Pannotia to Pangaea: Neoproterozoic and Paleozoic Orogenic Cycles in the Circum-Atlantic Region: A celebration of the career of Damian Nance

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Special Publication 503 celebrates the career of R. Damian Nance. It features 27 articles, with more than 110 authors based in 18 different countries. The wide range of topics presented in this volume mirrors the breadth and depth of Damian’s contributions, interests and expertise. Like Damian’s papers, the contributions range from the predominantly conceptual to detailed field work, but all are targeted at understanding important tectonic processes. Their scope not only varies in scale from global to regional to local, but also in the range of approaches required to gain that understanding. Thus, there are contributions on the processes responsible for the formation and breakup of supercontinents, the controversial amalgamation of Pannotia, the generation and destruction of Paleozoic oceans, and the development of the Appalachian–Ouachita–Caledonide–Variscan orogens (Fig. 1). In addition to field work, the approaches to gain that understanding include examining the relationships between stratigraphy and structural geology, precise geochronology, geochemical and isotopic fingerprinting, geodynamic modelling, regional syntheses, palaeogeographic modelling, and plain, old-fashioned arm-waving!

The Pannotia controversy

When Damian with Tom Worsley and Judith Moody proposed the existence of a supercontinent cycle with a series of papers in the 1980s (Nance et al. 1986; Moody et al. 1988), the amalgamation of Gondwana in the Neoproterozoic, as evidenced by the collisional Pan-African orogenic events, was arguably their best defined pre-Pangaeian supercontinent. These early publications examined the potential relationship between tectonic events and biogeochemical cycles, as exemplified in the late Neoproterozoic–Early Cambrian by the amalgamation of Gondwana spanning a time interval characterized by dramatic climate swings, profound changes in the chemistry of the oceans and atmosphere, and the evolution of multicellular animals (see Hoffman 1991; Hoffman et al. 1998; Narbonne 2010; Knoll 2013).

As reconstructions became more refined, several authors proposed that Gondwana was part of a larger entity called Pannotia that included Laurentia, Baltica and possibly Siberia (e.g. Stump 1987; Dalziel 1997). Recent syntheses have contested the status of Pannotia as an Ediacaran supercontinent because of its small size relative to Pangaea (about half) and limited duration (it was probably breaking up in its centre as continents were colliding with its margins). Rodinia, which amalgamated during global-scale c. 1.1–0.9 Ga orogenesis, is arguably the most widely accepted of the pre-Pangaeian supercontinents (McMenamin and McMenamin 1990; Li et al. 2008). Many syntheses claim that the transition from Rodinia to Pangaea represents a single supercontinent cycle (e.g. Li et al. 2019). Resolution of the ‘Pannotia controversy’ is fundamental to understanding the supercontinent cycle. If the transition from Rodinia to Pangaea represents a single supercontinent cycle, then Pangaea probably formed by extroversion, i.e. predominantly subduction of the exterior ocean system that surrounded Rodinia (Li et al. 2019). In contrast, Murphy and Nance (2008) maintain that Pannotia formed by the amalgamation of the ocean exterior to Rodinia (extroversion), but that Pangaea was formed from Pannotia by closure of the interior Iapetus and Rhei oceans (introversion).
In this volume, four papers (Murphy et al., Heron et al., Evans and Kroner et al.) tackle the controversial status of Pannotia as an Ediacaran supercontinent. Murphy et al. (2020) point out that an over-arching question is whether the assembly of the Gondwanan portion of Pannotia influenced global-scale mantle convection patterns (Nance and Murphy 2019; Pastor-Galán et al. 2019). Such patterns, if they existed, must be factored into models for the amalgamation of Pangaea. Deducing the mantle legacy (mantle convection patterns) of Pannotia to achieve a Pannotia configuration to test the hypothesis of a Pannotian supercontinent by combining geological and palaeogeographical constraints from different regions. They reconstruct the Paleozoic kinematics of Laurentia, Gondwana, Siberia and the peri-Gondwanan terranes relative to the East European Craton (including Baltica). Their approach is to ‘back-rotate’ from a Pangaea-A configuration to accommodate the Paleozoic opening of the Iapetus, Rheic and Paleo-Arctic oceans. These back rotations achieve a Pannotia configuration, thus supporting their interpretation of its status as a supercontinent and indicating that the transition from Rodinia to Pangaea represents two complete supercontinent cycles. They also identify two fundamental phases of Iapetus Ocean opening and closure.

**Regional Neoproterozoic tectonics**

The Neoproterozoic Era was characterized by collisonal (Pan-African) orogenic belts as Gondwana amalgamated, and by subduction-related orogenesis along its periphery. In the Pan-African collisional belt of Namibia, Hoffman (2020) describes the stratigraphic and structural record of a lithospheric cusp (or syntaxis). Such cusps (where arcs are joined end-to-end) are features of modern arc systems, associated with the buckling of subducted slabs, but are rarely identified in the geological record. Hoffman describes a potential cusp where the Kaoko belt and the Damara orogen meet at right angles. In the vicinity of the hypothesized cusp, the regional stratigraphy dominated by marine carbonates was uplifted to form a megakarst landscape with associated mass slides and was then

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**Fig. 1.** Palaeocontinental reconstruction (c. 500 Ma; after Domeier 2016) showing the relative locations of the contributions to this volume. Events in many of the papers span a considerable duration of time, or may deviate in time from c. 500 Ma so that the location shown on this map is not necessarily intended to provide a geological context for tectonic events documented in the papers. Papers 1–4 (Murphy et al., Heron et al., Evans and Kroner et al.) are global studies and their locations are not shown. 5, Hoffman; 6, van Staal et al.; 7, Arenas et al.; 8, Lindner et al.; 9, Errami et al.; 10, Andresen; 11, Dalslåen et al.; 12, Slagstad et al.; 13, Walker et al.; 14, McConnel et al.; 15, Archibald and Murphy; 16, Schofield et al.; 17, Dostal et al.; 18, Hildebrand and Whalen; 19, Piper and Pe-Piper; 20, Park and Hinds; 21, Dennis, 22., Juárez-Zúñiga et al.; 23, Álvaro et al.; 24, Sánchez-Martínez et al.; 25, Gutiérrez-Alonso et al.; 26, Palawski et al.; 27, Pereira et al. Abbreviations: FA, Famatina; MX, Mexico; CA, Carolina; WA, West Avalonia; EA, East Avalonia; IB, Iberia; AM, Armorica; CH, Clew Bay-Highland Border; MV, Midland Valley–South Mayo; DW, Dashwoods; LB, Lushes Bight; PI, Eastern Piedmont; CU, Cuyania.
rapidly buried by foredeep syn-orogenic deposits. Abrupt drowning of the carbonate platform and burial by foredeep deposits is interpreted to reflect lithospheric flexure and aborted subduction beneath the promontory of the Congo Craton. The timing of these events suggests that they occurred about 50 myr before terminal Pan-African collision.

As Gondwana amalgamated, subduction zones between the colliding blocks were expelled and arc magmatism became established along much of Gondwana’s periphery producing orogens characterized by a diverse collage of arcs and back-arc basins. For nearly 35 years (e.g. Nance 1986a; Nance et al. 1991, 2002, 2008, 2012), one focus of Damian’s research has been the evolution of the ‘peri-Gondwanan’ terranes that were distributed along the northern margin of Gondwana in the late Neoproterozoic and early Paleozoic. This volume has several contributions from these terranes.

van Staal et al. (2020) propose a model to explain the Neoproterozoic–Early Cambrian evolution of West Avalonia. Oubduction of the c. 760 Burin ophiolite of SE Newfoundland (Krogh et al. 1988; Murphy et al. 2008) onto a continental ribbon before 750 Ma (compare Henderson et al. 2016) was followed by several pulses of island arc magmatism, including the main phase between c. 640 and 565 Ma. Most reconstructions for the peri-Gondwanan terranes during this main phase (including papers in this volume) position them along the northern Gondwanan margin outboard of Amazonia, West Africa and the Saharan metacraton. According to the van Staal et al. model, however, West Avalonia and Ganderia were positioned at this time on opposite sides of a shrinking (Puncoviscana) ocean with oppositely verging subduction zones. In the late Ediacaran, West Avalonia accreted to Amazonia in a position that was outboard of Ganderia but along-strike from East Avalonia. Magmatism was terminated by strike-slip activity that shuffled the peri-Gondwanan terranes along the continental margin prior to the diachronous opening of the Rheic Ocean beginning at c. 500 Ma during which Avalonia and Ganderia separated from the Gondwana (e.g. Nance and Linnemann 2008; van Staal et al. 2012).

The geology of the peri-Gondwanan terranes dominates many of the Variscan massifs of continental Europe. These massifs preserve a complex evolution of arc-related orogenesis in the late Neoproterozoic and early Paleozoic that was overprinted in the late Paleozoic by tectonothermal events associated with the amalgamation of Pangaea. Arenas et al. (2020) maintain that the Neoproterozoic to Devonian evolution of Gondwana’s West African–Iberia margin includes the generation and emplacement of ophiolite sequences at c. 100 myr intervals between 700 and 400 Ma. During much of this time interval, this portion of the northern Gondwanan margin was active and all ophiolites have supra-subduction zone geochemical signatures. The oldest known ophiolite (the c. 697 Ma Bou Azzer ophiolite) occurs in the Anti-Atlas Mountains, and the remainder are exposed in Iberia. Arenas et al. attribute the c. 100 Ma time intervals to cyclic events of mantle upwelling, possibly related to episodic deep mantle convection patterns.

Lindner et al. (2020) present new U–Pb and geochemical data from a region in the eastern Bohemian massif that preserves an unusually protracted Neoproterozoic history. These rocks include orthogneisses which are rare examples of Mesoproterozoic granites, paragneisses which preserve evidence of an early Neoproterozoic platformal sequence, and late Neoproterozoic volcanic-arc granitoids typical of Avalonia. U–Pb age data from orthogneiss and paragneiss yield ages that can be readily correlated with rock units in West Amazonia such as the Rondonia–San Ignácio (1.55–1.3 Ga) and Sunusá (1.3–1.1 Ga) tectonic provinces. Their interpretation supports previous studies that proposed Amazonian affinities (e.g. Friedl et al. 2000; Keppie et al. 2008a, 2012; Nance et al. 2009) as well as models for along-margin terrane transport (Fernández-Suárez et al. 2002; Linnemann et al. 2012; Nance et al. 2012) from Amazonia to positions outboard of the West African craton.

Recently published geochemical and geochronological data have provided new insights into the genetic relationship between the Anti-Atlas of Morocco and the Variscan massifs of continental Europe. Errami et al. (2020) provide new U–Pb detrital and magmatic zircon ages from late Ediacaran stratigraphic successions in the Eastern Saghro massif of the Anti-Atlas Mountains. The detrital age populations can be assigned to Neoproterozoic tectothermal events in peri-Gondwanan terranes and to input from nearby Eburnian (c. 2.1 Ga) basement. Deformation of the Saghro Group reflects closure of a back-arc basin prior to intrusion of 603 Ma granitoids and is attributed to Pan-African transpressive collision that had finished by c. 600 Ma. This sequence was followed by deposition of the M’gouna and Ouarazzate groups in a transtensional regime (Thomas et al. 2002) related to the c. 570 Ma onset of Cadomian subduction.

Caledonides

The breakup of Pannotia from c. 615 Ma onwards occurred as Laurentia, Gondwana and Baltica rifted from each other to form the Iapetus Ocean (Tegner et al. 2019 and references therein). The ocean widened until the Late Cambrian, and then started to close following the initiation of east-dipping subduction zones (present reference frame) close to the margin of Laurentia (Cocks and Torsvik 2006).
Accretion of magmatic arcs to the margin of Laurentia during the Early to Mid-Ordovician was followed by development of a west-dipping subduction system and further closure of Iapetus (Dewey and Ryan 1990). Avalonia rifted from Gondwana in the Early Ordovician and collided with Baltica in the Late Ordovician (Fortey and Cocks 2003). The composite continent then converged obliquely with Laurentia through the Silurian (Soper et al. 1992). The culminating Mid to Late Silurian Scandinavian orogeny formed the Caledonides, exposed in Scandinavia, Greenland, Britain and Ireland.

Andresen (2020) provides a new interpretation of the relatively poorly known Late Ordovician convergence zone between Baltica and Avalonia, based on structural mapping and published detrital zircon studies in the Hardangervidda region of central south Norway. It is argued that a thin-skinned thrust belt developed owing to underthrusting of Baltica beneath Avalonia, and that whereas Cambrian strata were derived from Baltica sources, Middle to Late Ordovician sedimentary rocks have a Gondwanan provenance. Docking of these two continents was not therefore ‘soft’ (Torsvik and Rehnström 2003) but affected a large area of SW Baltica both structurally and sedimentologically.

The Norwegian–Swedish sector of the Caledonides contains a cross-section from the Baltica foreland structurally upwards and westwards into para-autochthonous thrust sheets, lapetan oceanic terranes and continental allochthons thought to have been derived from Laurentia (Stephens and Gee 1985). A common theme in recent publications has been the increased tectonic complexity now recognized within this framework. Dalslåen et al. (2020) document the Early to Middle Ordovician convergence zone between Baltica and Avalonia, based on structural mapping and published detrital zircon studies in the Hardangervidda region of central south Norway. It is argued that a thin-skinned thrust belt developed owing to underthrusting of Baltica beneath Avalonia, and that whereas Cambrian strata were derived from Baltica sources, Middle to Late Ordovician sedimentary rocks have a Gondwanan provenance. Docking of these two continents was not therefore ‘soft’ (Torsvik and Rehnström 2003) but affected a large area of SW Baltica both structurally and sedimentologically.

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Late Silurian, which resulted in SSE-verging folding and thrusting.

**Appalachians–Mexico**

After completion of his PhD, Damian cut his teeth on Appalachian geology with several field campaigns in southern New Brunswick in the 1970s, and in the Cobequid Highlands of mainland Nova Scotia in the 1980s. In the late 1990s he was lured by Duncan Keppie to southern Mexico to work on the Acatlán Complex, which is an infill of Paleozoic rocks with an outcrop area the size of Massachusetts (e.g. Ortega-Gutiérrez et al. 1999). By linking its development to that of the Rheic Ocean, the Paleo-Pacific and the Gulf of Mexico (Nance et al. 2006; Keppie et al. 2008b), his research provided genetic linkages between the Acatlán Complex and Appalachian geology as well as with the assembly and breakup of Pangaea. It is appropriate that this special publication has contributions from each of these regions.

Dostal et al. (2020) present new geochemical data from felsic rocks in the Uppermost Silurian–Lower Devonian Tobique Group in northern New Brunswick, Canada. These rocks are part of a bimodal sequence that oversteps the boundaries between peri-Gondwanan terranes accreted to composite Laurentia as the Iapetus Ocean closed. Previous work (e.g. Dostal et al. 2016) shows that the mafic rocks are continental tholeiites. The felsic rocks have geochemical characteristics typical of post-collisional and extensional A2-type granites (Eby 1992) generated by crustal anatexis. The authors attribute the rapid transition from compressional to extensional magmatism to reflect a slab breakoff event in the aftermath of the accretion of Ganderia to Laurentia.

In recent years, a consensus model for the Upper Ordovician Taconic Orogeny in New England and western New York involves development of a Lower–Middle Ordovician island arc over an eastward-dipping subduction zone, its accretion to Laurentia at c. 470 Ma, and then a subduction polarity flip which produced Upper Ordovician arc magmatism beneath the amalgamated continental margin. However, some features that are expected outcomes of this model (Early Ordovician deformation, foreland basin development and tuffs deposited on the Laurentian carbonate platform) are notably absent (Karabinos et al. 2017). In an attempt to resolve these issues, Hildebrand and Whalen (2020) show that the post-Taconic igneous rocks have compositions typical of a post-collisional slab failure setting, obviating the need for a post-Taconic west-dipping subduction zone. In this model, the Late Ordovician Taconic orogeny is the result of an arc–continent collision above an east-dipping subduction zone followed by slab failure.

In his many years of field work in Maritime Canada, Damian and his students spent a lot of time trying to understand the evolution of the Minas Fault Zone, which defines the boundary between the Avalon and Meguma terranes and is exposed primarily in mainland Nova Scotia and southern New Brunswick. We have two updated syntheses from regions affected by the Minas Fault Zone, the Cobequid Highlands of Nova Scotia and the southern coastal sections of New Brunswick. Piper and Pe-Piper (2020) point out that the Cobequid Highlands lie at the intersection of NE–SW and east–west major intra-continental shear systems. The NE–SW system was probably initiated in the late Neoproterozoic and guided the emplacement of bimodal plutons in the Late Devonian–Early Carboniferous. The east–west Minas Fault Zone formed in the Late Carboniferous as a response to collision between Africa and Laurentia. The ages and changing style of the earlier Late Devonian–Early Carboniferous deformational events are documented by the U–Pb crystallization ages of synkinematic plutons and for the Late Carboniferous–Early Permian events by biostratigraphic studies of syntectonic strata as well as by dated igneous rocks and minerals in faults and veins.

In 1986, Damian proposed that the Late Carboniferous tectonostratigraphic evolution of southern New Brunswick could be explained by the development of a positive flower structure during dextral transpressive motion of the Meguma terrane relative to the Avalon terrane (Nance 1986b). Park and Hinds (2020) present a detailed regional stratigraphic and structural analysis, integrated with recent geochronology, that verifies this overall model. Additionally, they find evidence for three major transpressive flower structures that developed diachronously, as well as for kinematic linkages of these flower structures with regional fault systems. They present an integrated model that explains the origin of these structures from the perspective of a regional dextral strike-slip regime.

Dennis et al. (2020) describe for the first time the origin and setting of the youngest rocks in the Appalachians of wholly Gondwanan origin. They identify sedimentary successions in the Carolina terrane which they assign to both upper-plate and lower-plate asymmetric passive margin fragments that rifted from Gondwana in the Late Cambrian when the Rheic Ocean formed. The upper plate succession consists of 1–2 km thick Middle Cambrian trilobite-bearing mudstones whereas the lower plate succession is dominated by clastic rocks with western Amazonian detritus that overlies Carolinian volcanic arc basement.

The late Paleozoic evolution of southern Mexico is critical to our understanding of late Paleozoic–early Mesozoic palaeogeography along the western margin of Pangaea during its amalgamation. Late
Paleozoic sequences have been variously interpreted to reflect subduction of Rheic Ocean lithosphere prior to Pangaea amalgamation (Ortega-Gutiérrez et al. 2018) or subduction of Proto-Pacific oceanic lithosphere after amalgamation (Keppie et al. 2008b; Nance et al. 2010). Juárez-Zúñiga et al. (2020) provide new petrographic and U–Pb–Hf (zircon) analyses of felsic to intermediate volcanic pebbles in a conglomerate from the Matzitzi Formation, whose provenance constrains this palaeogeography (Centeno-García et al. 2009). The pebbles are attributed to erosion of a Permian arc that was probably itself emplaced over Mesoproterozoic (Oaxaquia) basement along the margins of the Proto-Pacific Ocean.

### Variscides

The Variscan belt in Europe and NW Africa represents the eastern extremity of the broad Ouachita–Alleghanian–Variscan orogenic system that formed by closure of the Rheic Ocean and led to the amalgamation of Pangaea via the progressive collision of north Gondwana with the southern outer margin of Laurussia (Nance et al. 2010). Gondwana–Laurussia collision probably began at c. 400 Ma when a promontory in north Gondwana collided with Laurussia (Matte 1986; Quesada 1991; Kroner and Romer 2013; Arenas et al. 2014; Wu et al. 2020). This severed continuity of the Rheic Ocean and the convergence zone was transformed into a complex Mediterranean-style tectonic environment (Murphy et al. 2016). The collisional suture is discontinuously exposed around a broad curvilinear structure (Ibero-Armorican arc) from SW Iberia, through NW Iberia, SW England and France to the Bohemian Massif (e.g. Martínez Catalán et al. 2007). Evidence of the suture has been reported from the Pontides and the Alborz mountains in Iran, but detailed characterization is obscured by severe overprinting during the Cenozoic Alpine orogeny (e.g. Dokuz et al. 2011). Overprinting also obscures original relationships along the eastern flank of the aforementioned Gondwanan promontory facing the Paleotethys Ocean, with the exception ofCorsica and Sardinia (Avigad et al. 2012). In these two Mediterranean islands, evidence of subduction starting c. 360 Ma ago is provided by high-pressure metamorphic units and dismembered ophiolites, which are also recognized in the Alps despite pervasive Alpine overprinting. Therefore, the Variscan orogeny is not only due to the closure of the Rheic Ocean; at some stage in the Gondwana–Laurussia collision process the Paleotethys was subducted beneath the promontory and eventually beneath Laurussia (Wu et al. 2020).

Variscan pre-collisional stages are investigated in two papers. Sánchez Martínez et al. (2020) present new U–Pb zircon ages (498–492 Ma) from orthogneiss and metagabbro of the Vila de Cruces ophiolite (NW Iberia). They also present data from two different metagabbro samples containing scattered zircon grains with an average age of c. 1150 Ma, interpreted as xenocrysts included in the gabbro during its ascent along the Gondwana margin. The authors conclude that an unexposed Mesoproterozoic basement might have existed in this part of the Gondwanan margin and the protolith of the Vila de Cruces ophiolite formed as a section of oceanic or transitional lithosphere in a back-arc setting. Alvaro et al. (2020) present a palaeogeographic restoration of the southwestern European margin of Gondwana during Cambrian–Ordovician time. The reconstruction relies on the relative positions of Variscan tectonostratigraphic units as indicated by four palaeogeographic proximal-to-distal transects, which permit recognition of: (1) a Furongian (Toledanian or ‘lacaun normandie’) breakup unconformity (Ossa-Morena/North-Armorican and Central Iberian/Central-Armorican belts (2) a Mid–Ordovician (Sardic) unconformity across the Occitan and Pyrenean Domains and SW Sardinia. In support of their model, the authors also report similar palaeogeographic variations in zircon provenance patterns, the occurrence of climatically sensitive subtropical facies, mineral indicators across platform-to-basinal transects, and the migration of peaks in trilobite and cinctan (echinoderm) diversity.

At the core of the broad Ibero-Armorican arc, a tight late Variscan orocline (Cantabrian orocline) has been documented in detail (Weil et al. 2019 and references therein). The Cantabrian zone of the Iberian massif represents the Variscan foreland on the Gondwanan side of the suture. For this area, Gutiérrez-Alonso et al. (2020) present a multidimensional analysis of new and published detrital zircon ages from samples covering the continuous stratigraphic record (Ediacaran–Carboniferous) with the aims of detecting possible changes in the provenance of sediments through time and examining the role of sediment recycling. The analysis allows recognition of a continuous source of sediments from the Ediacaran to the Late Devonian punctuated by a sudden ephemeral change in the Early Cambrian that the authors attribute to local causes during the inception of the Paleozoic passive margin of Gondwana.

Finally, two papers deal with aspects of the geology of the South Portuguese zone (SPZ) of SW Iberia. The SPZ has Laurussian affinity and collided with the southwestern margin of the Gondwana promontory after complete subduction of the relict Rheic Ocean in Late Mississippian time (see Oliveira et al. 2019; Quesada et al. 2019, and references therein). Pasławski et al. (2020) describe the bimodal, predominantly submarine volcanic succession with which the world-famous Iberian Pyrite belt
massive sulfide province is associated. Volcanic rocks are intruded by the Sierra Norte Batholith (Gladney et al. 2014). Based on their field and U–Pb zircon data, the authors propose that the emplacement of the Iberian Pyrite belt igneous rocks was both pre- and syn-collisional, with protracted magmatic activity in both subaerial and subaqueous settings from c. 370 to c. 338 Ma. In their model, magmatism was initiated primarily by lithospheric delamination related to tectonic escape and crustal thinning of the lower plate. Pereira et al. (2020) present new isotopic data from Carboniferous syn-orogenic turbidites in the SPZ. These data are consistent with the progressive denudation of a continental magmatic arc built on the Laurussian margin. The oldest strata (Mértola turbidites) inherited their geochemical and isotopic characteristics from a dissected Middle–Late Devonian continental magmatic arc with an intermediate–felsic composition. The progressive erosion of its plutonic roots and older continental basement rocks is consistent with the increasing contribution of recycled ancient continental crust evident in the younger Mira and Brejeira formations. The pronounced similarity between the Nd $T_{DM}$ model ages and detrital zircon populations of the younger formations suggests that they share a common Laurussian (West Avalonia/Meguma terrane) type source but a contribution from Gondwanan (Ossa–Morena) type sources cannot be ruled out.

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**References**

Arenas, R., Díez Fernández, R., Sánchez Martínez, S., Gerdes, A., Fernández-Suárez, J. and Albert, R. 2014. Two-stage collision: exploring the birth of Pangea in the Variscan terranes. *Gondwana Research*, 25, 756–763, https://doi.org/10.1016/j.gr.2013.08.009

Álvaro, J.J., Casas, J.M. and Quesada, C. 2020. Reconstructing the pre-Variscan puzzle of Cambro–Ordovician basement rocks in the southwestern European margin of Gondwana. *The Geological Society of London, Special Publications*, 503, https://doi.org/10.1144/SPS503-2020-89

Andresen, A. 2020. Lithostratigraphic and structural data from Hardangervidda, S Norway, support extended interaction between Avalonia and Baltica. *The Geological Society of London, Special Publications*, 503, https://doi.org/10.1144/SPS503-2020-79

Archibald, D.B. and Murphy, J.B. 2020. A slab failure origin for the Donegal composite batholith, Ireland as indicated by trace-element geochemistry. *The Geological Society of London, Special Publications*, 503, https://doi.org/10.1144/SPS503-2020-6

Arenas, R. and Sánchez Martínez, S. et al. 2020. 100 myr cycles of oceanic lithosphere generation in peri-Gondwana: Neoproterozoic–Devonian ophiolites from the NW African–Iberian margin of Gondwana and the Variscan Orogen. *The Geological Society of London, Special Publications*, 503, https://doi.org/10.1144/SPS503-2020-3

Allerton, M.P. and Ghani, A.A. 2002. Slab breakoff: a model for Caledonian, Late Granite syn-collisional magmatism in the orthotectonic (metamorphic) zone of Scotland and Donegal, Ireland. *Lithos*, 62, 65–85, https://doi.org/10.1016/S0024-4937(02)00111-1

Avigad, D., Gerdes, A., Morag, N. and Bechstädt, T. 2012. Coupled U–Pb–Hf of detrital zircons of Cambrian sandstones from Morocco and Sardinia: implications for provenance and Precambrian crustal evolution of North Africa. *Gondwana Research*, 21, 690–703, https://doi.org/10.1016/j.gr.2011.06.005

Braid, J.A., Murphy, J.B., Quesada, C., Bickerton, L. and Mortensen, J.K. 2012. Probing the composition of unexposed basement, South Portuguese Zone, Southern Iberia: implications for the connections between the Appalachian and Variscan orogens. *Canadian Journal of Earth Sciences*, 49, 591–613, https://doi.org/10.1139/e11-071

Centeno-García, E., Mendoza-Rosas, C.C. and Silva-Romo, G. 2009. Sedimentología de la Formación Matzitzi (Paleozoico superior) y signifício de sus componentes volcánicos, región de Los Reyes Metzontla–San Luis Atotolitlán, Estado de Puebla, *Revista Mexicana de Ciencias Geológicas*, 26, 18–36, http://www.scielo.org.mx/pdf/rmcg/v26n1/v26n1a3.pdf

Cocks, L.M.R. and Torsvik, T.H. 2006. European geodynamics in a global context from the Vendian to the end of the Palaeozoic. *Geological Society, London, Memoirs*, 32, 83–95, https://doi.org/10.1144/GSL.MEM.2006.032.01.05

Dalsøren, B.H., Gasser, D., Grenne, T., Augland, L.E. and Andresen, A. 2020. Early–Middle Ordovician sedimentation and bimodal volcanism at the margin of Iapetus:
Nance, R.D., Murphy, J.B. and Keppie, J.D. 2002. A Cordilleran model for the evolution of Avalonia. *Tectonophysics*, **352**, 11–31. https://doi.org/10.1016/S0040-1951(02)00187-7

Nance, R.D., Miller, B.V., Keppie, J.D., Murphy, J.B. and Dostal, J., 2006. The Acadian Complex, southern Mexico: record spanning the assembly and breakup of Pangaea. *Geology*, **34**, 867–860. https://doi.org/10.1130/G22642.1

Nance, R.D., Murphy, J.B. et al. 2008. Neoproterozoic–early Palaeozoic tectonostratigraphy and palaeogeography of the peri-Gondwanan terranes: Amazonian v. West African connections. *Geological Society, London, Special Publications*, **297**, 345–383, https://doi.org/10.1144/SP297.17

Nance, R.D., Keppie, J.D., Miller, B.V., Murphy, J.B. and Dostal, J. 2009. Palaeozoic palaeogeography of Mexico: constraints from detrital zircon age data. *Geological Society, London, Special Publications*, **327**, 239–269, https://doi.org/10.1144/SP327.12

Nance, R.D., Gutiérrez-Alonso, G. et al. 2010. Evolution of the Rheic Ocean. *Gondwana Research*, **17**, 194–222, https://doi.org/10.1016/j.gr.2009.08.001

Nance, R.D., Gutiérrez-Alonso, G. et al. 2012. A brief history of the Rheic Ocean. *Geoscience Frontiers*, **3**, 125–135, https://doi.org/10.1016/j.gsf.2011.11.008

Nance, R.D., Neace, E.R., Braid, J.A., Murphy, J.B., Dupuis, N. and Shail, R.K. 2015. Does the Meguma Terrane extend into SW England? *Geoscience Canada*, **42**, 61–76, https://doi.org/10.12789/geocanj.2014.41.056

Narbonne, G.M. 2010. Ocean chemistry and early animals. *Science*, **328**, 53–54, https://doi.org/10.1126/science.1186688

Oliveira, J.T., Quesada, C. et al. 2019. South Portuguese terrane: a continental affinity exotic unit. In: Quesada, C. and Oliveira, J.T. (eds) *The Geology of Iberia: A Geodynamic Approach*. Springer, Cham, 173–206, https://doi.org/10.1007/978-3-030-10519-8_6

Ortega-Gutiérrez, F., Elias-Herrera, M., Reyes-Salas, M., Macias-Romo, C. and López, R. 1999. Late Ordovician–Early Silurian continental collision orogeny in southern Mexico and its bearing on Gondwana–Laurentia connections. *Geology*, **27**, 719–722, https://doi.org/10.1130/0091-7613(1999)027<0719:LESCOB>2.3.CO;2

Ortega-Gutiérrez, F., Elías-Herrera, M., Morán-Zenteno, D.J., Solari, L., Weber, B. and Luna-González, L. 2018. The pre-Mesozoic metamorphic basement of Mexico, 1.5 billion years of crustal evolution. *Earth Science Reviews*, **183**, 2–37, https://doi.org/10.1016/j.earscirev.2018.03.006

Park, A.F. and Hinds, S.J. 2020. Structure and stratigraphy in the Pennsylvaniaan tectonic zone of southern New Brunswick, Canada: the ‘Maritime coastal disturbance’ revisited. *The Geological Society of London, Special Publications*, **503**, https://doi.org/10.1144/SP503-2019-234

Paslawski, L.E., Braid, J.A., Quesada, C. and McFarlane, C.M. 2020. Geochronology of the Iberian Pyrite Belt and the Sierra Norte Batholith: lower plate magmatism during supercontinent amalgamation? *The Geological Society of London, Special Publications*, **503**, https://doi.org/10.1144/SP503-2020-5

Pastor-Galán, D., Nance, R.D., Murphy, J.B. and Spencer, C.J. 2019. Supercontinents: myths, mysteries and milestones. *Geological Society, London, Special Publications*, **470**, 39–64.

Pereira, M.F., Gama, C., da Silva, I.D., Fuenlabrada, J.M., Silva, J.B. and Medina, J. 2020. Isotope geochemistry evidence for Laurussian-type sources of South Portuguese Zone Carboniferous turbidites (Variscan Orogeny). *The Geological Society of London, Special Publications*, **503**, https://doi.org/10.1144/SP503-2019-163

Piper, D.J.W. and Pe-Piper, G. 2020. Evolution of late Palaeozoic shearing in the Cobequid Highlands: constraints on the fragmentation of the Appalachian Orogen in Nova Scotia along intra-continental shear zones. *The Geological Society of London, Special Publications*, **503**, https://doi.org/10.1144/SP503-2019-239

Quesada, C. 1991. Geological constraints on the Palaeozoic tectonic evolution of tectonostratigraphic terranes in the Iberian Massif. *Tectonophysics*, **185**, 225–245, https://doi.org/10.1016/0040-1951(91)90446-Y

Quesada, C., Braid, J.A. et al. 2019. SW Iberia suture zone: oceanic affinity units. In: Quesada, C. and Oliveira, J.T. (eds) *The Geology of Iberia: A Geodynamic Approach*. Springer, Cham, 131–171, https://doi.org/10.1007/978-3-030-10519-8_5

Sánchez Martínez, S., Arenas, R., Albert, R., Gerdes, A. and Fernández-Suárez, J. 2020. Updated geochronology and isotope geochemistry of the Vila de Cruces Ophiolite: a case study of a peri-Gondwanan back-arc ophiolite. *The Geological Society of London, Special Publications*, **503**, https://doi.org/10.1144/SP503-2020-8

Schofield, D.J., Potter, J., Barr, S.M., Horák, J.M., Millar, LL. and Longstaffe, F.J. 2016. Reappraising the Neoproterozoic ‘East Avalonian’ terranes of southern Great Britain. *Gondwana Research*, **35**, 257–271, https://doi.org/10.1016/j.gr.2015.06.001

Schofield, D.J., Leslie, A.G., Wilby, P.R., Dartnall, R., Waldron, J.W.F. and Kendall, R.S. 2020. Tectonic evolution of Anglesey and adjacent mainland North Wales. *The Geological Society of London, Special Publications*, **503**, https://doi.org/10.1144/SP503-2020-9

Slagstad, T., Saalmann, K. et al. 2020. Late Neoproterozoic–Silurian tectonic evolution of the Rødingsfjøll Nappe Complex, orogen-scale correlations and implications for the Scandinavian suture. *The Geological Society of London, Special Publications*, **503**, https://doi.org/10.1144/SP503-2020-10

Soper, N.J., Strachan, R.A., Holdsworth, R.E., Gayler, R.A. and Greiling, R.O. 1992. Sinistral transpression and the Silurian closure of Iapetus. *Journal of the Geological Society, London*, **149**, 871–880, https://doi.org/10.1014/gsigs.149.6.0871

Stephens, M.B. and Gee, D.G. 1985. A plate tectonic model for the evolution of the eugeoclinal terranes in the central Scandinavian Caledonides. In: Gee, D.G. and Sturt, B.A. (eds) *The Caledonide Orogen – Scandinavia and Related Areas*. Wiley, Chichester, 953–978.

Stump, E. 1987. Construction of the Pacific margin of Gondwanaland during the Pannotios cycle. In: McKenzie, G.D. (ed.) *Gondwana Six: Structure, Tectonics and Geophysics*. American Geophysical Union, Monographs, **40**, 77–87.
Tegner, C., Andersen, T.B. et al. 2019. A Mantle Plume Origin for the Scandinavian Dyke Complex: a ‘piercing point’ for 615 Ma plate reconstruction of Baltica? Geochimica, Geophysics, Geosystems, 20, 1075–1094, https://doi.org/10.1029/2018GC007941

Thomas, R.J., Chevallier, L.C. et al. 2002. Precambrian evolution of the Siroua Window, Anti-Atlas Orogen, Morocco. Precambrian Research, 118, 1–57, https://doi.org/10.1016/S0301-9268(02)00075-X

Torsvik, T.H. and Rehnstrøm, E.F. 2003. The Tornquist Sea and Baltica–Avalonia docking. Tectonophysics, 362, 67–82, https://doi.org/10.1016/S0040-1951(02)00631-5

van Staal, C.R., Whalen, J.B., Valverde-Vaquero, P., Zagorevski, A. and Rogers, N. 2009. Pre-Carboniferous, episodic accretion-related, orogenesis along the Laurentian margin of the northern Appalachians. Geological Society, London, Special Publications, 327, 271–316, https://doi.org/10.1144/SP327.13

van Staal, C.R., Barr, S.M. and Murphy, J.B. 2012. Provenance and tectonic evolution of Ganderia: constraints on the evolution of the Iapetus and Rheic oceans. Geology, 40, 987–990, https://doi.org/10.1130/G33302.1

van Staal, C.R., Barr, S.M., McCausland, P.J.A., Thompson, M.D. and White, C.E. 2020. Tonian–Ediacaran tectonomagmatic evolution of West Avalonia and its Ediacaran–Early Cambrian interactions with Ganderia: an example of complex terrane transfer due to arc–arc collision? The Geological Society of London, Special Publications, 503, https://doi.org/10.1144/SP503-2020-23

Whalen, J.W.F., Schofield, D.I., Murphy, J.B. and Thomas, C. 2014. How was the Iapetus Ocean infected by subduction? Geology, 42, 1095–1098, https://doi.org/10.1130/G36194.1

Weil, A., Pastor-Galán, D., Johnston, S.T. and Gutiérrez Alonso, G. 2019. Late/post Variscan orocline formation and widespread magmatism. In: Quesada, C. and Oliveira, J.T. (eds) The Geology of Iberia: A Geodynamic Approach. Springer, Cham, 2, 527–542, https://doi.org/10.1007/978-3-030-10519-8_14

Wu, L., Murphy, J.B. et al. 2020. The amalgamation of Pangea: paleomagnetic and geological observations revisited. Geological Society of America Bulletin, https://doi.org/10.1130/B35633.1
