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**Notes**

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# 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

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## ABSTRACT

**Detrital zircon laser ablation–inductively coupled plasma–mass spectrometry U-Pb age data from the Lower Ordovician Armorican Quartzite (deformed passive margin strata of Gondwanan affinity) of the Iberian Massif are presented herein. The *S*-shaped coupled Iberian oroclines defined within these zones palinspastically restore to a 2300 km linear Variscan orogen with a paleomagnetically constrained Late Carboniferous north-south trend. Detrital zircons are used to assess paleogeography and interpreted geometry of the Iberian portion of the Gondwana passive margin. A common signature is identified by (1) Neoproterozoic (ca. 500–850 Ma), (2) Stenian–Tonian (ca. 0.9–1.1 Ga), and lesser (3) Paleoproterozoic and (4) Archean populations (ca. 1.8–2.15 and 2.5–2.7 Ga, respectively). Minor site-to-site variation in relative proportion of widely ranging age groups suggests near-uniform distribution of a highly varied detrital input. Provenance analysis reveals strong correlations with Cambro-Ordovician clastic rocks from northeast African realms. Similarity with underlying sequences suggests a common paleogeography from the Ediacaran through early Paleozoic and persistence of a provenance distinction within the autochthonous Iberian Massif. Consistent northward paleoflow within widespread northeast African lower Paleozoic sedimentary cover suggests long-distance sedimentary transport across a North African peneplain from outlying basement terranes. We propose that the 2300-km-long Cantabrian–Central Iberian portion of the early Paleozoic Gondwana margin stretched east-west along the northern limits of the then low-lying Saharan Metacraton and Arabian-Nubian Shield. Accepting paleomagnetic constraints, a 90° counterclockwise rotation is required to reorient the Iberian portion to a pre-oroclinal (Late Carboniferous) north-south trend. The mechanisms for accommodating such a rotation are unclear.**

## INTRODUCTION

Detrital zircon age dating is a powerful tool in deciphering sedimentary provenance, and constraining paleogeography and tectonic evolution of continental realms. Sampling within restricted areas through thick stratigraphic successions can address questions regarding local tectonic evolution (e.g., May et al., 2013; LeMaskin, 2012). Alternatively, sampling over a wide area within a single stratigraphic level (formation) can yield formidable constraints on a variety of spatial variables at the point in time of interest, from relative location between continental masses to continental geometry and orientation.

This study presents detrital zircon age data sampled from the Lower Ordovician Armorican Quartzite (*sensu lato*) over a geographical area of roughly 150,000 km$^2$ within the Variscan orogen of Iberia. The Variscan orogen of Iberia is characterized by the continental-scale *S*-shaped Cantabrian–Central Iberian coupled oroclines (Aerden, 2004; Martínez Catalán, 2011; Shaw et al., 2012) (Fig. 1), and is divisible into a series of tectonostratigraphic zones. From the core of the Cantabrian orocline south, four of these zones, the (1) Cantabrian, (2) West Asturian–Leonese, (3) Central Iberian, and (4) Ossa-Morena, are considered parts of autochthonous Gondwana. Allochthonous terranes of the Iberian Variscan belt include (1) an ophiolite-bearing structural stack that overrides the hinterland zone 3 at the core of the Central Iberian orocline (e.g., Pérez-Estaún et al., 1991, and references therein), and (2) a swath of presumed-exotic continental crust independently sutured to the south of zone 4 (e.g., Martínez Catalán et al., 2007).

The Armorican Quartzite is characteristic of the lower Paleozoic Gondwana passive-margin sequence of zones 1–3. A 5–40-km-wide fault-bound band of rock at the boundary between zones 3 and 4 has, on the basis of structural data and stratigraphic correlations, been interpreted as being transitional between them (Pereira and Silva, 2001; Solá et al., 2008). The Ossa-Morena–Central Iberian transition zone, hereafter referred to as the transition zone (Fig. 1), extends north from the sinistral Badajoz-Cordoba shear zone to the Los Pedroches batholith (Linnemann et al., 2008, and references therein). It is characterized by a zone 4–type lower Ediacaran–Cambrian stratigraphic sequence overlain by a zone 3–type Ordovician sequence (Bandres et al., 2002; Pereira and Silva, 2001; Pereira et al., 2010). Though it is generally believed that no Armorican Quartzite equivalent exists within the Ordovician stratigraphic sequence of zone 4 (Robardet and Gutiérrez-Marco, 1990a, 1990b, 2004), the Sierra Albarrana Quartzites, exposed just south of the transition zone boundary and loosely constrained as early Paleozoic in age (Azor et al., 1991; Marcos et al., 1991), have been suggested as possible correlatives (Azor et al., 1991). The Cantabrian–Central Iberian coupled oroclines were defined in, and affect that portion of, the Variscan orogen located north of the transition zone; the nature of the relationship between the coupled oroclines and that portion of the Iberian Massif that lies to their south (zone 4 and the southern allochthon) remains unclear.

Paleomagnetic and structural studies have demonstrated that the Cantabrian orocline formed by lithospheric-scale vertical-axis rotation of an originally linear Variscan orogen in the Late Carboniferous–earliest Permian (Kollmeier

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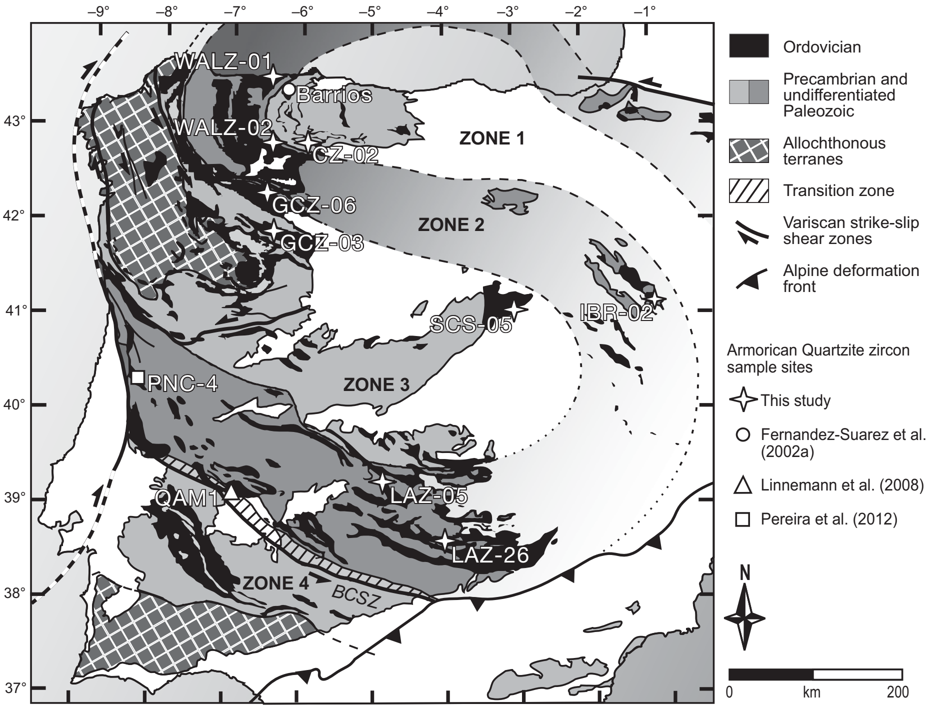


**Figure 1. Iberian Armorican Quartzite detrital zircon collection sites from this and previous studies in (the Cantabrian) zone 1 (Fernández-Suárez et al., 2002a), (the Central Iberian) zone 3 of Portugal (Pereira et al., 2012), and the zone 3–4 (Ossa-Morena) transition zone (Linnemann et al., 2008). The more darkly shaded external hinterland of the Variscan orogen reveals the geometry of the coupled Cantabrian–Central Iberian oroclines. The external hinterland (West Asturian–Leonese) zone 2 is continuous with the southern zone 3 through the unexposed hinge of the Central Iberian orocline, after Shaw et al. (2012). BCSZ—Badajoz-Cordoba shear zone.**

et al., 2000; Merino-Tomé et al., 2009; Pastor-Galán et al., 2011; Weil et al., 2000, 2001, 2010, 2013). Continuity between the Cantabrian and Central Iberian oroclines is supported by structural (Aerden, 2004), geophysical (Ardizone et al., 1989), sedimentological, and faunal data (Aramburu and García-Ramos, 1993; Robardet, 2002; Robardet and Gutiérrez-Marco, 1990b). Coeval development of the Cantabrian and Central Iberian oroclines is consistent with their coupled nature and with available paleomagnetic data (Table 1 and references therein). Palinspastic restoration of the coupled Iberian oroclines to a paleomagnetically constrained north-south trend (Weil et al., 2010) yields a 2300-km-long segment of the Variscan orogen (Fig. 2). The easterly autochthonous portion of the orogen consists primarily of a deformed west-facing (in present-day coordinates) lower Paleozoic passive-margin sequence of Gondwanan affinity (Murphy et al., 2008) referred to as the Cantabrian–Central Iberian margin (CCIM).

Interpretation of the Ibero-Variscan orogen as having originated as a north-south–striking linear belt requires along-strike continuity of stratigraphic units through the 2300 km length of the CCIM. This requirement is testable. If stratigraphic continuity along the margin can be demonstrated, efforts must be made to (1) constrain the paleogeographic origin of the CCIM along the Gondwana margin and (2) assess the relationship between the stratigraphic sequence of the CCIM and the passive-margin strata of southwestern Iberia that are also thought to be of Gondwanan affinity. Detrital zircon age data presented herein stem from samples of the Armorican Quartzite collected along a 1500 km length of the CCIM. Sampling a single formation (and hence a narrow time slice) over a large area enables us to (1) assess interpretation of the CCIM as having originated as a north-striking, west-facing, linear and coherent segment of the early Paleozoic Gondwana passive margin, (2) provide further constraints on the nature of the boundary between tectonostratigraphic zones 3 and 4 by assessing provenance distinctions across it, and (3) limit the paleogeography of the CCIM through sedimentary provenance analysis. Our study demonstrates that paleogeography can be effectively and reliably constrained using zircon provenance analyses that focus on comparison of peri-contemporaneous clastic sequences rather than on the comparison of clastic sequence against potential basement source. The detailed Early Ordovician "snapshot" of the Iberian Gondwana margin revealed through detrital zircon ages yields broad and significant implications for the pre-Ordovician paleogeography and post-Ordovician tectonic evolution of the Variscan orogen.

## GEOLOGIC SETTING

### The Armorican Quartzite

The Armorican Quartzite consists of thick-bedded (decameter to meter scale) clean quartzites, meta-sandstones, phyllitic siltstones, and rare layers of volcanic rock and shale. Sedimentological studies indicate a range of depositional facies that grade outward from proximal deltaic in zone 1 (Aramburu, 1989; Aramburu and García-Ramos, 1993; Aramburu et al., 2004) to shallow-water nearshore with tidal, shore-current, and storm influences in zones 2 and 3 (Gutiérrez-Marco et al., 2002, and references therein). Paleocurrent data indicate that dominant transport direction in the Armorican Quartzite is offshore, fanning outboard of the foreland core of the Cantabrian orocline in the north (Aramburu and García-Ramos, 1993; Shaw et al., 2012), and focusing inward toward allochthonous terranes at the core of the Central Iberian orocline in the south (Shaw et al., 2012). A K-bentonite (altered ash-fall tuff) interbedded within the Armorican Quartzite of zone 1 yielded a U-Pb zircon age of 477 ± 1 Ma (Gutiérrez-Alonso et al., 2007). Units correlative with the Armorican Quartzite occur in North and West Africa, as far east as Serbia, and in the Armorican and Bohemian massifs of France and Germany, respectively (Fernández-Suárez et al., 2002a; Gutiérrez-Alonso et al., 2007).

### 2.2 Existing Provenance Constraints

Autochthonous Iberia (zones 1–4) is stratigraphically linked with the North African Gondwanan realm (Noblet and Lefort, 1990), and Neoproterozoic–early Paleozoic paleogeographic reconstructions commonly place it adjacent to Morocco and the West African craton (e.g., Murphy et al., 2004, 2006; Nance and Murphy, 1994). Several recent models have proposed a variety of Central to East African early Paleozoic paleogeographic locations for Iberia, based on (1) paleontological grounds (Gutiérrez-Marco et al., 2002, and references therein), (2) detrital zircon studies within para-allochthonous terranes of northwestern Iberia

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TABLE 1. AVAILABLE PRE-VARISCAN PALEOMAGNETIC DATA FOR THE IBERIAN MASSIF* AND PYRENEES

| Name | Relative location within oroclinal pair | Likely age | D | I | D−1† | Paleo-latitude§ | $\alpha_{95}$ | Reference |
|---|---|---|---|---|---|---|---|---|
| San Pedro | Common limb of fold pair | Siluro-Devonian | 113° | +34° | 293° | 21°S | 10 | Perroud and Bonhommet, 1984 |
| Griotte | North limb of Cantabrian orocline | Siluro-Devonian | 224° | +51° | 44° | 30°S | 8.5 | Tait et al., 2000a |
| Almaden-1 | South limb of Central Iberian orocline | Silurian | 62° | –36° | 64° | 12°S | 14 | Perroud et al., 1991 |
| Almaden-2 | South limb of Central Iberian orocline | Devonian | 81° | –37° | 81° | 20°S | 10 | Parés and Van der Voo, 1992 |
| Beja | South limb of Central Iberian orocline | Early Carboniferous | 36° | –49° | 36° | 29°S | 16 | Ruffet, 1990 |

*Note:* D—declination; I—inclination.
*North of the Badajoz-Córdoba shear zone.
†Inverted declination corresponding to negative inclination implying, for the southern hemispheric latitudes, a north-seeking magnetization and normal polarity (R. Van der Voo, personal commun., 2011).
§Likely paleo-latitude based on a north-seeking magnetization and normal polarity.

(Díez Fernández et al., 2010; Fernández-Suárez et al., 2013), and (3) isotopic and inherited zircon studies of Central Iberian Cambro-Ordovician magmatic rocks (Bea et al., 2010). However, the assumption of a common paleogeographic history for a cohesive Iberian Massif may be flawed. Detrital zircons from Ediacaran–Cambrian clastic strata of zone 4 display a signature thought to be characteristic of a West African provenance (Fernández-Suárez et al., 2002b). In contrast, Ediacaran–lower Paleozoic clastic rocks of zones 1–3 contain significant numbers of Stenian–Tonian aged (ca. 0.9–1.1 Ga) zircons (Ábalos et al., 2012; Fernández-Suárez et al., 2000, 2013; Gutiérrez-Alonso et al., 2003; Talavera et al., 2012) for which there is no known source within the West African craton (Rocci et al., 1991). As Stenian–Tonian zircons have also been documented within Devonian and Carboniferous clastic rocks of zone 3 (Martínez Catalán, 2008) and Silurian through lowermost Permian clastic rocks of zone 1 (Pastor-Galán et al., 2013), they may be characteristic of the entire pre-Variscan Paleozoic sequence within northern and central Iberia.

How to reconcile the contrasting Ediacaran–early Paleozoic provenance of strata from zones 3 and 4 across the transitional boundary between them remains unclear, and complex late Neoproterozoic–Devonian histories have been postulated for the outlying zone 4 (Azor et al., 1994; Gómez-Pugnaire et al., 2003). Paleobiological data have been used to suggest a deep- water distal origin for the early Paleozoic Gondwanan zone 4 platform (Robardet and Gutiérrez-Marco, 1990a, 1990b, 2004), the manner and timing by which it arrived at its present-day relative position with respect to zone 3 remaining unclear. Owing to the inherent ambiguities, the geometry of the coupled Iberian oroclines cannot yet be defined across the transition zone, and we consider the palinspastically restored (pre-orocline) CCIM independently of both the transition zone and zone 4.

## SAMPLING

The laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) U-Pb age analyses of detrital zircons presented in this study are from samples collected at nine locations within zones 1, 2, and 3 (Fig. 1). Collection was aimed at covering the ~1500-km-long portion of the CCIM that today constitutes the northern and central Iberian Massif (Fig. 2). No samples were collected from the less-discrete Pyrenean continuation of the northern limb of the Cantabrian orocline. Sample WALZ-01, which represents the study's northernmost sampling site, was collected at Playa de Cueva in Canero, Asturias. Sample WALZ-02 was taken within the upper sequence of the Los Cabos Group (local formation name), just south of the Presa (dam) de las Ondinas, Palacios del Sil, León. Sample CZ-02 was collected on the western side of the dam at Barrios de Luna, León, from which the local formation name Barrios de Luna is taken, at a stratigraphic height of 20 m above the K-bentonite bed dated at 477 ± 1 Ma by Gutiérrez-Alonso et al. (2007). Samples GCZ-03 and GCZ-06 are from within the Galician-Castillian Zone, a northern subdivision of zone 3 (Lotze, 1945), from the northern limb of the Alcañices syncline at San Pedro de Las Herrerias, Zamora, and the northern limb of the Truchas syncline north-northwest of Corporales, Truchas, Zamora, respectively. Sample SCS-05 was collected within the Spanish Central System (easternmost Galician-Castillian subzone) northwest of Bustares, Guadalajara, in a basal unit of the Armorican Quartzite for-

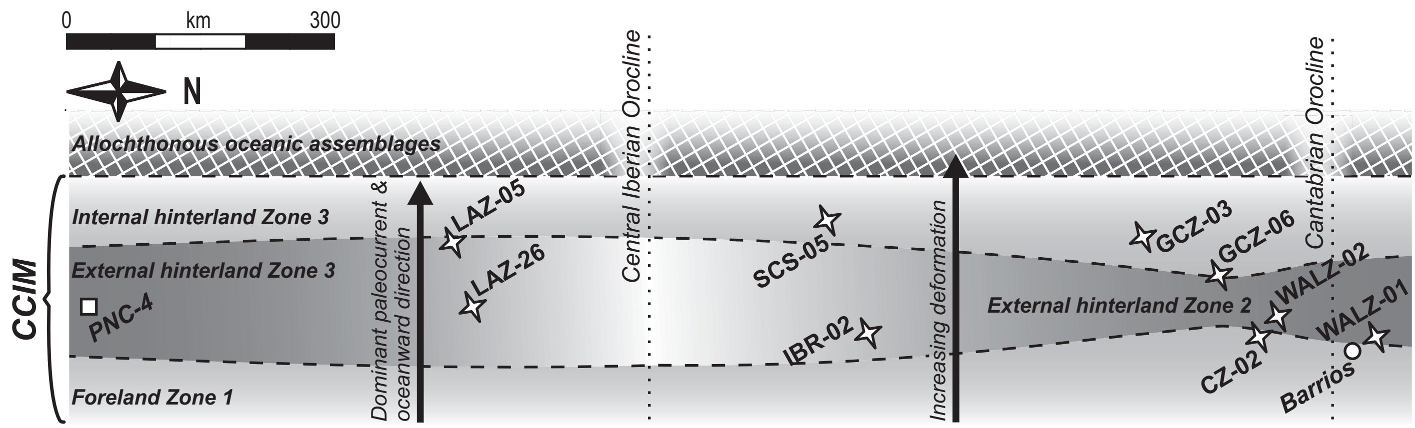


**Figure 2. Relative locations of sample collection sites along the ~1500-km-long studied segment of the palinspastically restored Iberian Variscan belt, after Shaw et al. (2012). Neither margin-parallel shortening preceding oroclinal formation nor strike-perpendicular shortening likely to have been assumed during bending are restored. The deformed CCIM (Cantabrian–Central Iberian margin) consists of, from coastal to distal shelf, autochthonous zones 1, 2, and 3.**

TABLE 2. MAJOR ELEMENT GEOCHEMISTRY FOR THE ARMORICAN QUARTZITE OF THE IBERIAN MASSIF

| | | CZ-02 | WALZ-01 | WALZ-02 | IBR-2 | GCX-03 | GCZ-06 | SCS-05 | LAZ-05 | LAZ-26 |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | (%) | 98.25 | 91.55 | 98.51 | 97.41 | 97.43 | 95.56 | 89.2 | 91.87 | 93.48 |
| $TiO_2$ | (%) | 0.16 | 0.178 | 0.13 | 0.152 | 0.199 | 0.578 | 0.623 | 0.176 | 0.313 |
| $Al_2O_3$ | (%) | 0.56 | 4.22 | 0.5 | 0.88 | 1 | 1.7 | 6.1 | 2.51 | 2.83 |
| $Fe_2O_3$ | (%) | 0.2 | 0.28 | 0.34 | 0.19 | 0.51 | 0.33 | 0.54 | 3.91 | 2.34 |
| MnO | (%) | 0* | 0* | 0.016 | 0.002 | 0.005 | 0* | 0* | 0.004 | 0* |
| MgO | (%) | 0* | 0* | 0* | 0* | 0* | 0.01 | 0.09 | 0* | 0* |
| CaO | (%) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| $Na_2O$ | (%) | 0* | 0* | 0* | 0* | 0* | 0.06 | 0* | 0* | 0* |
| $K_2O$ | (%) | 0.15 | 1.95 | 0.14 | 0.23 | 0.31 | 0.38 | 1.93 | 0.13 | 0.4 |
| $P_2O_5$ | (%) | 0.027 | 0.029 | 0.015 | 0.029 | 0.026 | 0.032 | 0.034 | 0.053 | 0.056 |
| LOI | (%) | 0.19 | 0.77 | 0.00 | 0.20 | 0.09 | 0.50 | 1.18 | 1.08 | 0.89 |
| Sum† | (%) | 99.55 | 98.99 | 99.66 | 99.10 | 99.58 | 99.16 | 99.71 | 99.74 | 100.32 |

*Note:* SuperQ quantitative analysis of glass discs conducted using a Phillips PW2400 spectrometer at the Regional Geochemical Centre, St. Mary's University, Halifax, Nova Scotia B3H 3C3, Canada.

*Negative calculated quantity, assumed to be zero.

†Total values do not include trace elements.

mation. Sample IBR-02 was taken at La Ermita de la Virgen de Herrera, south of Herrerra de los Navarros, Zaragoza, in the eastern Iberian Cordillera, discontinuous in exposure but commonly correlated with zone 2. Samples LAZ-26 and LAZ-05 were collected from within the Luso Alcudian southern subdivision of zone 3 (Lotze, 1945). LAZ-26 was collected from west of Puertollano, Ciudad Real, and LAZ-05 from the northeast limb of the Anticlinorio de Guadalupe west of Helechosa de los Montes, Toledo, where the base of the Armorican Quartzite formation is locally conglomeratic and which represents the southernmost sampling site along the palinspastically restored CCIM. Coordinate data for each collection site are provided within Table A1 in the GSA Data Repository[1].

Samples were selected in the field based on grain size and textural maturity. Petrographic and geochemical analyses reveal the samples to be mineralogically mature, consisting mainly of quartz grains (up to 99%; see Table 2 for major element geochemistry; trace element geochemistry is provided in Table A2 in the Data Repository). Most of the samples studied are unmetamorphosed or were recrystallized under low-grade conditions, excepting sample SCS-05, for which metamorphic grade is slightly higher. Previous detrital zircon studies of the Armorican Quartzite within the Iberian Massif are limited to three publications providing single-sample analyses, one of which is based on a sample collected within the transition zone (Fernández-Suárez et al., 2002a; Linnemann et al., 2008; Pereira et al., 2012) (see Figs. 1, 2). Other samples from lower Paleozoic Iberian clastic rocks not including the Armorican Quartzite are reported in Martínez Catalán et al. (2004) and Talavera et al. (2012).

[1]GSA Data Repository item 2014083, coordinate data for zircon sample collection sites within the Armorican Quartzite of the Iberian Massif (Table A1), minor element geochemistry for the Armorican Quartzite of the Iberian Massif (Table A2) and detailed laser ablation–inductively coupled plasma–mass spectrometry U-Pb analysis results for the Armorican Quartzite of the Iberian Massif (Table A3), is available at http://www.geosociety.org/pubs/ft2014.htm or by request to editing@geosociety.org.

## ANALYTICAL TECHNIQUES

Initial preparation of field samples was conducted at the Salamanca and Complutense (Madrid) Universities. Fresh samples were crushed with a jaw crusher then pulverized with a disc mill. Zircons were isolated by heavy-fraction enrichment on a Wilfley table followed by density separation using diodomethane ($CH_2I_2$) and magnetic separation in a Franz isodynamic separator. Final stages of sample preparation and LA-ICP-MS U-Pb analysis were conducted at the Sektion Geochronologie of the Senckenberg Naturhistorische Sammlungen Dresden, Museum für Mineralogie und Geologie (Germany). A representative suite of zircon grains were mounted, and set in resin blocks. Resin-mounted zircons were then hand polished to approximately half their thickness, bringing a full cross section flush with the surface; each mount was cleaned in a 5% $HNO_3$ bath prior to ablation. Each sample is characterized by a similar range of zircon morphology. Grains are rose colored to colorless and relatively fine. Larger grains (up to 350 µm c-axis in LAZ-05) are euhedral to subrounded prisms whereas smaller grains (as little as 25 µm diameter) are well rounded.

Zircons were analyzed for U, Th, and Pb isotopes by LA-ICP-MS techniques using a Thermo-Scientific Element 2 XR sector field ICP-MS coupled to a New Wave UP-193 Excimer Laser System. Each analysis consisted of 15 s of background acquisition followed by 35 s of data acquisition with laser pits 20, 25, or 35 µm wide, depending on the crystal size, and no more than 15 µm deep. A common-Pb correction based on the interference- and background-corrected $^{204}$Pb signal and a model-Pb composition (Stacey and Kramers, 1975) was carried out where necessary. The necessity of the correction was judged on whether the corrected $^{207}$Pb/$^{206}$Pb lay outside of the internal errors of the measured ratios. Raw data were corrected for background signal, common Pb, laser-induced elemental fractionation, instrumental mass discrimination, and time-dependent elemental fractionation of Pb/Th and Pb/U using a Microsoft Excel spreadsheet program developed by Axel Gerdes (Institute of Geosciences, Johann Wolfgang Geothe-University Frankfurt, Frankfurt am Main, Germany). Reported uncertainties were propagated by quadratic addition of the external reproducibility obtained from the standard zircon GJ1 (~0.6% and 0.5%–1% for the $^{207}$Pb/$^{206}$Pb and $^{206}$Pb/$^{238}$U, respectively) during individual analytical sessions and the within-run precision of each analysis. For further detail on analytical protocol and data processing see Frei and Gerdes (2009).

## DETRITAL ZIRCON AGES

### Data Treatment

A minimum of 120 U-Pb age determinations were performed on each sample (one analysis in the center of each grain). Analyses with discordance higher than 10% (i.e., concordance <90% or >110%) were rejected. The remaining U-Pb data are represented in concordia diagrams (Fig. 3) drawn using Isoplot 3.7 (Ludwig, 2009), and in relative probability plot and histogram combined displays (Fig. 4) generated with the AgeDisplay Excel-based macro (Sircombe, 2004). Complete data tables are available as Table A3 in the Data Repository. Age assignment for each analysis ("Reported age" column in Table A3) is as follows: for analyses whose 2σ error ellipses overlap the concordia curve, the chosen age and 2σ error are the concordia age and error (Ludwig, 2009) as calculated by Isoplot 3.7. For analyses that are less than 10%

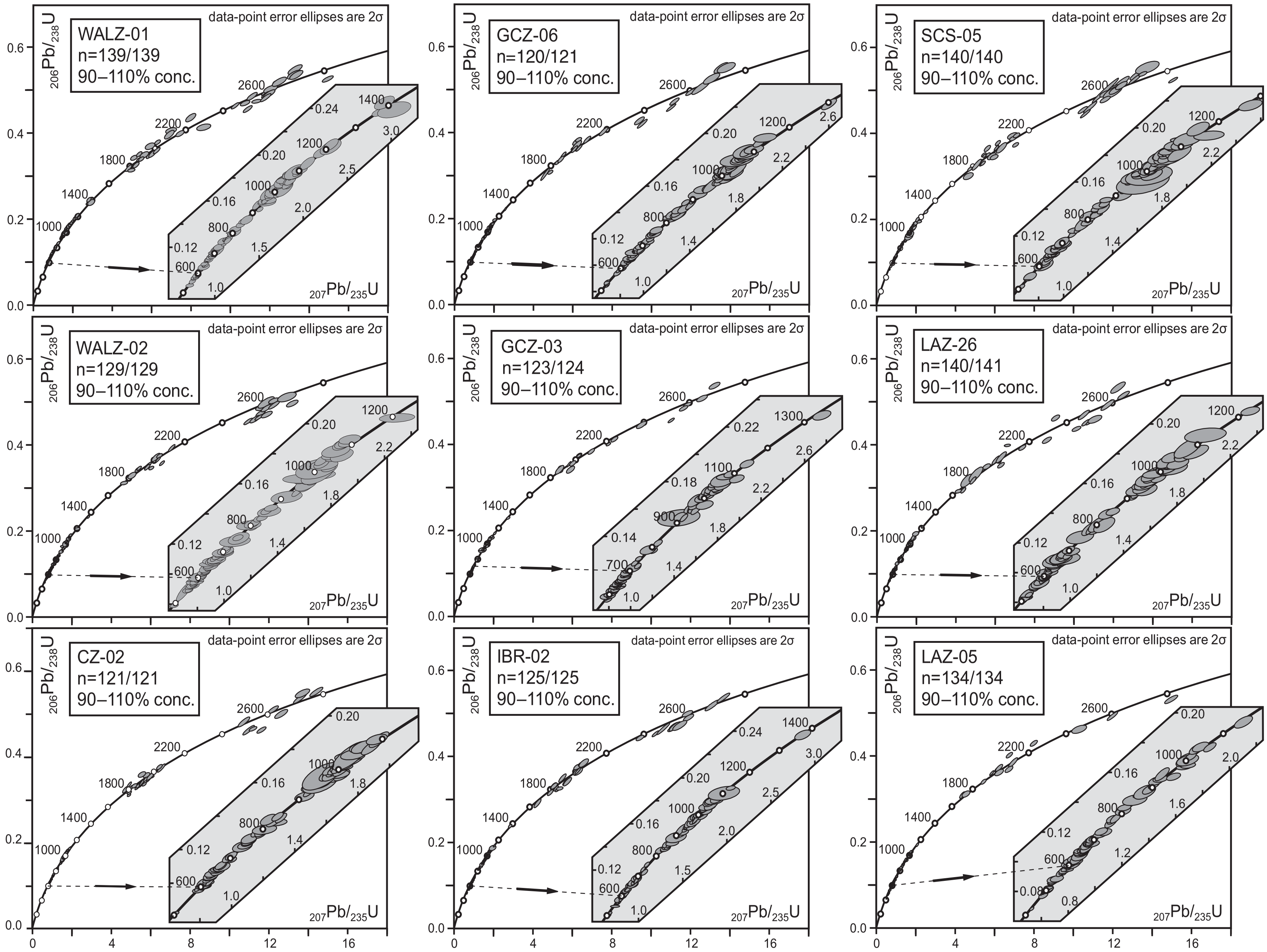


**Figure 3. Concordia plots of laser ablation–inductively coupled plasma–mass spectrometry U-Pb analyses of detrital zircon grains for each of the nine sample sites from within the Lower Ordovician Armorican Quartzite of the Cantabrian–Central Iberian margin. Insets show enlargement of younger ages (n—number of grains displayed/number of concordant analyses). For graphical clarity, outlying Archean-aged grains from samples GCZ-03 (3434 Ma; ± 30 2σ error; 98% concordance), GCZ-06 (3434 Ma; ± 21 2σ error; 101% concordance), and LAZ-26 3382 Ma; ± 15 2σ error; 96% concordance) are not plotted.**

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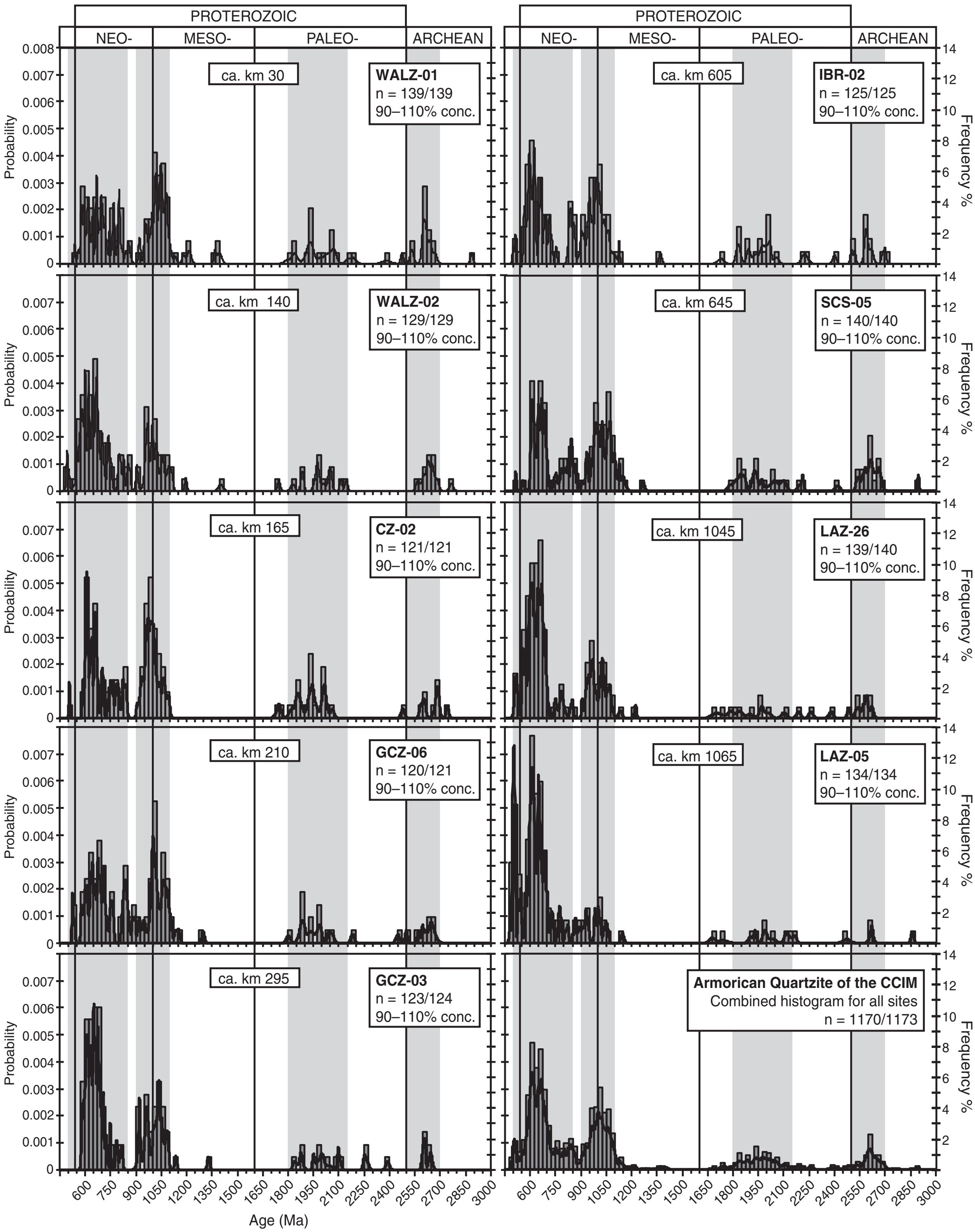


**Figure 4. Combined histogram and probability distribution density plots of detrital zircon grains for each of the nine sample sites within the Lower Ordovician Armorican Quartzite of the Cantabrian–Central Iberian margin (CCIM) and for all samples combined. Distances south along the studied 1500 km segment of the palinspastically restored CCIM are given from a northernmost reference, site WALZ-01. n—number of grains displayed/number of concordant analyses. For graphical clarity, outlying Archean-aged grains from GCZ-03 (3434 Ma; ± 30 2σ error; 98% concordance), GCZ-06 (3434 Ma; ± 21 2σ error; 101% concordance), and LAZ-26 (3382 Ma; ± 15 2σ error; 96% concordance) are not plotted.**

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discordant but whose corresponding 2σ ellipses do not intercept the concordia curve we have chosen either the $^{207}Pb/^{206}Pb$ or the $^{206}Pb/^{238}U$ age depending on which corresponding isotope ratio was measured with greater precision in that particular analysis.

### Data Analysis

Detrital zircon ages are examined in the context of the coupled Iberian oroclines; samples are ordered by relative north-to-south location along the palinspastically restored 1500-km-long segment of the CCIM (Fig. 2). Four dominant U-Pb age population groups define a detrital zircon signature common across the studied area. Each sample contains a nearly continuous suite of zircon ages between ca. 550 and 1100 Ma, accounting for 70%–80% of the total number of concordant grains analyzed per sample. Two statistical peaks sandwiching a prevalent 850–900 Ma minimum within this range suggest two distinct age populations, (1) Neoproterozoic (ca. 500–850 Ma) and (2) Stenian–Tonian (ca. 0.9–1.1 Ga). Less-dominant Paleoproterozoic (ca. 1.8–2.15 Ga) and Archean (ca. 2.5–2.7 Ga) populations have more poorly defined peaks at 1.9 and 2.6 Ga, respectively. The greatest degree of variability between samples is expressed within Paleozoic zircons. Most samples contain fewer than 5% grains with concordant Cambrian–earliest Ordovician ages; sample LAZ-05 is the exception, with 18.6%. The youngest concordant age (481 ± 11 Ma) was measured in sample LAZ-05. Our samples are characterized by a paucity of late Paleoproterozoic to early Mesoproterozoic zircons, with only a fraction of a percent of all concordant grains within the range of 1.3–1.7 Ga.

Statistical comparison of age distributions between sampling sites and with external data sets during provenance analysis is carried out through multiple two-sample Kolmogorov-Smirnov (K-S) tests in a manner similar to those employed by previous studies seeking to assess common provenance (Amidon et al., 2005; Barbeau et al., 2009; Berry et al., 2001; DeGraaff-Surpless et al., 2003; Dickinson et al., 2010). The K-S test assigns a value of difference (D) that corresponds to a sample size–dependent probability value (P) that both sample groups were randomly selected from identical parent populations. We accept any two samples that pass the test at the 5% confidence level ($P \geq 0.05$) as derived from erosion of the same source area, and accept any two samples passing the test at the 0.1% confidence level ($0.05 > P \geq 0.001$) as not significantly different. We caution, however, that use of the K-S is best reserved as a quantitative supplement to first-order qualitative visual comparisons of detrital zircon age spectra, particularly when assessing common provenance on a regional scale. K-S tests were performed using an Excel-based macro developed at the Arizona LaserChron Center in the Department of Geosciences at the University of Arizona (Guynn and Gehrels, 2010). In an effort to buffer against the observed high variability of detrital input from geologic events that are recent with respect to the depositional age of the Armorican Quartzite, tests were conducted using only "reported age" values (Table A3) and preferred age values from external data sets older than 500 Ma.

## INTERPRETATION AND DISCUSSION

### Provenance Relationships within Iberia

The detrital zircon age spectra identified within each of the nine studied samples provide constraints on the nature and geometry of the CCIM. Our samples are characterized by an age spectra consistent with those reported by previous studies from zone 1 (sample Barrios; Fernández-Suárez et al., 2002a) and zone 3 (sample PNC-4; Pereira et al., 2012), which represent north and south end-member locations along the palinspastically restored CCIM, respectively. An along-strike trend, characterized by a southward decrease in the Stenian–Tonian signature balanced by a southward increase in the Neoproterozoic signature, is apparent. The trend is made most evident by comparison of our palinspastically restored northern and southern end-member sites (WALZ-01 and LAZ-05, respectively) with the previously published data sets (Fig. 5). Northern samples, WALZ-01 and Barrios, are characterized by robust Stenian–Tonian populations (31.6% and 22% concordant grains, respectively). In contrast, the southernmost samples, LAZ-05 and PNC-4, have similar Stenian–Tonian populations (10.4% and 8%, respectively), but significantly greater numbers of middle to late Neoproterozoic (59.7% and 60%, respectively), as well as significant Cambrian (17.9% and 20%, respectively) zircons. The degree of along-strike variability is also apparent within the site-to-site two-sample K-S test results (Table 3). While comparisons between sites along the first 650 km of the restored margin pass the K-S test, southern sites LAZ-26 and LAZ-05 are statistically similar to one another but significantly different from 50% of the northern sites, perhaps reflecting the large gap in data (400 km along strike between sites SCS-05 and LAZ-26) through the buried hinge of the Central Iberian orocline. The consistency of detrital age populations across zones 1–3 is nevertheless suggestive of the CCIM having constituted a coherent component of the Early Ordovician Gondwanan passive margin characterized by deposition on a uniform shelf receiving detrital input from both stable cratonic sources and areas of relatively recent tectonic activity.

The age spectra in our data differ from those reported by Linnemann et al. (2008) for the Armorican Quartzite of the transition zone (Fig. 6). Sample QAM-1 fails each two-sample K-S test with high D value (>0.5; Table 3), and though Linnemann et al. (2008) reported only a small number of concordant ages (n = 31), a paucity of Mesoproterozoic zircons in their sample contrasts with the strong Stenian–Tonian signal that is characteristic of Armorican Quartzite samples from the CCIM. An absence of Mesoproterozoic zircons, as that observed in the transition zone sample, is commonly considered a hallmark of West African provenance (e.g., Abati et al., 2010), and is likewise a defining characteristic of Ediacaran–Cambrian clastic sedimentary strata of zone 4 (Fernández-Suárez et al., 2002b). Though recent studies have revealed a minor Stenian–Tonian signature within Middle Cambrian clastic rocks of the Moroccan Anti-Atlas (Avigad et al., 2012), the population is absent within older (Ediacaran and Lower Cambrian) sequences in the region, as well as absent within lower Paleozoic sequences of the Algerian Tuareg Shield (Linnemann et al., 2011). It was previously recognized that zones 3 and 4 could be distinguished based on detrital zircon provenance in Ediacaran rocks (e.g., Fernández-Suárez et al., 2000, 2002b; Gutiérrez-Alonso et al., 2003). The boundary between the "West African–type" zone 4 and the CCIM (zones 1–3), characterized by clastic detritus of Stenian-Tonian age, can now be located along the northern boundary of the transition zone. This provenance distinction, previously thought to be restricted to Ediacaran strata, persists through the Early Ordovician deposition of the Armorican Quartzite.

### Ordovician Paleogeography

Our detrital zircon data place limits on the sedimentary provenance of the Armorican Quartzite, and hence the Early Ordovician paleogeographic location of the CCIM. The dominant Cryogenian–Ediacaran population is consistent with derivation from basement within West Gondwana. Neoproterozoic igneous rocks and related immature sedimentary sequences in West Gondwana are attributed to long-lived subduction along the northern Gondwana margin forming the Cadomian-Avalonian arc (Nance et al., 2008, and references therein), and to the Pan-African–Brasiliano orogenic

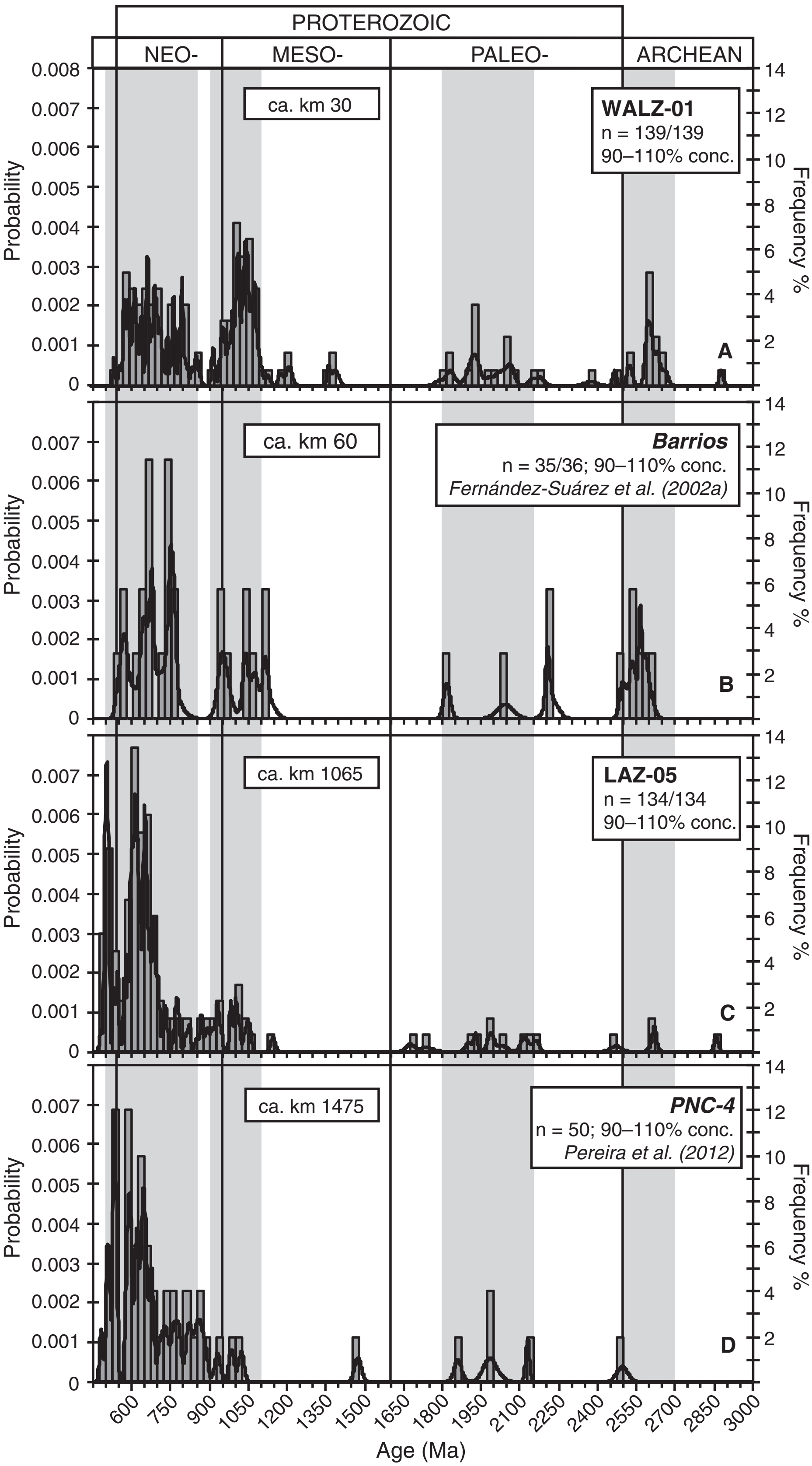


**Figure 5. Sample size–normalized histogram and probability density plots comparing previous U-Pb detrital zircons studies form the Armorican Quartzite of the Cantabrian–Central Iberian margin (CCIM) with the most proximal sample sites from this study. Samples represent northern (A) WALZ-02 and (B) Barrios, and southern (C) LAZ-05 and (D) PNC-04, end-member locations along the palinspastically restored CCIM. Displayed preferred ages are selected on the criteria established in each original publication; originally published data with greater than 10% discordance are excluded. n—number of grains displayed/number of concordant analyses; concordant analyses excluded for graphical clarity are single grains >3.0 Ga.**

belts, which record the amalgamation of Gondwana (500–800 Ma) (e.g., Cawood and Buchan, 2007; Hoffman, 1991; Unrug, 1997). Younger zircons (<500 Ma) can be attributed to Cambro-Ordovician magmatism likely related to rifting of the north margin of Gondwana. Rifting explains the Cambro-Ordovician departure of peri-Gondwanan terranes, including Avalonia (Díaz García, 2002; Díez Montes, 2006; Montero et al., 2007; Valverde-Vaquero et al., 2005), the opening and growth of the Rheic Ocean, and the development of the north-Gondwanan passive margin upon which the Armorican Quartzite was deposited. The youngest concordant age (481 ± 11 Ma) is in agreement with the previously established 477 Ma depositional age of the Armorican Quartzite (Gutiérrez-Alonso et al., 2007).

Stenian–Tonian crustal material is typically associated with the supercontinent Rodinia (e.g., Hoffman, 1991), but known material within the specific range of 0.9–1.1 Ga is limited within the stable cratonic realms of West Gondwana. The younger component of the range (0.9–1.0) exists within the Sunsas-Aguapei belts of the Amazonian craton (Teixeira et al., 1989). Older Mesoproterozoic rocks (1.0–1.6 Ga) are documented within the Namaqua-Natal belt along the southern limit of the Kaapvaal craton (Eglington, 2006), within the Kibaran and Irumide belts along the respective western and southern margins of the Tanzania craton (Cahen et al., 1984; De Waele et al., 2009; Johnson et al., 2007), and as lesser components within the dominantly Neoproterozoic Mozambique belt along the eastern margin of the Tanzania craton (Kröner, 2001). The Armorican Quartzite, however, contains very few Mesoproterozoic zircons older than 1.1 Ga. Isolated regions

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TABLE 3. COMPARISON OF DETRITAL ZIRCON AGE SPECTRA WITH THE ARMORICAN QUARTZITE USING THE K-S STATISTICAL TEST

At the 0.05 significance level the studied populations have:

| P < 0.001 | (a statistically significant difference) | 0.05 > P > 0.001 | (no statistically significant difference) | P > 0.05 | (a statistically significant similarity) |
|---|---|---|---|---|---|

| | **WALZ-01** | ***Barrios**** | **WALZ-02** | **CZ-02** | **GCZ-06** | **GCZ-03** | **IBR-02** | **SCS-05** | **LAZ-26** | **LAZ-05** | ***PNC-4***† | ***QAM-1***§ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **WALZ-01** n = 139139 | | 0.496 | 0.019 | 0.111 | 0.378 | 0.001 | 0.074 | 0.998 | < 0.001 | < 0.001 | < 0.001 | < 0.001 |
| ***Barrios**** n = 36/36 | 0.155 | | 0.509 | 0.329 | 0.437 | 0.313 | 0.524 | 0.335 | 0.057 | 0.001 | 0.015 | < 0.001 |
| **WALZ-02** n = 127/129 | 0.188 | 0.155 | | 0.076 | 0.181 | 0.826 | 0.199 | 0.015 | 0.121 | < 0.001 | 0.010 | < 0.001 |
| **CZ-02** n =121/121 | 0.149 | 0.180 | 0.162 | | 0.906 | 0.005 | 0.752 | 0.239 | < 0.001 | < 0.001 | < 0.001 | < 0.001 |
| **GCZ-06** n = 118/121 | 0.113 | 0.165 | 0.139 | 0.073 | | 0.019 | 0.468 | 0.626 | < 0.001 | < 0.001 | < 0.001 | < 0.001 |
| **GCZ-03** n = 121/124 | 0.239 | 0.182 | 0.079 | 0.221 | 0.195 | | 0.031 | 0.001 | 0.320 | 0.003 | 0.019 | < 0.001 |
| **IBR-02** n = 124/125 | 0.158 | 0.154 | 0.135 | 0.086 | 0.108 | 0.183 | | 0.169 | 0.003 | < 0.001 | < 0.001 | < 0.001 |
| **SCS-05** n = 140/140 | 0.047 | 0.176 | 0.191 | 0.128 | 0.093 | 0.246 | 0.137 | | < 0.001 | < 0.001 | < 0.001 | < 0.001 |
| **LAZ-26** n = 141/141 | 0.319 | 0.249 | 0.145 | 0.277 | 0.276 | 0.118 | 0.225 | 0.285 | | 0.051 | 0.095 | < 0.001 |
| **LAZ-05** n = 127/134 | 0.431 | 0.370 | 0.256 | 0.404 | 0.391 | 0.227 | 0.365 | 0.431 | 0.166 | | 0.964 | < 0.001 |
| ***PNC-4***† n = 49/50 | 0.430 | 0.343 | 0.273 | 0.418 | 0.352 | 0.258 | 0.368 | 0.435 | 0.205 | 0.084 | | < 0.001 |
| ***QAM-1***§ n = 31/31 | 0.687 | 0.647 | 0.648 | 0.716 | 0.687 | 0.706 | 0.657 | 0.725 | 0.614 | 0.546 | 0.513 | |

**P Values**

**D Values**

*Note:* K-S—Kolmogorov-Smirnov. Ages <500 Ma excluded from analyses, error incorporated.
*Fernandez-Suarez et al. (2002a).
†Pereira et al. (2012).
§Linnemann et al. (2008).

within the Neoproterozoic Arabian-Nubian Shield that contain 0.9–1.1 Ga components (Be'eri-Shlevin et al., 2009; Eyal et al., 2014; Hargrove et al., 2006; Morag et al., 2012) are not substantial enough to account for the robust 0.9–1.1 Ga population within the Armorican Quartzite of the CCIM. In addition, the low topographic relief and widespread sedimentation that characterized north-central and northeast Africa during the early Paleozoic (e.g., Avigad et al., 2012; Noblet and Lefort, 1990) yielded Cambro-Ordovician clastic sequences that are distinct from local basement, both in terms of detrital age range and geochemistry (Avigad et al., 2012, 2005; Morag et al., 2011). Though the source of Stenian–Tonian material deposited along the early Paleozoic north Gondwana passive margin remains enigmatic, a dominant northward sediment transport direction recorded within the widely distributed Cambro-Ordovician sedimentary cover (Morag et al., 2011) supports a model of long-distance sediment transport across a North African peneplain from basement terranes exposed somewhere to the south (in modern-day coordinates), and is consistent with deposition of the uniform and mineralogically mature Armorican Quartzite along the north Gondwana margin.

Available North African detrital zircon age data are divisible, by basement geology and geographic sampling location, into four main groups. These are, from east to west, (1) the Arabian-Nubian Shield of the Red Sea region, (2) the Saharan metacraton of Libya, (3) the Tuareg Shield of Algeria, and (4) the Anti-Atlas of Morocco. Each of the four distinct age populations present within the Armorican Quartzite are observed within peri-contemporaneous clastic sedimentary rocks preserved within the north-central and northeast African realms of the Saharan metacraton and Arabian-Nubian Shield. Sampled Ordovician units from the Saharan metacraton are the Cambrian Hasawnah (Altumi et al., 2013; Meinhold et al., 2011), Middle Ordovician Hawaz (Meinhold et al., 2011), and Upper Ordovician Mamuyinat (Morton et al., 2012) formations of the Murzuq and Kufra basins. Units sampled in and around the Arabian-Nubian Shield are the Cambro-Ordovician Tabuk Group in Saudi Arabia (Garzanti et al., 2013), the Ordovician Enticho sandstone of northwestern Ethiopia (Avigad et al., 2007), Cambrian sandstones from the Elat region of southern Israel (Avigad et al., 2003; Kolodner et al., 2006), and stratigraphically correlatable Cambro-Ordovician sandstones from the Aqaba region of southern Jordan (Kolodner et al., 2006). With the exception of the Cambrian Hasawnah Formation whose detrital zircons are dominantly Neoproterozoic, each of these units exhibits (1) Neoproterozoic (ca. 500–850 Ma), (2) Stenian–Tonian (ca. 0.9–1.1 Ga), (3) Paleoproterozoic (ca. 1.8–2.15 Ga), and (4) Archean (2.5–2.7 Ga) age populations in magnitudes similar to those observed in the Armorican Quartzite. In the Cambro-Ordovician Aijer Fur, Middle Ordovician d'In Azaoua, and Upper Ordovician Tamadjut formations of the Tuareg Shield to the east, Mesoproterozoic and Archean populations are virtually absent, replaced by stronger Neoproterozoic and older Paleoproterozoic (2.0–2.2 Ga) populations (Linnemann et al., 2011). In the Anti-Atlas, the age spectra within the Lower Cambrian Serie de Base are similar to those in the Tuareg. However, a small Stenian–Tonian population is evident by the Middle Cambrian within the quartz-rich sandstones of the Grés de Tabanit and Schistes á Paradoxies (Avigad et al., 2012). Detrital age data from Ordovician clastic rocks of the Anti-Atlas are unavailable for comparison.

Two-sample K-S tests were run between individual sample sites from the Armorican Quartzite of the CCIM and data sets amalgamated from

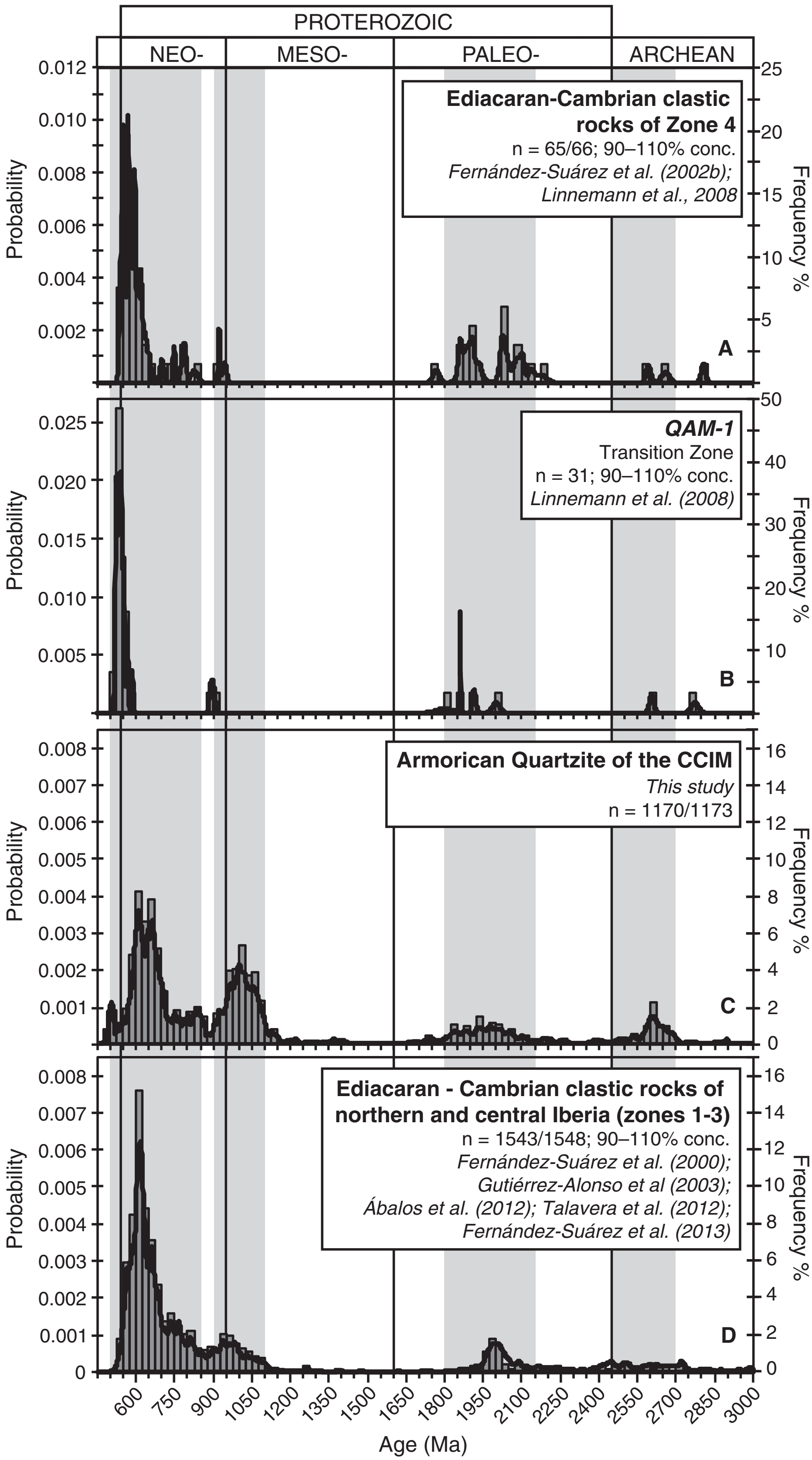


**Figure 6. Sample size–normalized histogram and probability density plots comparing U-Pb detrital zircon ages for (A) Ediacaran–Cambrian clastic rocks of zone 4, (B) sample QAM-1 of the (zone 3–4) transition zone, (C) the Armorican Quartzite of this study, and (D) Ediacaran and Cambrian clastic rocks from zones 1–3. Displayed preferred ages are selected on the criteria established in each original publication; originally published data with greater than 10% discordance are excluded. n—number of grains displayed/number of concordant analyses; concordant analyses excluded for graphical clarity are single grains >3.0 Ga. Note that the *y*-axis scale is exaggerated in A and B in order to accommodate significant Neoproterozoic peaks.**

sample sites of the best age equivalence (ideally Early Ordovician) from each North African region (both independently and then partnered with each neighbor). From the test results, we can confirm the affinities deduced by first-order visual comparison and examine the degree to which the length-parallel trends of the CCIM are mirrored within North Africa (Table 4). A pattern is immediately evident, with Armorican Quartzite sites of the northern and central CCIM showing the greatest degree of similarity with the Saharan metacraton and Arabian-Nubian Shield, and with southerly sites (LAZ-26, LAZ-05, and PNC-4) showing similarities with the Anti-Atlas and Tuareg Shield. However, as the along-strike distance from the northerly WALZ-01 to the southerly PNC-4 is less than half the length of the North African Gondwana margin (with the Red Sea closed), the apparent correlations cannot be simultaneously supported.

The provenance comparisons for which the K-S tests were conducted are further examined by visual comparison of kernel function probability distributions. Each individual and partnered North African data set is plotted against the full data set for the Armorican Quartzite, and against a small grouping (2–3 sites) of those Armorican Quartzite sites assumed (based in part on the K-S test results) to be of the nearest along-strike proximity (Fig. 7). Data sets from northwestern Africa are also compared with a combined data set for southern Iberia, which includes transition zone sample QAM-1 (Linnemann et al., 2008) and the available ages from Ediacaran–Cambrian clastic rocks of zone 4 (Fernández-Suárez et al., 1999; Linnemann et al., 2008). The kernel functions reveal strong correlations between northern sites (WALZ-01,

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WALZ-02, and Barrios) and the Arabian-Nubian Shield (Fig. 7H), between north-central sites (CZ-02, GCZ-03, and GCZ-06) and the combined Arabian-Nubian Shield and Saharan metacraton data set (Fig. 7I), and between central sites (SCS-05 and IBR-02) and the Saharan metacraton (Fig. 7J). The K-S tests and kernel function comparisons give strong and consistent evidence that the northern 650 km of the studied 1500 km segment of the CCIM formed a portion of the early Paleozoic Gondwana passive margin which ran the length between the Saharan metacraton and Arabian-Nubian Shield. Though the K-S tests do not suggest correlation between southern sites (LAZ-05, LAZ-26, PNC-4) and the Saharan metacraton, it is implied that the remaining 850 km of the CCIM continued along its northern limit, reaching just short of the Tuareg Shield to the west. Kernel function comparisons support this implication; aside from the magnitude and location of respective Paleoproterozoic peaks, the age spectra of the southern sites and the combined Saharan metacraton–Tuareg Shield data set are highly similar (Fig. 7K).

The kernel function for the southern sites does not fit well with that of the independent Tuareg Shield data set (Fig. 7L), in contrast with the positive results from the K-S statistical comparison for these sites. Despite diminishing in frequency southward along strike, Mesoproterozoic zircons remain a strong component within the age spectra of the southern CCIM. The Tuareg Shield lacks a Mesoproterozoic population. In addition, a strong Paleoproterozoic (2.1 Ga) peak in the Tuareg spectra is absent within the southern sites. With a strong Neoproterozoic peak and an absence of Mesoproterozoic zircon, the detrital age spectra of the Tuareg Shield is much more similar to those of sample QAM-1 and the Ediacaran–Cambrian clastic rocks of zone 4 (Fig. 7L). Though the comparison between the southern sites and the combined Tuareg Shield–Anti-Atlas data set is also relatively weak (Fig. 7M), the southern sites compare well with the independent Anti-Atlas data (Fig. 7N). However, given the strength of correlation between the northern to central CCIM and more easterly African realms, a West African provenance for the southern sites implies that parts of the margin separated by a comparable along-strike distance during the Early Ordovician were juxtaposed during the Variscan orogeny and are now separated by an as yet unrecognized tectonic boundary. The age spectra within southerly sites LAZ-26, LAZ-05, and PNC-4 are best described as Saharan metacraton–type signatures perturbed by an increased input of the strong Neoproterozoic component identified within the Tuareg Shield.

We propose that the 2300-km-long Cantabrian–Central Iberian portion of the Gondwana margin was situated in an Early Paleozoic Central to East African position stretching east-west along the northern limits of the then low-lying Saharan metacraton and Arabian-Nubian Shield (Fig. 8). Of all the North African data sets, the age spectra of the Tuareg Shield and the combined Tuareg Shield–Anti-Atlas data set most closely resemble those of sample QAM-1 and the Ediacaran–Cambrian clastic rocks of zone 4, though Paleoproterozoic and Archean ages do not correlate strongly (Figs. 7L, 7M). This suggests that the southernmost regions of Iberia, heretofore excluded from palinspastic restora-

TABLE 4. COMPARISON OF DETRITAL ZIRCON AGE SPECTRA FROM THE ARMORICAN QUARTZITE OF IBERIA WITH DETRITAL ZIRCON AGE SPECTRA FROM NORTH AFRICAN REALMS USING THE K-S STATISTICAL TEST WITH ERRORS

At the 0.05 significance level the studied populations have:

P < 0.001 (a statistically significant difference) — 0.05 > P > 0.001 (no statistically significant difference) — P > 0.05 (a statistically significant similarity)

W → E; N ↓ S

| | ***AA*** *<br>n = 212<br>*Middle Cambrian* | ***AA + TS***<br>n = 553/555 | ***TS***†<br>n = 341/343<br>*Upper Cambrian(?)–Middle Ordovician* | ***TS + SMC***<br>n = 575/579 | ***SMC***§<br>n = 234/236<br>*Middle Ordovician* | ***SMC + ANS***<br>n = 428/432 | ***ANS***#<br>n = 196/198<br>*Lower–Middle Ordovician* |
|---|---|---|---|---|---|---|---|
| **WALZ-01**<br>n = 138/139 | P < 0.001<br>D = 0.339 | P < 0.001<br>D = 0.361 | P < 0.001<br>D = 0.380 | P < 0.001<br>D = 0.250 | P = 0.348<br>D = 0.100 | P = 0.090<br>D = 0.122 | P < 0.001<br>D = 0.251 |
| ***Barrios*****<br>n = 35/36 | P = 0.022<br>D = 0.270 | P = 0.004<br>D = 0.304 | P = 0.002<br>D = 0.326 | P = 0.170<br>D = 0.191 | P = 0.598<br>D = 0.137 | P = 0.460<br>D = 0.148 | P = 0.344<br>D = 0.170 |
| **WALZ-02**<br>n = 127/129 | P = 0.011<br>D = 0.181 | P < 0.001<br>D = 0.196 | P < 0.001<br>D = 0.214 | P = 0.143<br>D = 0.113 | P = 0.015<br>D = 0.172 | P = 0.251<br>D = 0.103 | P = 0.416<br>D = 0.101 |
| **CZ-02**<br>n =120/121 | P < 0.001<br>D = 0.323 | P < 0.001<br>D = 0.346 | P < 0.001<br>D = 0.360 | P < 0.001<br>D = 0.226 | P = 0.128<br>D = 0.131 | P = 0.371<br>D = 0.094 | P = 0.001<br>D = 0.226 |
| **GCZ-06**<br>n = 118/121 | P < 0.001<br>D = 0.308 | P < 0.001<br>D = 0.317 | P < 0.001<br>D = 0.339 | P < 0.001<br>D = 0.218 | P = 0.041<br>D = 0.156 | P = 0.494<br>D = 0.086 | P = 0.014<br>D = 0.182 |
| **GCZ-03**<br>n = 124/124 | P = 0.091<br>D = 0.141 | P = 0.053<br>D = 0.134 | P = 0.002<br>D = 0.196 | P = 0.008<br>D = 0.165 | P = 0.002<br>D = 0.205 | P = 0.009<br>D = 0.167 | P = 0.094<br>D = 0.142 |
| **IBR-02**<br>n = 122/125 | P < 0.001<br>D = 0.307 | P < 0.001<br>D = 0.302 | P < 0.001<br>D = 0.299 | P = 0.006<br>D = 0.168 | P = 0.082<br>D = 0.140 | P = 0.707<br>D = 0.071 | P = 0.008<br>D = 0.191 |
| **SCS-05**<br>n = 139/140 | P < 0.001<br>D = 0.364 | P < 0.001<br>D = 0.366 | P < 0.001<br>D = 0.380 | P < 0.001<br>D = 0.246 | P = 0.693<br>D = 0.076 | P = 0.091<br>D = 0.121 | P < 0.001<br>D = 0.251 |
| **LAZ-26**<br>n = 136/140 | P = 0.286<br>D = 0.107 | P = 0.140<br>D = 0.109 | P = 0.019<br>D = 0.153 | P = 0.005<br>D = 0.162 | P < 0.001<br>D = 0.255 | P < 0.001<br>D = 0.245 | P < 0.001<br>D = 0.233 |
| **LAZ-05**<br>n = 127/134 | P = 0.001<br>D = 0.220 | P = 0.024<br>D = 0.147 | P = 0.002<br>D = 0.190 | P < 0.001<br>D = 0.227 | P < 0.001<br>D = 0.395 | P < 0.001<br>D = 0.357 | P < 0.001<br>D = 0.340 |
| ***PNC-4***††<br>n = 49/50 | P = 0.044<br>D = 0.219 | P = 0.198<br>D = 0.160 | P = 0.066<br>D = 0.199 | P = 0.006<br>D = 0.253 | P < 0.001<br>D = 0.436 | P < 0.001<br>D = 0.335 | P = 0.002<br>D = 0.292 |

*Note:* K-S—Kolmogorov-Smirnov. Ages <500 Ma excluded from analyses, error incorporated.
*Anti-Atlas of Morocco (Avigad et al., 2012).
†Tuareg Shield of Libya (Linnemann et al., 2011).
§Saharan metacraton (Meinhold et al., 2011; Morton et al., 2012).
#Arabian-Nubian Shield (Avigad et al., 2007; Garzanti et al., 2013; Kolodner et al., 2006).
**Fernàndez-Suàrez et al. (2002a).
††Pereira et al. (2012).

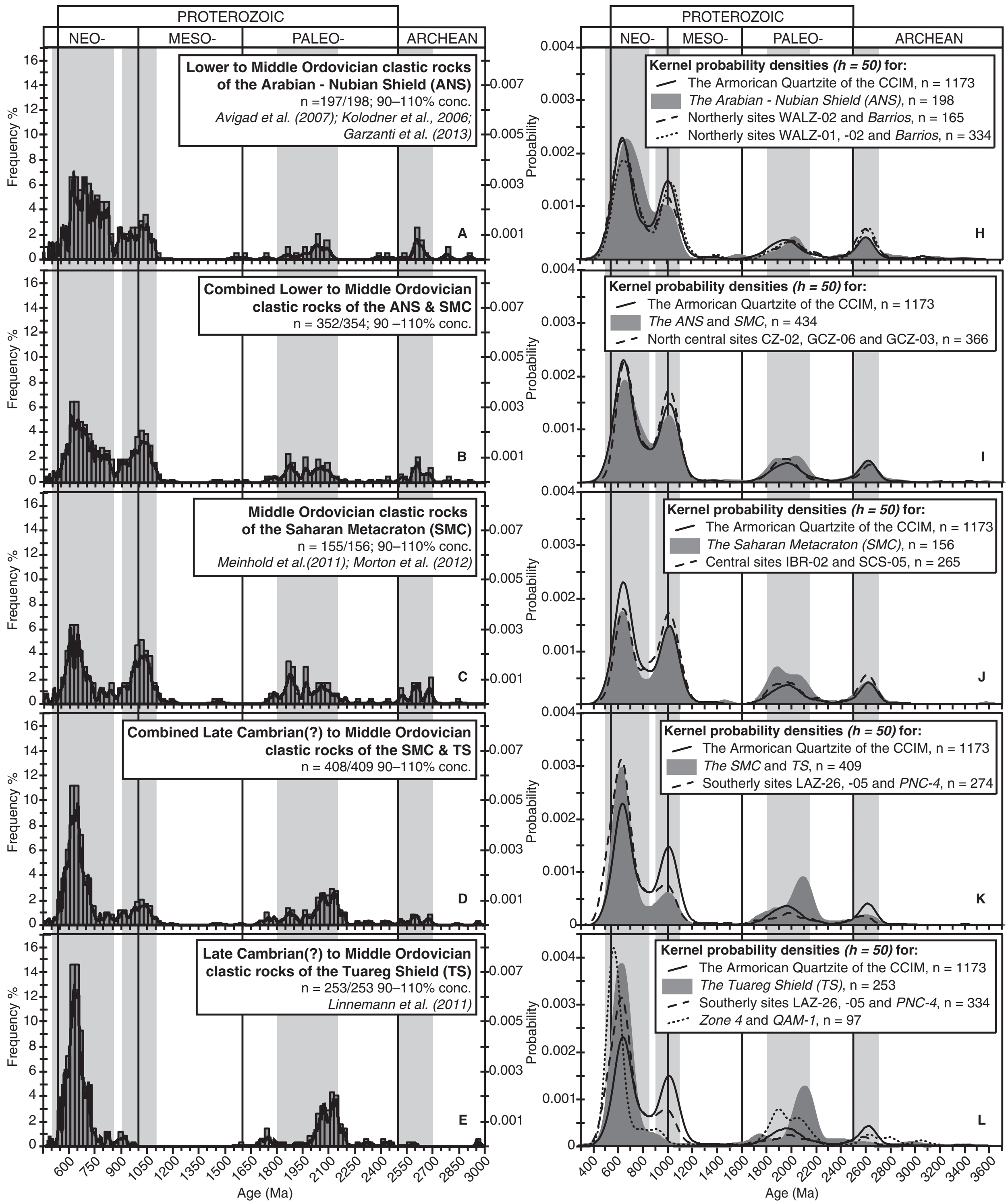


**Figure 7 (*on this and following page*). Sample size–normalized histograms of U-Pb detrital zircons ages for lower Paleozoic clastics of North African realms (A–G) and kernel probability density plots comparing those data with the data set from Armorican Quartzite of this study (CCIM—Cantabrian–Central Iberian margin). (H) Lower to Middle Ordovician clastic rocks of the Arabian-Nubian Shield versus northern sites (WALZ-01, WALZ-02, and Barrios). (I) Combined Lower to Middle Ordovician clastic rocks of the Arabian-Nubian Shield and the Saharan metacraton versus north-central sites (CZ-02, GCZ-06, and GCZ-03). (J) Middle Ordovician clastic rocks of the Saharan metacraton versus central sites (IBR-02 and SCS-05). (K) Combined Late Cambrian(?) to Middle Ordovician clastic rocks of the Saharan metacraton and Tuareg Shield versus southerly sites (LAZ-26, LAZ-05, and PNC-4). (L) Late Cambrian(?) to Middle Ordovician clastic rocks of the Tuareg Shield versus southerly sites and a combined southern Iberian data set including transition zone sample QAM-1 and available ages from Ediacaran–Cambrian clastic rocks of zone 4.**

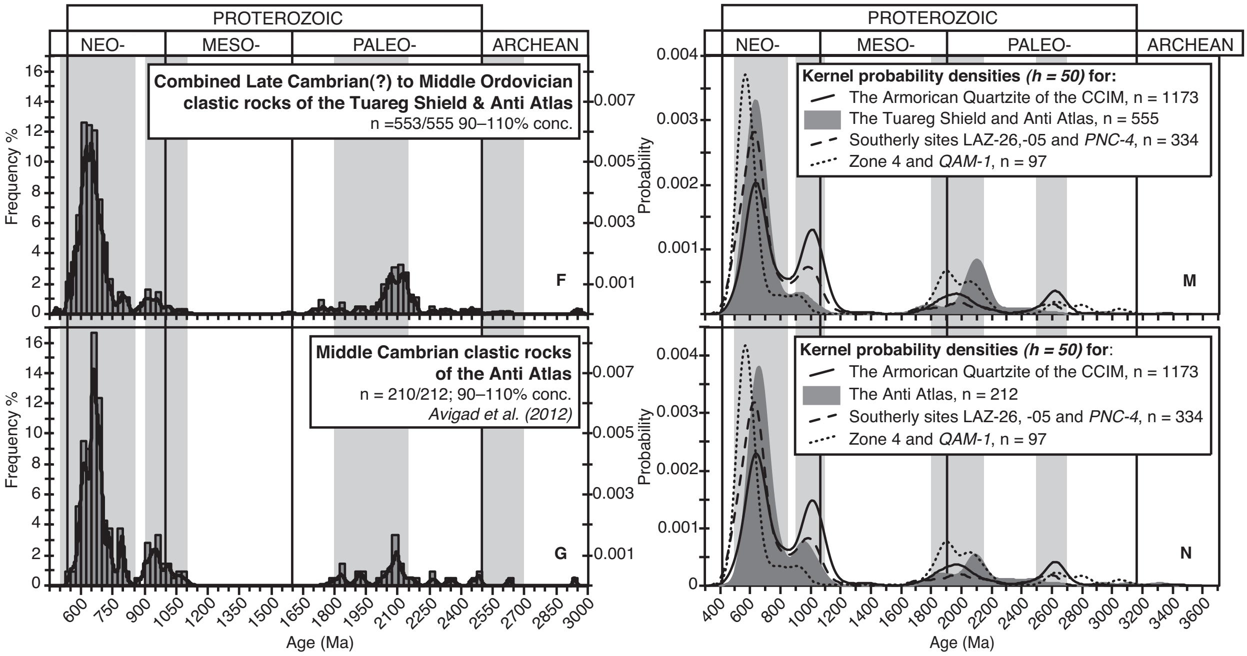


**Figure 7 (*continued*). (M) Combined Late Cambrian(?) to Middle Ordovician clastic rocks of the Tuareg Shield and Anti-Atlas versus southern sites and the combined southern Iberian data set. (N) Middle Cambrian clastic rocks of the Anti-Atlas versus southern sites and the combined southern Iberian data set. Displayed preferred ages are selected on the criteria established in each original publication; originally published data with greater than 10% discordance and post-depositional (secondary growth rim) age data are excluded.**

tions of the CCIM, may represent its westerly continuation. The reappearance of a Stenian–Tonian population in the Middle Cambrian clastic rocks of the Anti-Atlas argues against a common provenance with zone 4, suggesting that no part of autochthonous Iberia originated directly adjacent to the West African craton.

A range of factors hinder the precision with which clastic sedimentary rocks can, through detrital zircon geochronology, be matched with their basement source terrane or terranes (e.g., Cawood et al., 2003; Lawrence et al., 2011). The strength with which the length-parallel trends of the CCIM systematically correlate with east-west variability in North African clastic rocks, despite a lack of correlation with the known age range of North African basement terranes, demonstrates the (1) precision with which paleogeographic affinities can be drawn through comparison of detrital zircon age range in pericontemporaneous clastic rocks, (2) dangers of making paleogeographic assumptions based on comparison of clastic sequence and potential basement source(s), and, (3) importance of conducting detrital zircon provenance studies at appropriate geographic scale (see Sircombe et al., 2001).

Previous interpretations of Iberia as having originated in a Central to East African realm during the Ordovician have been supported by paleontological data (Gutiérrez-Marco et al., 2002, and references therein), detrital zircons studies of Ediacaran–lower Paleozoic rocks in northwestern Iberia (Díez Fernández et al., 2010, 2012, 2013; Fernández-Suárez et al., 2013), and isotopic and inherited zircon studies of Central Iberian Cambro-Ordovician magmatic rocks (Bea et al., 2010). Bea et al. (2010) observed that the age range and geochemical characteristics of xenocrystic zircon entrained in Cambro-Ordovician granitoids of zone 3 are consistent with derivation of these intrusions from melting of crust similar to that of the Egyptian Western Desert, a sub-region of the northwestern Saharan metacraton whose age is constrained by whole-rock Nd model ages. The observation suggests that zone 3 was "pinned" to the Western Desert, but requires further examination in the context of the Central Iberian orocline. As the 62 samples from three different domains (Ollo de Sapo, Schistose Greywacke, and Urra) considered by Bea et al. (2010) span a length of roughly 1000 km along the restored CCIM, the resolved paleogeographic constraints are of no greater precision than those obtained by the detrital zircon provenance analysis presented herein. Ranges of the species of west Algerian– to Saudi Arabian–type fauna within the Lower Ordovician sequences of zones 1–3 (Gutiérrez-Marco et al., 2002, and references therein) do not exhibit dependence on location along strike. Paleontological correlations can therefore offer no precise constraints on the location of the CCIM along the north Gondwana margin. However, continuity of faunal assemblages along the margin further supports a latitude-parallel (east-west) orientation during the Early Ordovician.

## Pre-Ordovician Paleogeography

Despite the interpreted Neoproterozoic to early Paleozoic evolution of the north Gondwana margin, where long-lived subduction forming the Cadomian-Avalonian arc was superseded by (1) its Cambro-Ordovician departure, (2) the opening of the Rheic Ocean, and (3) the development of a passive margin, each defining age population identified within the Armorican Quartzite is characteristic within nearly every studied sample from the Ediacaran and Cambrian clastic sequences that underlie it in northern and central Iberia (zones 1–3) (Ábalos et al., 2012; Fernández-Suárez et al., 2013; Gutiérrez-Alonso et al., 2003; Talavera et al., 2012). The one exception is sample OD-1 from the Cambrian Candána-Herrería Sandstones of zone 1 (Fernández-Suárez et al., 2013), for which an anomalous absence of Stenian–Tonian zircons and accentuated Paleoproterozoic and Archean populations can only be explained as reflecting a change in detrital input into a comparatively local depositional basin. The Armorican Quartzite is, by comparison with the detrital zircon age spectra typical for most Ediacaran–Cambrian clastic rocks in zones 1–3, characterized by a weak-

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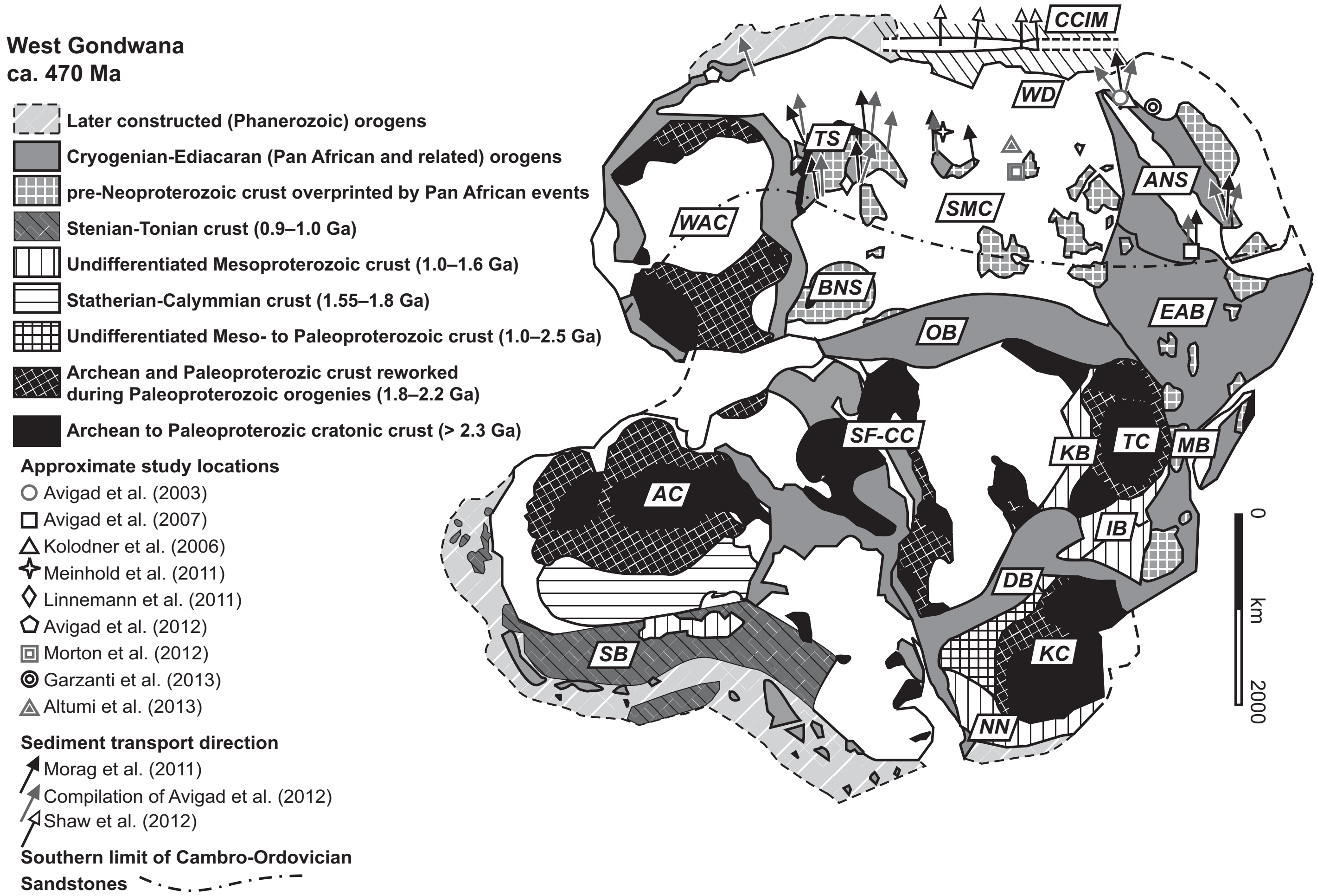


**Figure 8. Ca. 470 Ma reconstruction of West Gondwana showing the Cantabrian–Central Iberian passive margin (CCIM) in the proposed paleogeographic location adjacent to the Saharan metacraton (SMC) and Arabian-Nubian Shield (ANS); relative locations of other peri-Gondwanan Variscan terranes are not considered. North African detrital zircon study location sites are, based on sample age and geographic location, those used for statistical and detailed visual comparison (black), and those excluded from statistical and detailed visual comparison (gray). Modified from the compilation of Linnemann et al. (2011). North African sedimentary data after Morag et al. (2011). Geology of Madagascar after Kröner (2001). AC—Amazonian craton; BNS—Benin-Nigeria Shield; DB—Damara belt; EAB—East African belt; KB—Kibaran belt; KC—Kaapvaal craton; IB—Irumide belt; MB—Mozambique belt; NN—Namaqua-Natal belt; OB—Oubanguide belt; SB—Sunsás belt; SF-CC—São Francisco–Congo craton; TC—Tanzania craton; TS—Tuareg Shield; WAC—West African craton; WD—Western Desert.**

ened Neoproterozoic signature, a more robust Stenian–Tonian signature, and definable Paleoproterozoic and Archean peaks (Fig. 9). The occurrence of Stenian–Tonian zircons in the Ediacaran sequences, which predate passive margin development and presumably the low-relief delivery pathway of such material from southerly sources, cannot be directly explained.

When Stenian–Tonian zircons were first identified in Ediacaran sequences of northern and central Iberia (Fernández-Suárez et al., 2000, 2002b; Gutiérrez-Alonso et al., 2003) the Amazonian craton contained the only known source within north Gondwana, leading to suggestion that these strata originated in a peri-Amazonian realm. But as the stratigraphic ties between the Armorican Quartzite and North African Gondwana were well understood, Fernández-Suárez et al. (2002a, 2002b) and Gutiérrez-Alonso et al. (2003) interpreted the Gondwanan margin of zones 1–3 to have been translated at least 4000 km eastward from an Amazonian location in the latest Neoproterozoic along a dextral transcurrent fault system to reach an African position prior to deposition of the Armorican Quartzite. Stenian–Tonian zircons known within the Barrios sample of zone 1 were attributed to recycling of 0.9–1.0 Ga material from underlying sedimentary sequences in a West African depositional realm (Fernández-Suárez et al., 2002a). The maturity of the Armorican Quartzite, however, implies long-distance transport and argues against recycling from immediately underlying strata as an explanation for the Stenian–Tonian zircons contained within it. As we have also now identified the depositional realm of the Armorican Quartzite as Central to East African, the required translation distance (from an Amazonian to a Central African realm) increases significantly, to an excess of 5000 km. An assumed 50-million-year transit time (between 540 and 490 Ma) would require relative plate motions in excess of 10 cm $yr^{-1}$. Such sustained and rapid translation along a strike-slip fault system is unlikely; there is no modern analogue strike-slip fault characterized by such high rates of relative translation. The likelihood of a Neoproterozoic peri-Amazonian origin is further countered by

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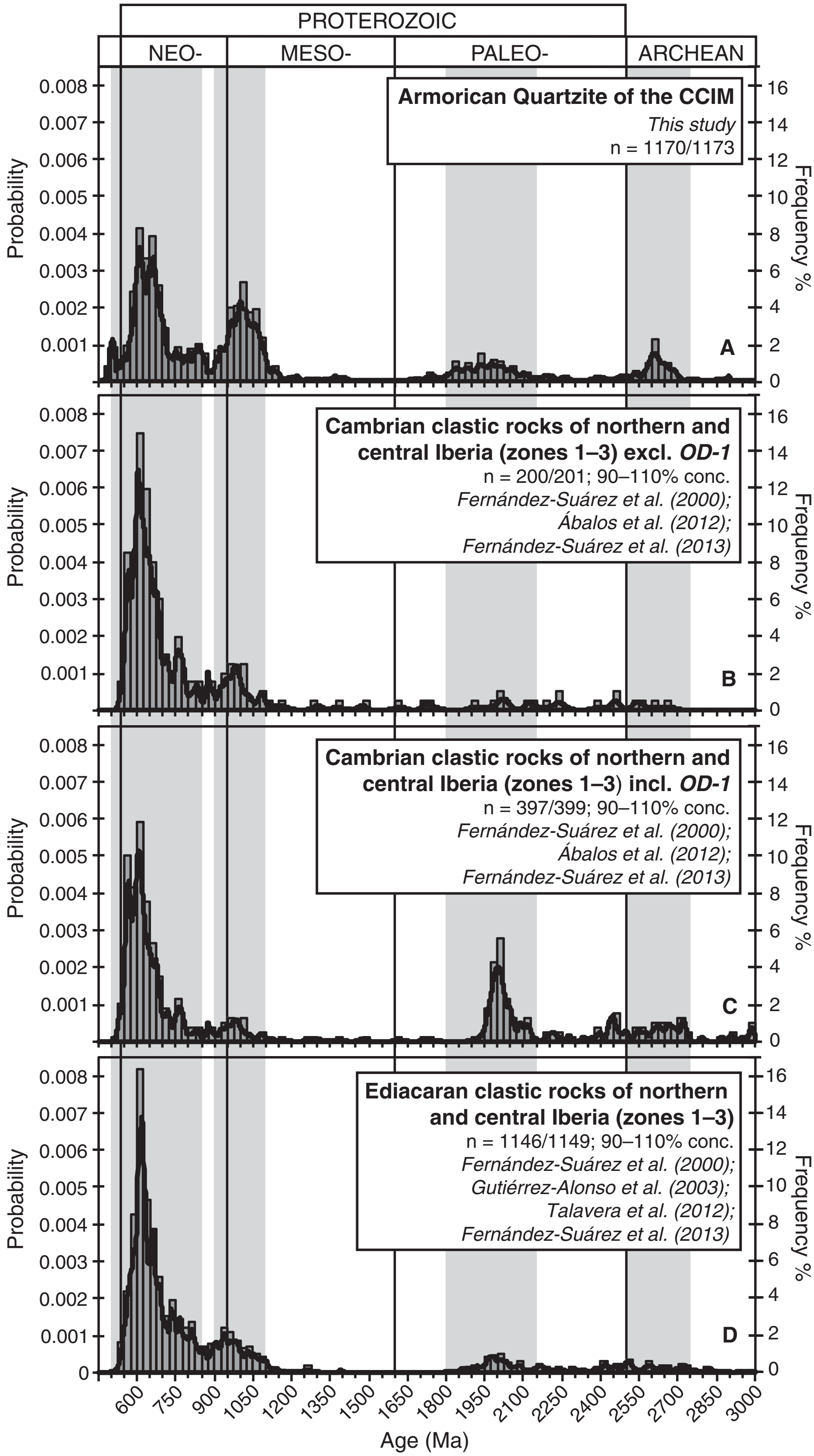


**Figure 9. Sample size–normalized histograms and probability density plots comparing U-Pb detrital zircons ages of (A) the Armorican Quartzite of this study with U-Pb detrital zircon ages of Cambrian clastic rocks from zones 1–3, both (B) excluding and (C) including anomalous sample OD-1 (Fernández-Suárez et al., 2013), and (D) Neoproterozoic clastic rocks from zones 1–3 (CCIM—Cantabrian–Central Iberian margin). Displayed preferred ages are selected on the criteria established in each original publication; originally published data with greater than 10% discordance are excluded. n—number of grains displayed/number of concordant analyses; concordant analyses excluded for graphical clarity are single grains >3.0 Ga.**

an absence of zircons attributable to Rondonian–San Ignacio (ca. 1.25–1.45 Ga) or Rio Negro–Jurunea (ca. 1.5–1.75 Ga) orogenic belts (Nance and Murphy, 1994; Teixeira et al., 1989), both of which are considered characteristic of clastic sediments of Amazonian provenance (Barr et al., 2003; Friedl et al., 2000; Keppie et al., 1998). Detrital micas from the Cambrian Candána-Herrería Sandstones of zone 1 (same formation and locality as anomalous Zr sample OD-1; Fernández-Suárez et al., 2013) that yield 1.58–1.78 Ga Ar-Ar ages (Gutiérrez-Alonso et al., 2005) have no known source.

There is little evidence suggesting a significant change in the paleogeographic location of Iberia from the Ediacaran through the Early Ordovician. The increasing magnitude of Stenian–Tonian, Paleoproterozoic, and Archean populations observed over this time period may reflect a decrease in the diluting effect of a strong Neoproterozoic signature. This is consistent with the interpreted evolution of regional geodynamic setting from a Neoproterozoic (Cadomian) subduction environment to an early Paleozoic stable (Rheic) passive margin, and with the rapid erosion of local Neoproterozoic basement as indicated by the development, by the Late Cambrian, of a North African peneplain.

### Post-Ordovician Tectonic Implications

Models of Gondwanan paleogeography during the early to middle Paleozoic suggest that the CCIM occupied a portion of the Gondwana passive margin that shifted from an Early Ordovician south-polar position into an east-west–striking, north-facing orientation as Gondwana drifted steadily northward (e.g., Stampfli and

Borel, 2002; Torsvik et al., 2012). The east-west strike of the margin during deposition contrasts with the paleomagnetically constrained north-south strike of these rocks in the Late Carboniferous during Variscan orogenesis. A Central to East African paleogeographic position during the Early Ordovician therefore implies that the CCIM rotated 90° counterclockwise after deposition of the Armorican Quartzite but prior to the termination of the Variscan orogeny. How to accommodate such a rotation is unclear. Though the Paleozoic drift history of Gondwana is not well constrained, current paleomagnetic data do not support significant counterclockwise rotation of Gondwana between the Early Ordovician and the Late Carboniferous (e.g., Tait et al., 2000b; Torsvik et al., 2012). If Gondwana did not rotate during this time period, post-depositional separation of the CCIM from autochthonous Gondwana, an event for which there is no known geologic evidence, would be required.

## CONCLUSIONS

We interpret the CCIM as having originated as a continuous linear portion of the north Gondwana Cambro-Ordovician passive margin. The detrital zircon age spectra of the CCIM is best explained as a product of erosion of source terranes exposed, in modern-day coordinates, to the south of the Saharan metacraton and Arabian-Nubian Shield. A paleogeographic model in which the palinspastically restored CCIM is a component of the Ediacaran–early Paleozoic Central to East African Gondwanan margin extending along the northern limits of the then low-relief Saharan metacraton and Arabian-Nubian Shield satisfies known sedimentary, petrologic, and paleontological constraints. The suggested east-west trend maintained by the CCIM prior to and during deposition of the Armorican Quartzite contrasts with the north-south trend it held immediately prior to buckling of the orogen about a vertical axis of rotation giving rise to the coupled secondary Ibero-Variscan Cantabrian and Central Iberian oroclines. Ninety degrees of counterclockwise rotation are required to bring the CCIM from an Ediacaran–early Paleozoic position as a component of the north-facing Gondwana passive margin to a pre-oroclinal (Late Carboniferous) north-south trend.

The West African signature observed within the Armorican Quartzite of the transition zone implies that (1) the boundary between zone 4 and the Central to East African CCIM is the zone 3–transition zone boundary, and (2) part (if not all) of the Iberian autochthon southward of that boundary represents a more distal western continuation of the CCIM. The manner by which these distinct parts of autochthonous Iberia came to be juxtaposed remains to be determined.

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