons and four analyses of standard 91500. After each analytical session, the raw data were downloaded to a PC for off-line processing. Raw count rates were integrated by averaging consecutive groups of 15 sweeps into single readings. The data were then processed using LAMTRACE, a data-reducing programme for laser ablation ICP-MS written by Simon E. Jackson, Macquarie University, Sydney, Australia. Net background-corrected count rates for each isotope were used for calculation of sample ages. Age and error calculation are as described in [6,8] with two exceptions: (i) we use the standard reference zircon 91500 instead of the 02123 in-house standard, and (ii) we use measured $^{207}\text{Pb}/^{235}\text{U}$ ratios in our calculations. The data reported have internal precision (2σ) based on counting statistics of each individual analysis.

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.

3. Results

A total of 120 analyses were performed on single grains (one analysis per grain) from both samples. Of these, 37 were rejected based on the criteria reported below. The results for selected analyses are given in Table 1 and presented as concordia diagrams and histograms in Figs. 2 and 3, respectively.

Although the analytical methodology (see above) ensures ablation of homogeneous zircon

Table 1
Laser ablation ICP-MS U–Pb analyses (concordant analyses in bold type)

| Samp./Anal.# | Isotopic ratios (2σ errors) | | | Age (Ma) | | | Best age estimate (Ma) |
|--------------|-------------------------------------|----------------------------------|-----------------------------------|----------------------------------|----------------------------------|-----------------------------------|------------------------|
| | $^{206}\text{Pb}/^{238}\text{U}$ | $^{207}\text{Pb}/^{235}\text{U}$ | $^{207}\text{Pb}/^{206}\text{Pb}$ | $^{206}\text{Pb}/^{238}\text{U}$ | $^{207}\text{Pb}/^{235}\text{U}$ | $^{207}\text{Pb}/^{206}\text{Pb}$ | |
| ZD-6 | | | | | | | |
| Z1 | 0.0794 ± 0.0004 | 0.6511 ± 0.0036 | 0.0594 ± 0.0002 | 493 ± 4 | 509 ± 4 | 582 ± 16 | 582 ± 16 |
| Z2 | 0.0836 ± 0.0006 | 0.6810 ± 0.0057 | 0.0591 ± 0.0003 | 518 ± 8 | 527 ± 7 | 568 ± 22 | 568 ± 22 |
| Z3 | 0.0838 ± 0.0007 | 0.6936 ± 0.0044 | 0.0600 ± 0.0003 | 519 ± 8 | 535 ± 5 | 602 ± 24 | 602 ± 24 |
| Z4 | 0.0838 ± 0.0005 | 0.7029 ± 0.0063 | 0.0608 ± 0.0004 | 519 ± 6 | 541 ± 7 | 632 ± 30 | 632 ± 30 |
| Z5 | 0.0856 ± 0.0005 | 0.7067 ± 0.0048 | 0.0599 ± 0.0003 | 529 ± 6 | 543 ± 6 | 598 ± 20 | 598 ± 20 |
| Z6 | 0.0872 ± 0.0005 | 0.7086 ± 0.0047 | 0.0589 ± 0.0003 | 540 ± 6 | 544 ± 6 | 564 ± 22 | 564 ± 22 |
| Z7 | 0.0875 ± 0.0005 | 0.7069 ± 0.0060 | 0.0586 ± 0.0005 | 541 ± 5 | 543 ± 7 | 550 ± 20 | 541 ± 3 |
| Z8 | 0.0884 ± 0.0007 | 0.7521 ± 0.0064 | 0.0617 ± 0.0003 | 546 ± 8 | 569 ± 7 | 662 ± 20 | 662 ± 20 |
| Z9 | 0.0889 ± 0.0008 | 0.7536 ± 0.0068 | 0.0615 ± 0.0002 | 549 ± 9 | 570 ± 8 | 654 ± 16 | 654 ± 16 |
| Z10 | 0.0898 ± 0.0007 | 0.7569 ± 0.0066 | 0.0611 ± 0.0004 | 554 ± 8 | 572 ± 8 | 642 ± 30 | 642 ± 30 |
| Z11 | 0.0898 ± 0.0004 | 0.7418 ± 0.0034 | 0.0599 ± 0.0003 | 554 ± 5 | 563 ± 4 | 600 ± 20 | 600 ± 20 |
| Z12 | 0.0926 ± 0.0007 | 0.7542 ± 0.0067 | 0.0591 ± 0.0004 | 571 ± 9 | 571 ± 8 | 568 ± 28 | 571 ± 4 |
| Z13 | 0.0928 ± 0.0008 | 0.7541 ± 0.0075 | 0.0589 ± 0.0003 | 572 ± 9 | 571 ± 9 | 562 ± 22 | 571 ± 4 |
| Z14 | 0.0959 ± 0.0010 | 0.7888 ± 0.0077 | 0.0596 ± 0.0006 | 591 ± 12 | 591 ± 9 | 588 ± 42 | 591 ± 5 |
| Z15 | 0.0971 ± 0.0007 | 0.7995 ± 0.0065 | 0.0597 ± 0.0003 | 597 ± 8 | 597 ± 7 | 592 ± 20 | 597 ± 4 |
| Z16 | 0.0990 ± 0.0012 | 0.8188 ± 0.0094 | 0.0600 ± 0.0004 | 609 ± 14 | 607 ± 11 | 600 ± 32 | 607 ± 5 |
| Z17 | 0.1026 ± 0.0006 | 0.8935 ± 0.0072 | 0.0632 ± 0.0003 | 629 ± 7 | 648 ± 8 | 714 ± 22 | 714 ± 22 |
| Z18 | 0.1114 ± 0.0013 | 0.9966 ± 0.0175 | 0.0649 ± 0.0010 | 681 ± 15 | 702 ± 18 | 768 ± 64 | 768 ± 64 |
| Z19 | 0.1185 ± 0.0007 | 1.1105 ± 0.0077 | 0.0680 ± 0.0002 | 722 ± 8 | 758 ± 7 | 866 ± 12 | 866 ± 12 |
| Z20 | 0.1233 ± 0.0007 | 1.1522 ± 0.0075 | 0.0678 ± 0.0003 | 749 ± 8 | 778 ± 7 | 860 ± 18 | 860 ± 18 |
| Z21 | 0.2772 ± 0.0033 | 4.3681 ± 0.0590 | 0.1143 ± 0.0005 | 1577 ± 34 | 1706 ± 22 | 1868 ± 14 | 1868 ± 14 |
| Z22 | 0.2824 ± 0.0020 | 4.6787 ± 0.0426 | 0.1201 ± 0.0005 | 1603 ± 20 | 1763 ± 15 | 1958 ± 16 | 1958 ± 16 |
| Z23 | 0.2909 ± 0.0025 | 4.6014 ± 0.0428 | 0.1147 ± 0.0004 | 1646 ± 25 | 1750 ± 15 | 1874 ± 12 | 1874 ± 12 |
| Z24 | 0.2912 ± 0.0019 | 4.6276 ± 0.0305 | 0.1152 ± 0.0004 | 1647 ± 19 | 1754 ± 11 | 1882 ± 12 | 1882 ± 12 |
| Z25 | 0.3005 ± 0.0028 | 5.3919 ± 0.1202 | 0.1301 ± 0.0026 | 1694 ± 28 | 1884 ± 38 | 2098 ± 68 | 2098 ± 68 |
| Z26 | 0.3025 ± 0.0018 | 5.0316 ± 0.0327 | 0.1206 ± 0.0007 | 1704 ± 17 | 1825 ± 11 | 1964 ± 22 | 1964 ± 22 |
| Z27 | 0.3068 ± 0.0018 | 5.3052 ± 0.0355 | 0.1254 ± 0.0003 | 1725 ± 18 | 1870 ± 11 | 2034 ± 8 | 2034 ± 8 |
| Z28 | 0.3104 ± 0.0026 | 4.9953 ± 0.0495 | 0.1167 ± 0.0007 | 1743 ± 25 | 1819 ± 17 | 1906 ± 22 | 1906 ± 22 |
| Z29 | 0.3159 ± 0.0027 | 5.3759 ± 0.0430 | 0.1234 ± 0.0003 | 1770 ± 27 | 1881 ± 14 | 2004 ± 10 | 2004 ± 10 |
| Z30 | 0.3180 ± 0.0022 | 5.8373 ± 0.0946 | 0.1331 ± 0.0018 | 1780 ± 21 | 1952 ± 28 | 2138 ± 48 | 2138 ± 48 |
| Z31 | 0.3342 ± 0.0021 | 5.2517 ± 0.0373 | 0.1140 ± 0.0003 | 1859 ± 21 | 1861 ± 12 | 1862 ± 10 | 1862 ± 6 |
| Z32 | 0.3485 ± 0.0070 | 5.5957 ± 0.1158 | 0.1165 ± 0.0003 | 1927 ± 67 | 1915 ± 36 | 1902 ± 10 | 1902 ± 8 |
| Z33 | 0.3487 ± 0.0040 | 5.9122 ± 0.0656 | 0.1229 ± 0.0005 | 1929 ± 38 | 1963 ± 19 | 1998 ± 14 | 1998 ± 14 |
| Z34 | 0.3642 ± 0.0034 | 6.5804 ± 0.0691 | 0.1310 ± 0.0006 | 2002 ± 32 | 2057 ± 19 | 2110 ± 16 | 2110 ± 16 |
| Z35 | 0.3829 ± 0.0021 | 7.0189 ± 0.0316 | 0.1329 ± 0.0007 | 2090 ± 20 | 2114 ± 8 | 2136 ± 16 | 2136 ± 16 |
| Z36 | 0.4043 ± 0.0033 | 8.4528 ± 0.0718 | 0.1516 ± 0.0004 | 2189 ± 30 | 2281 ± 15 | 2364 ± 10 | 2364 ± 10 |
| Z37 | 0.4513 ± 0.0039 | 11.0716 ± 0.1163 | 0.1779 ± 0.0006 | 2401 ± 35 | 2529 ± 20 | 2632 ± 12 | 2632 ± 12 |
| Z38 | 0.4582 ± 0.0049 | 11.5137 ± 0.1267 | 0.1822 ± 0.0005 | 2431 ± 43 | 2566 ± 21 | 2672 ± 8 | 2672 ± 8 |
| Z39 | 0.5168 ± 0.0041 | 16.2267 ± 0.1314 | 0.2277 ± 0.0004 | 2685 ± 35 | 2890 ± 15 | 3034 ± 6 | 3034 ± 6 |
| Z40 | 0.5369 ± 0.0029 | 16.9163 ± 0.0998 | 0.2285 ± 0.0005 | 2771 ± 24 | 2930 ± 11 | 3040 ± 6 | 3040 ± 6 |
| Z41 | 0.5726 ± 0.0043 | 21.3067 ± 0.1385 | 0.2698 ± 0.0013 | 2919 ± 35 | 3153 ± 13 | 3304 ± 16 | 3304 ± 16 |
| Z42 | 0.6207 ± 0.0036 | 22.9077 ± 0.1489 | 0.2676 ± 0.0014 | 3113 ± 29 | 3223 ± 13 | 3292 ± 16 | 3292 ± 16 |
| ZD-9 | | | | | | | |
| Z43 | 0.0904 ± 0.0007 | 0.7320 ± 0.0053 | 0.0587 ± 0.0002 | 558 ± 8 | 558 ± 6 | 556 ± 12 | 558 ± 4 |
| Z44 | 0.0894 ± 0.0005 | 0.7324 ± 0.0050 | 0.0594 ± 0.0003 | 552 ± 6 | 558 ± 6 | 580 ± 22 | 580 ± 22 |
| Z45 | 0.0874 ± 0.0007 | 0.7221 ± 0.0061 | 0.0599 ± 0.0004 | 540 ± 8 | 552 ± 7 | 598 ± 30 | 598 ± 30 |
| Z46 | 0.0898 ± 0.0006 | 0.7466 ± 0.0051 | 0.0603 ± 0.0002 | 555 ± 7 | 566 ± 6 | 612 ± 12 | 612 ± 12 |
| Z47 | 0.0886 ± 0.0005 | 0.7389 ± 0.0044 | 0.0605 ± 0.0002 | 547 ± 5 | 562 ± 5 | 620 ± 18 | 620 ± 18 |
| Z48 | 0.0878 ± 0.0008 | 0.7320 ± 0.0072 | 0.0605 ± 0.0003 | 543 ± 9 | 558 ± 8 | 620 ± 18 | 620 ± 18 |
| Z49 | 0.0904 ± 0.0008 | 0.7573 ± 0.0064 | 0.0607 ± 0.0002 | 558 ± 9 | 572 ± 7 | 630 ± 18 | 630 ± 18 |
| Z50 | 0.0863 ± 0.0006 | 0.7234 ± 0.0072 | 0.0608 ± 0.0004 | 533 ± 7 | 553 ± 8 | 632 ± 26 | 632 ± 26 |

Table 1 (Continued).

| Samp./Anal.# | Isotopic ratios (2 σ errors) | | | Age (Ma) | | | Best age estimate (Ma) |
|--------------|-------------------------------------|----------------------------------|-----------------------------------|----------------------------------|----------------------------------|-----------------------------------|------------------------|
| | $^{206}\text{Pb}/^{238}\text{U}$ | $^{207}\text{Pb}/^{235}\text{U}$ | $^{207}\text{Pb}/^{206}\text{Pb}$ | $^{206}\text{Pb}/^{238}\text{U}$ | $^{207}\text{Pb}/^{235}\text{U}$ | $^{207}\text{Pb}/^{206}\text{Pb}$ | |
| Z51 | 0.0934 ± 0.0005 | 0.7849 ± 0.0050 | 0.0610 ± 0.0003 | 576 ± 5 | 588 ± 6 | 636 ± 24 | 636 ± 24 |
| Z52 | 0.0974 ± 0.0009 | 0.8219 ± 0.0081 | 0.0612 ± 0.0001 | 599 ± 11 | 609 ± 9 | 646 ± 10 | 646 ± 10 |
| Z53 | 0.0867 ± 0.0008 | 0.7315 ± 0.0068 | 0.0612 ± 0.0003 | 536 ± 9 | 557 ± 8 | 646 ± 18 | 646 ± 18 |
| Z54 | 0.0915 ± 0.0013 | 0.7754 ± 0.0118 | 0.0614 ± 0.0004 | 565 ± 15 | 583 ± 13 | 654 ± 32 | 654 ± 32 |
| Z55 | 0.0898 ± 0.0009 | 0.7633 ± 0.0082 | 0.0616 ± 0.0006 | 554 ± 11 | 576 ± 10 | 660 ± 40 | 660 ± 40 |
| Z56 | 0.0917 ± 0.0009 | 0.7816 ± 0.0098 | 0.0618 ± 0.0003 | 566 ± 11 | 586 ± 11 | 666 ± 18 | 666 ± 18 |
| Z57 | 0.0895 ± 0.0006 | 0.7627 ± 0.0044 | 0.0618 ± 0.0002 | 552 ± 7 | 576 ± 5 | 666 ± 16 | 666 ± 16 |
| Z58 | 0.0924 ± 0.0008 | 0.7885 ± 0.0078 | 0.0619 ± 0.0004 | 569 ± 9 | 590 ± 9 | 670 ± 24 | 670 ± 24 |
| Z59 | 0.1183 ± 0.0012 | 1.0132 ± 0.0105 | 0.0621 ± 0.0003 | 721 ± 14 | 711 ± 11 | 676 ± 22 | 676 ± 22 |
| Z60 | 0.0980 ± 0.0008 | 0.8409 ± 0.0071 | 0.0622 ± 0.0003 | 603 ± 9 | 620 ± 8 | 682 ± 22 | 682 ± 22 |
| Z61 | 0.0897 ± 0.0007 | 0.7712 ± 0.0079 | 0.0624 ± 0.0006 | 554 ± 9 | 580 ± 9 | 686 ± 44 | 686 ± 44 |
| Z62 | 0.1012 ± 0.0008 | 0.8825 ± 0.0072 | 0.0632 ± 0.0004 | 622 ± 10 | 642 ± 8 | 714 ± 28 | 714 ± 28 |
| Z63 | 0.1031 ± 0.0008 | 0.9042 ± 0.0093 | 0.0636 ± 0.0004 | 632 ± 9 | 654 ± 10 | 728 ± 24 | 728 ± 24 |
| Z64 | 0.1092 ± 0.0005 | 0.9851 ± 0.0126 | 0.0654 ± 0.0006 | 668 ± 6 | 696 ± 13 | 786 ± 40 | 786 ± 40 |
| Z65 | 0.1115 ± 0.0007 | 1.0195 ± 0.0076 | 0.0663 ± 0.0003 | 681 ± 8 | 714 ± 8 | 814 ± 22 | 814 ± 22 |
| Z66 | 0.1299 ± 0.0008 | 1.1972 ± 0.0104 | 0.0669 ± 0.0006 | 787 ± 9 | 799 ± 10 | 832 ± 38 | 832 ± 38 |
| Z67 | 0.1397 ± 0.0010 | 1.2926 ± 0.0103 | 0.0671 ± 0.0005 | 843 ± 12 | 842 ± 9 | 840 ± 32 | 843 ± 5 |
| Z68 | 0.2842 ± 0.0027 | 4.7056 ± 0.0391 | 0.1200 ± 0.0004 | 1613 ± 28 | 1768 ± 14 | 1956 ± 12 | 1956 ± 12 |
| Z69 | 0.3123 ± 0.0013 | 5.2156 ± 0.0235 | 0.1211 ± 0.0004 | 1752 ± 13 | 1855 ± 8 | 1972 ± 10 | 1972 ± 10 |
| Z70 | 0.3391 ± 0.0013 | 5.8282 ± 0.0303 | 0.1246 ± 0.0003 | 1882 ± 12 | 1951 ± 9 | 2022 ± 10 | 2022 ± 10 |
| Z71 | 0.2954 ± 0.0020 | 5.1531 ± 0.0392 | 0.1265 ± 0.0002 | 1669 ± 20 | 1845 ± 13 | 2048 ± 6 | 2048 ± 6 |
| Z72 | 0.2949 ± 0.0021 | 5.2888 ± 0.0439 | 0.1300 ± 0.0005 | 1666 ± 21 | 1867 ± 14 | 2098 ± 14 | 2098 ± 14 |
| Z73 | 0.3464 ± 0.0055 | 6.5536 ± 0.1167 | 0.1372 ± 0.0024 | 1917 ± 53 | 2053 ± 31 | 2190 ± 62 | 2190 ± 62 |
| Z74 | 0.3710 ± 0.0029 | 7.1334 ± 0.0578 | 0.1395 ± 0.0002 | 2034 ± 27 | 2128 ± 14 | 2220 ± 6 | 2220 ± 6 |
| Z75 | 0.4170 ± 0.0025 | 8.3922 ± 0.0814 | 0.1460 ± 0.0010 | 2247 ± 23 | 2274 ± 18 | 2298 ± 24 | 2298 ± 24 |
| Z76 | 0.3812 ± 0.0032 | 7.7401 ± 0.0418 | 0.1473 ± 0.0007 | 2082 ± 30 | 2201 ± 10 | 2314 ± 18 | 2314 ± 18 |
| Z77 | 0.5333 ± 0.0077 | 12.4708 ± 0.1796 | 0.1696 ± 0.0007 | 2755 ± 64 | 2641 ± 27 | 2552 ± 14 | 2552 ± 14 |
| Z78 | 0.4551 ± 0.0090 | 11.0839 ± 0.2250 | 0.1766 ± 0.0011 | 2418 ± 80 | 2530 ± 38 | 2620 ± 22 | 2620 ± 22 |
| Z79 | 0.4536 ± 0.0020 | 11.2347 ± 0.0528 | 0.1796 ± 0.0005 | 2411 ± 18 | 2543 ± 9 | 2648 ± 8 | 2648 ± 8 |
| Z80 | 0.5299 ± 0.0039 | 13.4333 ± 0.0994 | 0.1839 ± 0.0009 | 2741 ± 33 | 2711 ± 14 | 2686 ± 16 | 2686 ± 16 |
| Z81 | 0.5418 ± 0.0046 | 14.5080 ± 0.1190 | 0.1942 ± 0.0004 | 2791 ± 38 | 2784 ± 16 | 2776 ± 6 | 2779 ± 4 |
| Z82 | 0.5936 ± 0.0045 | 19.7721 ± 0.1186 | 0.2416 ± 0.0012 | 3004 ± 36 | 3080 ± 12 | 3130 ± 16 | 3130 ± 16 |
| Z83 | 0.7534 ± 0.0052 | 28.8080 ± 0.1815 | 0.2773 ± 0.0006 | 3620 ± 38 | 3447 ± 12 | 3346 ± 6 | 3346 ± 6 |

domains, analyses with > 20% discordance (calculated from $^{206}\text{Pb}/^{238}\text{U}/[^{207}\text{Pb}/^{206}\text{Pb}]$ age) were rejected. The time-resolved analysis software reports signal intensity (counts per second) for every mass sweep performed by the mass spectrometer. This protocol, allowing acquisition of signals as a function of time (a proxy for ablation depth profile), permits the recognition of isotopic heterogeneity and therefore the detection of inclusions, high common Pb associated to fractures or areas of radiation damage, and inherited Pb components (older cores). All analyses whose time-resolved signals showed any suspect features were excluded from the data set irrespective of their discordance. Using this approach, it can be as-

sumed confidently that discordance in the selected analyses is not due to mixing of differently aged zircon domains but by lead loss and perhaps minor U–Pb laser-induced elemental fractionation, undetectable in the time-resolved signals. Such fractionation does not affect the measured $^{207}\text{Pb}/^{206}\text{Pb}$ ratios.

The ages reported in this paper are not common Pb-corrected as ^{204}Pb measurements are rendered useless by the isobaric interference from Hg, a contaminant present in the argon supply gas. ^{204}Hg interferes on ^{204}Pb and the ^{202}Hg peak is commonly too small to allow a reliable overlap correction of acceptable precision [22].

Since the LA-(quadrupole)-ICP-MS technique

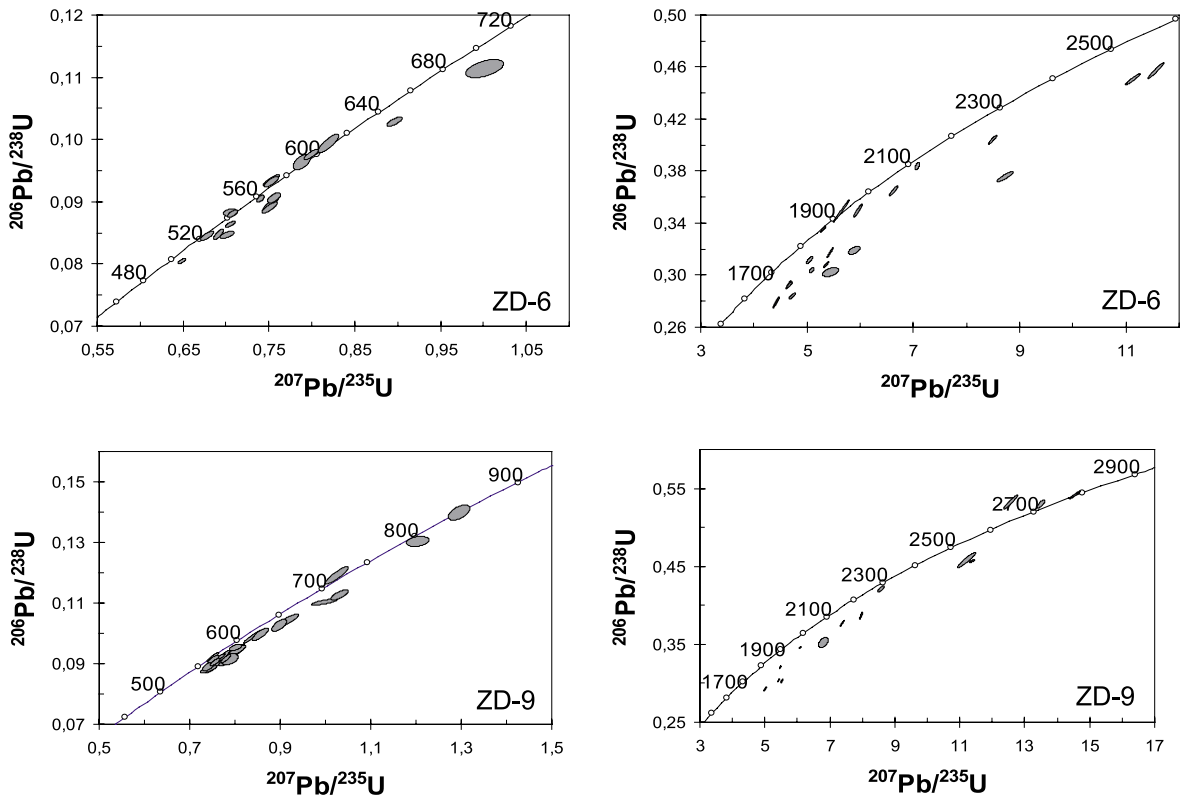


Fig. 2. Concordia plots of U–Pb analytical data from samples ZD-6 and ZD-9. Ellipses represent 2σ uncertainties.

using a natural zircon standard does not allow reliable determination of ^{204}Pb , an alternative option would be to use the ^{208}Pb correction [23]. However, this method can only be applied if the ThO^+/UO^+ ratio [23] can be simultaneously determined with acceptable precision or assuming concordance of $^{206}\text{Pb}/^{238}\text{U}$ and $^{208}\text{Pb}/^{232}\text{Th}$ ages. As the assumption cannot be justified a priori, it is felt that this correction method should not be applied to analyses such as those reported in this study (cf. [24]). The $^{208}\text{Pb}/^{232}\text{Th}$ ratio (not reported in Table 1) is very sensitive to common Pb contamination, resulting in $^{208}\text{Pb}/^{232}\text{Th}$ ages that are significantly older than the $^{206}\text{Pb}/^{238}\text{U}$ ages. This feature offers a qualitative criterion to detect zircons with high common Pb content in LA-ICP-MS analyses [9]. In this study we found this feature only in analyses where $^{206}\text{Pb}/^{238}\text{U}$ – $^{207}\text{Pb}/^{206}\text{Pb}$ discordance is $>20\%$ and therefore would have been rejected irrespective of this fact.

Furthermore, it should be emphasised that most zircons do not contain significant amounts of common Pb and that for most Proterozoic zircons, common Pb corrections would be within the analytical uncertainty of the analyses reported here. For example, a SHRIMP study of zircons from a Neoproterozoic sedimentary formation of SW Iberia (stratigraphically equivalent to that in which sample ZD-6 was collected) [25] shows that the percentage of common ^{206}Pb relative to total measured ^{206}Pb is less than 0.5% in 80% of the analyses and $>1\%$ in only 10% of the analyses reported. In [25] all analyses with significant amounts of common Pb are $>25\%$ discordant (usually with reverse discordance) and have high Th contents. Finally, it should be noted that the age clusters derived from common Pb-corrected U–Pb data in [25] coincide with those reported in this study for a formation of stratigraphic equivalence (see below).

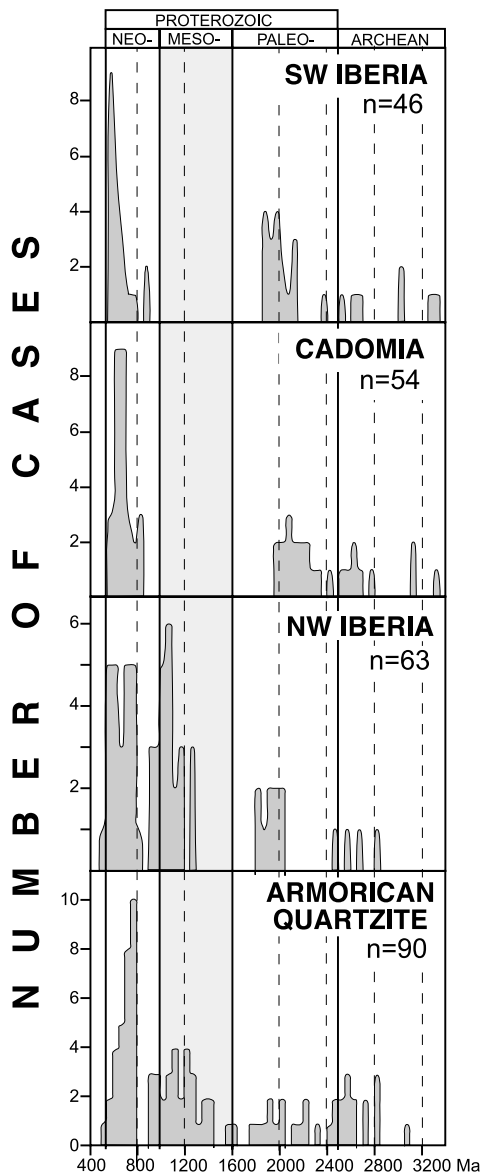


Fig. 3. Histograms of U–Pb ages for analysed samples from Ossa Morena Zone, SW Iberia (ZD-6) and north Armorican Domain (ZD-9) compared to previously analysed samples from NW Iberia [6] and the Armorican quartzite [17].

Considering the above arguments, we are confident that, in the carefully screened analyses reported here, only a very small percentage of the discordant $^{207}\text{Pb}/^{206}\text{Pb}$ ages might be slightly older than the ‘correct age’. As the purpose of this study is to define age clusters in detrital zircon

populations representing major crust formation events, the possible uncertainty associated with some of the discordant ages is insignificant to the interpretation of the data and has no influence on the main conclusions reached in this study. As a routine further precaution, those discordant analyses whose $^{207}\text{Pb}/^{206}\text{Pb}$ ages have no concordant counterparts are not used to derive geological conclusions, i.e. we only consider conclusions that would not be affected if solely $^{207}\text{Pb}/^{206}\text{Pb}$ or $^{206}\text{Pb}/^{238}\text{U}$ ages were used. As is the case in this study, the reliability of detrital zircon LA-ICP-MS U–Pb data is strengthened by the reproducibility of age patterns in samples that are considered equivalent on the basis of independent geological criteria [6].

In the data presented here, a few data points plot slightly above concordia (Fig. 2; i.e. the $^{207}\text{Pb}/^{206}\text{Pb}$ age is younger than the $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ ages). This phenomenon of reverse discordance is frequently observed in both SIMS and LA-ICP-MS U–Pb analyses and although not well understood, it is generally attributed to redistribution of radiogenic lead on a micron scale [24,26] or associated with poor correction for U–Pb fractionation (fractionation in the sample deviates significantly from that in the standard) [8]. In either case, the $^{207}\text{Pb}/^{206}\text{Pb}$ ratio gives the best age estimate as the effect is comparable to moving the point up or down a discordia line going through 0 Ma (assuming that no other sources for discordance play a significant role).

The ages reported in the histograms of Fig. 3 and labelled ‘best age estimate’ in Table 1 are obtained as follows: For concordant analyses (ages whose corresponding isotope ratios have a 2σ error ellipse that, to a greater or lesser extent, overlaps the concordia curve) we use concordia ages and errors as defined by Ludwig [27]. For discordant analyses we use the $^{207}\text{Pb}/^{206}\text{Pb}$ ages and 2σ errors.

If we assume that discordant analyses can be attributed to Pb loss and since the effect of possible episodic lead loss at intermediate ages cannot be evaluated, individual $^{207}\text{Pb}/^{206}\text{Pb}$ dates represent minimum ages of growth for a given zircon. Again, as in these types of studies the clustering of grain ages is the crucial indicator of zircon-

forming high-grade events and since the effect of Pb loss is to disperse zircon ages [4] (i.e. broadening the spectra), the presence of well-defined clusters must be considered geologically significant.

The U–Pb ages in sample ZD-6 (Ossa Morena Zone, SW Iberia) show a predominance of zircons in the range 540–860 Ma (Figs. 2A and 3). The youngest zircon has a $^{206}\text{Pb}/^{238}\text{U}$ age of 541 ± 6 Ma (concordia age of 541.4 ± 2.4 Ma) and a less precise $^{207}\text{Pb}/^{206}\text{Pb}$ age of 550 ± 20 Ma (2σ). Concordant zircon ages in this cluster spread between ca 541 and 608 Ma, whereas discordant ages ($< 20\%$ discordance) spread from ca 560 to 866 Ma. Of these discordant analyses (Table 1) seven fall within the range of concordant analyses and eight have older $^{207}\text{Pb}/^{206}\text{Pb}$ ages from 632 to 866 Ma. Although no concordant zircons in this older range were dated in this study, Ordóñez Casado [25] reported common Pb-corrected SHRIMP ages for zircons in a stratigraphically equivalent formation spanning 541 ± 19 to 847 ± 26 Ma.

The second zircon cluster is of Palaeoproterozoic age (ca 1860–2300 Ma; Table 1). The youngest zircon in this group is sub-concordant (2.2% discordance) with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1860 ± 10 Ma. 15 zircons have ages ranging from ca 1860 to 2130 Ma (Table 1, Figs. 2B and 3). One zircon yielded an older discordant $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2364 ± 10 Ma. Five zircons yielded $^{207}\text{Pb}/^{206}\text{Pb}$ Archaean ages in the range ca 2600–3300 Ma (Fig. 3) with discordance $< 12\%$.

Zircon U–Pb ages in sample ZD-9 (Brittany) show a pattern similar to that of ZD-6 (Table 1, Figs. 2C,D and 3). The youngest age cluster is of Neoproterozoic age, ca 550–840 Ma. The youngest zircon in this group is concordant (-0.4% discordance) with a $^{206}\text{Pb}/^{238}\text{U}$ age of 558 ± 8 Ma, within analytical error of the $^{207}\text{Pb}/^{206}\text{Pb}$ age of the youngest zircon in sample ZD-6. The oldest zircon in this cluster has a concordia age of 843 ± 5 with 85% probability of concordance, very similar to the $^{207}\text{Pb}/^{206}\text{Pb}$ age of the oldest zircon of this group in sample ZD-6 (866 ± 12 Ma).

The second most abundant group consists of Palaeoproterozoic zircons with ages ranging from ca 1950 to 2300 Ma (Table 1, Figs. 2D

and 3). As in SW Iberia, a few zircons yielded Archaean ages (2550–3350 Ma). Each of these age groups is consistent with U–Pb IDTIMS single-grain data from detrital zircons in the stratigraphically equivalent Jersey Shale Formation [28].

4. Discussion

4.1. Significance of U–Pb ages

The ages of the youngest detrital zircons in both formations are equivalent within analytical uncertainty, suggesting a coeval maximum late Neoproterozoic depositional age. These data are in agreement with other studies [18] and support their stratigraphic equivalence. This is an important constraint when interpreting detrital zircon ages, particularly at active continental margins like the Cadomian–Avalonian orogen, where palaeogeographic settings and source area exposures can vary significantly in short time intervals.

The similar U–Pb age populations of the detrital zircons in late Neoproterozoic greywackes from SW Iberia and the North Armorian Domain both indicate provenance from a crustal source formed shortly before deposition and older cratonic sources. Those Neoproterozoic ages in the range ca 540–560 to 620–650 Ma match the span of the main episodes of magmatic activity related to subduction and arc construction along the northern Gondwanan margin (compilation in [29]). Zircons with Neoproterozoic ages older than ca 650 Ma could have been generated either during the early arc phase [6,11] or they could represent detritus from rocks generated in Neoproterozoic interior orogens related to the assembly of west Gondwana [30,31].

Palaeoproterozoic zircon ages match the spread of loosely constrained orogenic events recorded in the west African craton [32] and Amazonia [33,34]. The presence of these zircons in the studied rocks is in agreement with the existence of a Palaeoproterozoic (ca 1.8–2.1 Ga) basement in western Europe (Icartian basement) [35,36]. Archaean zircons dated in this study match the age spread of orogenic events recorded in cratonic

areas of west Africa [37–39] and Amazonia [34,40]. Therefore, the U–Pb age clusters found in the studied rocks indicate a clear Gondwanan signature for these late Neoproterozoic sedimentary formations.

4.2. Geodynamic implications

The Cadomian–Avalonian terranes of western Europe and Atlantic North America were developed upon, and recycled material from, a cratonic basement whose age and composition varied along the northern Gondwanan margin [1]. With the exception of the ca 2 Ga Icartian gneisses in Brittany and the Channel Islands [35,36], this basement is not exposed and insights into its age and composition must be gained indirectly through U–Pb and Sm–Nd isotopic studies of Neoproterozoic and early Palaeozoic rocks. Such studies have identified two main basement signatures; one with affinities to west Africa and the other with affinities to Amazonia. Characteristic of the latter is the presence of Mesoproterozoic zircons (1600–1000 Ma), coupled generally with higher initial ϵ_{Nd} values (e.g. [1]).

The most significant feature of the detrital zircon ages from SW Iberia and Brittany is therefore the absence of Mesoproterozoic zircons. This contrasts with Neoproterozoic and early Palaeozoic sedimentary rocks in NW Iberia (Fig. 3) and other areas of the Central European Variscides (West Sudetes and Erzgebirge [41] and Moravo–Silesian Zone [42]), and with those reported from West Avalonia [1,5,29].

The lack of Mesoproterozoic (Grenvillian, Sunas–Rondonian) detrital zircons suggests that the SW Iberian and north Armorican fragments of the Cadomian–Avalonian orogen like most of the Saxothuringian and Moldanubian zones of central Europe which show similar detrital age characteristics [43,44] occupied a realm that had no access to exposures of basement rocks containing Mesoproterozoic zircons. Of the likely cratonic provenances, only the west African craton lacks significant zircon-forming Mesoproterozoic events, suggesting that SW Iberia, the north Armorican Domain and parts of the Bohemian Massif probably lay adjacent to this craton at that time (Fig.

4A). NW Iberia, NE Bohemia and Moravo–Silesia, on the other hand, require a Mesoproterozoic basement source, suggesting closer proximity to Amazonia or Oaxaquia [45] (Fig. 4A).

The contrast in sedimentary provenance between west Africa and Amazonia is also reflected in Sm–Nd isotope signatures. Rocks with west African affinities show much lower initial ϵ_{Nd} values than those with Amazonian affinity. For example, the Neoproterozoic greywackes from NW Iberia record initial ϵ_{Nd} values between 0 and –5 [46], whereas greywackes of equivalent age in SW Iberia record initial ϵ_{Nd} values between –9 and –12 [47].

All these terranes formed part of the active northern margin of Gondwana (Fig. 4A) that featured both a magmatic arc and a variety of back-arc basins (e.g. [11]). A back-arc setting has been proposed for both NW Iberia [6] and NE Bohemia [41]. These regions may have been closer to the Gondwanan margin than the West Avalonian terranes, which are dominated by magmatic arc rocks and likely represent the main magmatic edifice on the Amazonian segment of the margin (Fig. 4A).

Subduction along the margin proceeded until either ridge–trench collision [11] or a change in subduction regime [6] caused progressive transition to a transform regime (Fig. 4B–D). The arrest of subduction is considered to have been diachronous along the margin (e.g. [11] 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 Neoproterozoic detrital zircons in rocks from Brittany and SW Iberia in relation to those from NW Iberia (Fig. 3).

In the western European Variscan Belt, terranes with differing (Amazonian versus west African) basement signatures were juxtaposed prior to the deposition of the Middle Ordovician Armorican quartzite [48], which oversteps the boundaries between these domains. This is the case of NW and SW Iberia (Fig. 1), the Armorican Massif and the different domains that make up the Bohemian Massif, and implies that crustal units separated by hundreds or thousands of km in the Neoproterozoic had been amalgamated before Middle

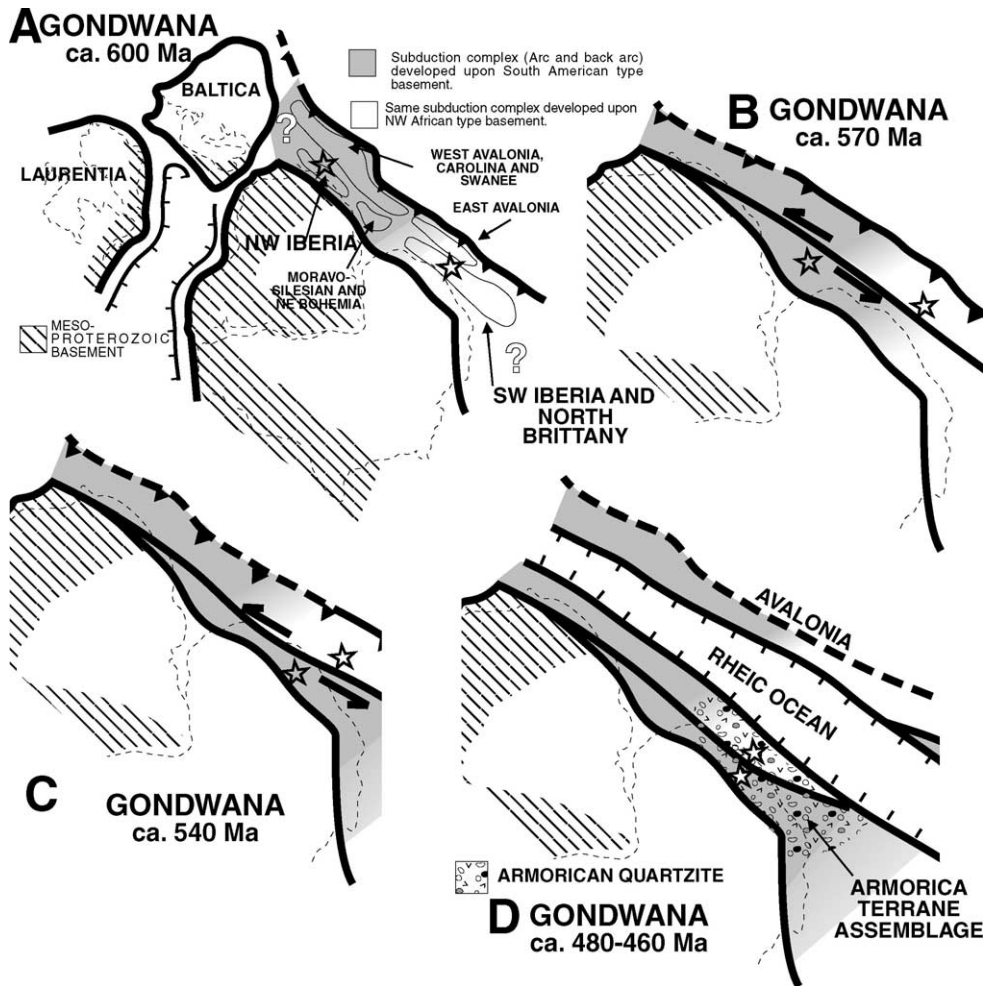


Fig. 4. Proposed Neoproterozoic terrane distribution (A,B) and early Palaeozoic tectonic evolution (C,D) along the northern Gondwanan margin (see text for details). Stars represent the hypothetical location of NW Iberia and SW Iberia/Brittany. Fig. 4A modified after [1] and [6].

Ordovician times. This amalgamation is supported by faunal, palaeomagnetic and geologic evidence which all indicate that NW and SW Iberia, the Armorican Massif and Bohemia had all been assembled adjacent to west Africa to form the Armorican realm (or Armorican Terrane Assemblage) by the Early to Middle Ordovician ([14] and references therein).

If the Armorican quartzite was deposited upon an extensive peri-African continental platform [48,49], then the abundance of Mesoproterozoic zircons in this formation in NW Iberia [17] (Fig. 3) suggests that the source for these zircons had

been tectonically transferred from an Amazonian realm before the deposition of the quartzite.

Therefore we propose that, prior to the Ordovician, NW Iberia (and other peri-African terranes of the Armorican Terrane Assemblage) were translated along the Gondwanan margin from an Amazonian realm towards the margin of west Africa. Later erosion of these tectonically transported crustal fragments produced detritus containing Mesoproterozoic zircons that was incorporated into the Armorican quartzite.

Further, we suggest that this dispersal took place along major transform faults roughly paral-

lel to the Gondwanan margin (Fig. 4) and proceeded until the peri-Amazonian terranes had docked against those that had occupied a peri-west African location since the Neoproterozoic (Fig. 4C). This would explain why peri-Gondwanan terranes with differing basement signatures are presently juxtaposed in 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 in the late Palaeozoic. Geological evidence for this docking may be recorded at the tectonic contact between the NW and the SW Iberian terranes [16,50] (Fig. 1), which we interpret as a reactivated early Palaeozoic terrane boundary. Deposition of the Armorican quartzite at ca 465 Ma [51] provides a minimum age constraint for the docking between west Africa and Amazonia-derived terranes.

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. 4D), which progressively separated from Gondwana until its docking to Laurentia–Baltica in the Silurian.

4.3. Further remarks

Margin-parallel strike-slip motion of terranes, as proposed here for north Gondwana, is observed in modern settings like the Cordilleran margin of North America [2] but has seldom been documented at this scale in ancient orogenic belts. We speculate that the peri-Gondwanan terranes with Amazonian affinities moved towards the west African margin in a manner akin to that in which California (west of the St. Andreas fault) is moving towards Alaska. The west African margin, in which subduction may still have been active when the strike-slip motion was initiated on the Amazonian side [11], could have acted as a back-stop to Africa-wards drifting terranes. Thus the Armorica Terrane Assemblage could be regarded as a bundling of terranes generated by

strike-slip motion along the northern Gondwanan margin.

5. Conclusions

Detrital zircon ages in Neoproterozoic and early Palaeozoic sedimentary rocks from western Europe provide a record of the geography and geodynamic evolution along the northern Gondwanan margin from ca 600 to 480 Ma. Such studies can provide first-order constraints on the histories of terrane dispersal and accretion, particularly in those cases where the geological record has been obscured by major orogenic events or subsequent plate reorganisation.

Constraining these processes in ancient orogenic belts can significantly improve our understanding of the geological record. We have demonstrated that U–Pb geochronology of detrital zircon populations can be used to test the role of transform margins in ancient orogens and crustal growth episodes.

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