Provenance and tectonic evolution of Ganderia: Constraints on the evolution of the Iapetus and Rheic oceans

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ABSTRACT

We provide estimates for the width, timing, and rates of opening and closing of the Iapetus and Rheic oceans, the evolution of which profoundly influenced Paleozoic global paleogeography. These estimates are primarily derived from the transfer of Ganderia and Avalonia from Gondwana to Laurentia, which led to closure of the Iapetus Ocean and opening of the Rheic Ocean. Ganderia, a long-lived arc terrane, separated from the paleo-Caribbean margin of Amazonia at 505 Ma with a latitudinal speed of ~9 cm/a northward, initiating the Rheic Ocean as a backarc basin. Ganderia's trailing edge was reduced to ~5 cm/a following opening of a 600–800-km-wide backarc basin within Ganderia at 475 Ma. Opening and closing of the Iapetus Ocean was largely driven by far-field stresses, slab pull in some places and slab rollback in others.

INTRODUCTION

The transfer of terranes from one continental margin to another is an important cause of orogenesis. Here we use a rich multidisciplinary data set to provide estimates for the rates of plate movements in the Paleozoic that resulted in the transfer of terranes from Gondwana to Laurentian as part of the Appalachian-Caledonide orogenic cycle.

The evolution of Ganderia (Fig. 1A), the tectonically most complex peri-Gondwanan terrane incorporated in the northern Appalachians (van Staal et al., 1996, 2009), is crucial to regional syntheses because its arrival at the Laurentian margin led to Late Ordovician closure of the main tract of the Iapetus Ocean in the northern Appalachians, and the Early Silurian accretion of its trailing edge caused the Salinic orogeny (Zagorevski et al., 2008; van Staal et al., 2009). In addition, Ganderia's departure from Gondwana opened the northern arm of the Rheic Ocean. Collectively, available data constrain paleogeography, width, time, and rates of opening and closing of both the Iapetus and Rheic Oceans.

GEOLOGICAL CHARACTERISTICS OF GANDERIA

Ganderia, together with Avalonia, Carolinia, and Meguma (Fig. 1A), are peri-Gondwanan terranes that were along the northern margin of West Gondwana in the late Neoproterozoic (Murphy et al., 2004). Detailed analysis of Ganderia's tectonic evolution and its differences from Avalonia were given in van Staal et al. (1996, 2009) and Hibbard et al. (2007). Ganderia and Carolinia may have been connected since the late Ediacaran (Hibbard et al. 2007). Both became progressively separated from Avalonia during the early Paleozoic diachronous opening of the Rheic Ocean. Subsequent oblique motions moved most of Avalonia inboard of Ganderia and created a narrow intervening oceanic seaway (Fig. 1B), resulting in contrasting histories. Silurian–Devonian subduction of Avalonia beneath Ganderia occurred after Ganderia had accreted to composite Laurentia (van Staal et al., 2009).

The oldest known rocks in Ganderia include the younger than 1.2 Ga marble of the Green Head Group (Barr et al., 2003) and 976 +8/–7 Ma massif-type alkalic anorthosite in southern New Brunswick (Tesfai, 2011). The presence of Mesoproterozoic and older(?) basement beneath Ganderia is also indicated by: (1) zircon inheritance and isotopic tracer studies of Neoproterozoic to Ordovician igneous rocks, (2) the occurrence of Mesoproterozoic (ca. 1.08 Ga) plutonic and gneissic boulders derived from nearby autochthonous basement in Lower Ordovician Ganderian strata of northern New Brunswick (van Staal et al., 1996, and references therein), and (3) dominant 1.2–1.5 Ga and subordinate 0.95–1.2 Ga signatures in detrital zircon populations from quartz-rich Upper Ediacaran–Lower Ordovician arenite (Fyffe et al., 2009) that are widespread in Ganderia and required a large continental source from late Ediacaran to Late Cambrian time.

Ensialic arc magmatism in Ganderia continued intermittently between 640 and 455 Ma. Short (10–15 m.y.) gaps in arc magmatism, representing soft collisional events, occurred during the late Ediacaran and Early Cambrian (when it was attached to Gondwana) and in the Ordovician (when it was an isolated microcontinent en route to Laurentia). Arcs developed include the 515–485 Ma Penobscot arc and the 475–455 Ma Popelogan-Victoria arc (van Staal et al., 2009; Zagorevski et al., 2010).

LINKS BETWEEN GANDERIA AND WESTERN GONDWANA

Several independent lines of evidence suggest that Ganderia was along the roughly north-south–trending paleo-Caribbean margin of Amazonia (Fig. 1C). (1) The Rondonian–San Ignacio (1.5–1.3 Ga) and Sunsas (1.25–1.0 Ga) belts of the Amazonia and the Grenvillian basement inliers in the northwestern Andes (e.g., Cordani et al., 2005) provide matching source terranes for the dominant Mesoproterozoic detrital zircon signatures in Ganderian basement. (2) The autochthonous Cambrian cover of Amazonia in Columbia contains Atlantic realm trilobites (e.g., *Paradoxides*) (Rushton, 1963), which are also prominent in coeval rocks in Ganderia (e.g., White et al., 1994). (3) Truncation of Grenvillian inliers along the northern margin of Gondwana (Chibcha terrane; Ramos, 2009) against the Caribbean coastline of Columbia suggests removal of a crustal fragment. (4) The autochthonous lower Paleozoic cover in Colombia records a Middle Cambrian transgression interpreted to reflect the departure of a large terrane (Ramos, 2009). Ganderia is an appropriate candidate for the departing terrane because it records (1) a rift-drift transition starting with 509–505 Ma bimodal rift-related volcanism, including mid-oceanic ridge basalt, (2) exhumation of lithospheric mantle onto the seafloor on the trailing Gander margin, and (3) deposition of transgressive Middle–Upper Cambrian arenite-black shale strata (White et al., 1994; Schulz et al., 2008). The co-occurrence of upper Mesoproterozoic–lower Neoproterozoic anorthosite bodies in the Chibcha terrane (Cordani et al., 2005) and in Ganderia (Tesfai, 2011) also supports this connection.

EDIACARAN–CAMBRIAN PALEOGEOGRAPHIC RECONSTRUCTIONS OF GANDERIA AND AMAZONIA

The full extent of the Ediacaran–Early Cambrian arc system in Ganderia is unknown, but its present-day strike length is at least 2500 km (Fig. 1A). Furthermore, Chew et al. (2008) and Cardona et al. (2009) presented evidence that an Ediacaran–Early Cambrian active margin also existed at the latitude of northern Peru (Fig. 1C). Escayola et al. (2011) correlated this arc system with the coeval Pampean arc system exposed further south in Argentina, implying that the proto-Andean margin faced an open ocean, and therefore that Amazonia was not attached to Laurentia and Baltica at that time. Both Laurentia and Baltica are generally considered to represent Amazonia's conjugate margins in Rodinia (Loewy et al., 2003), but geological evidence suggests that Iapetus did not open

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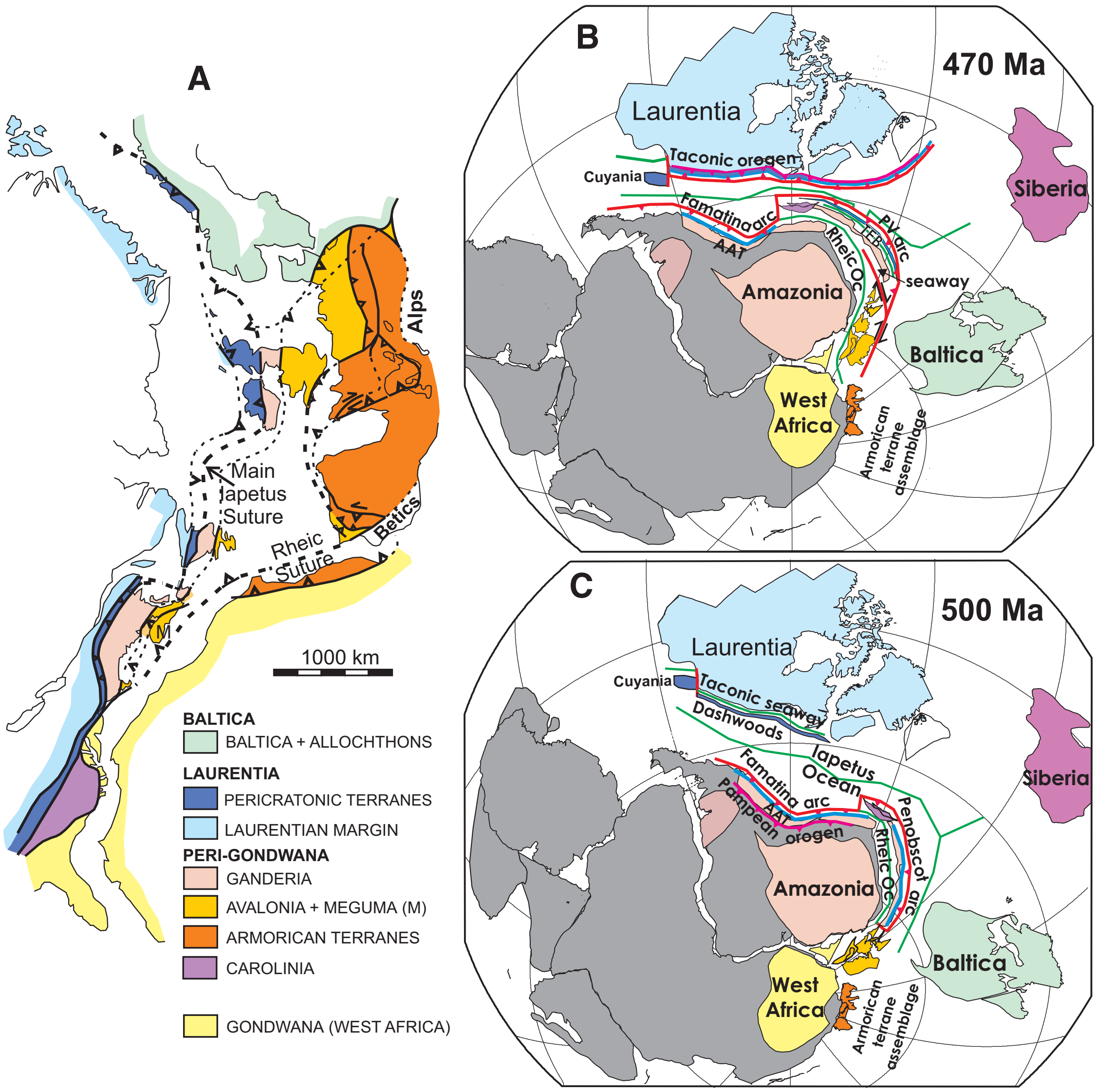

Figure 1. Paleogeography of Laurentia-Gondwana-Baltica and Iapetan tectonic elements. A: Prior to opening of Atlantic Ocean. B: Paleogeography ca. 470 Ma. AAT—Arequipa-Antofalla terrane; PV—Popelogan-Victoria; Oc—Ocean; TEB—Tetagouche-Exploits backarc basin. C: Paleogeography at 500 Ma. B and C are modified from Murphy et al. (2004). Northward subduction beneath Laurentia followed 490–470 Ma closure of Taconic seaway. Green lines in B and C are inferred spreading centers; blue lines are arcs; red and magenta lines are subduction and collision zones, respectively.

along the Laurentian margin until between 570 and 540 Ma (Waldron and van Staal, 2001). Therefore, the departure of Amazonia was not responsible for opening of the Iapetus Ocean south of Laurentia. An alternative solution is that Laurentia rifted from conjugate Amazonia in two stages (Escayola et al., 2011); prior to the 600 Ma opening the relatively narrow Puncoviscana Ocean, and then ca. 570 Ma, when departure of the Arequipa-Antofalla ribbon continent (Fig. 1C) opened the Iapetus Ocean.

INTEGRATION OF PALEOMAGNETIC DATA WITH TECTONIC MODELS OF GANDERIA

The junction of the paleo-Caribbean and paleo-Atlantic margins of greater Amazonia was at a latitude of ~45°S (IT in Fig. 2) by 525 Ma (Trindade et al. 2006) and parts of the paleo-Caribbean margin reached a latitude of ~49°S (BG in Fig. 2; Johnson and van der Voo, 1985) by ca. 505 Ma, using Ganderia (White et al., 1994) as a proxy (Fig. 1C). However, where this part of Ganderia was situated along this margin is unknown. Given this uncertainty, Amazonia appears to have been moving south with a minimum latitudinal velocity of ~2 cm/a between 525 and 500 Ma (Fig. 2). At the end of this interval, Ganderia started to drift away from Amazonia. With a present strike length of at least 2500 km, Ganderia may have extended over 23° of latitude, allowing for the possibility of an along-strike connection with Avalonia (Fig. 1C), which was at ~65°S during the Middle to Late Cambrian (Thompson et al., 2010). Proximity between parts of these two terranes during the Middle to Late Cambrian is consistent with similarities in lithologies and faunas during this period.

The leading edge of Ganderia (Popelogan-Victoria arc) arrived at the composite Laurentian margin by ca. 455 Ma (Zagorevski et al., 2008); this is consistent with paleolatitudes of 18°S–11°S for the 460–455 Ma Munsungun inlier (Maine) basalts (Fig. 2) (Potts et al., 1995) correlated with the Popelogan-Victoria arc (Schultz and Ayuso, 2003). Thus, the leading edge of Ganderia had a latitudinal drift rate of ~9 cm/a between 500 Ma and 455 Ma, identical to the drift rate for Avalonia between 490 and 460 Ma determined by Thompson et al. (2010). The similarity in rates suggests that Ganderia and Avalonia were on the same microplate after they had separated from Gondwana, although they were probably separated by a narrow seaway of trapped oceanic lithosphere at this stage (Fig. 1B; van Staal et al., 2009).

The latitudinal drift rate for Avalonia decreased to 5 cm/a by ca. 460 Ma (Thompson et al., 2010); we consider this rate to be a proxy for the drift rate of the trailing edge of Ganderia (Gander margin) at this time. This rate is consistent with docking of the Gander margin with composite Laurentia by ca. 430 Ma (van Staal et al., 2009) and with paleolatitudes of 19°S–11°S for 430–425 Ma rocks deposited on the Gander margin in Newfoundland and Ireland (MacNiocaill, 2000; Smethurst and McEnroe, 2003). The ~4 cm/a discrepancy in drift rates between the Popelogan-Victoria arc and the trailing Gander margin is attributed to rifting in the inter-

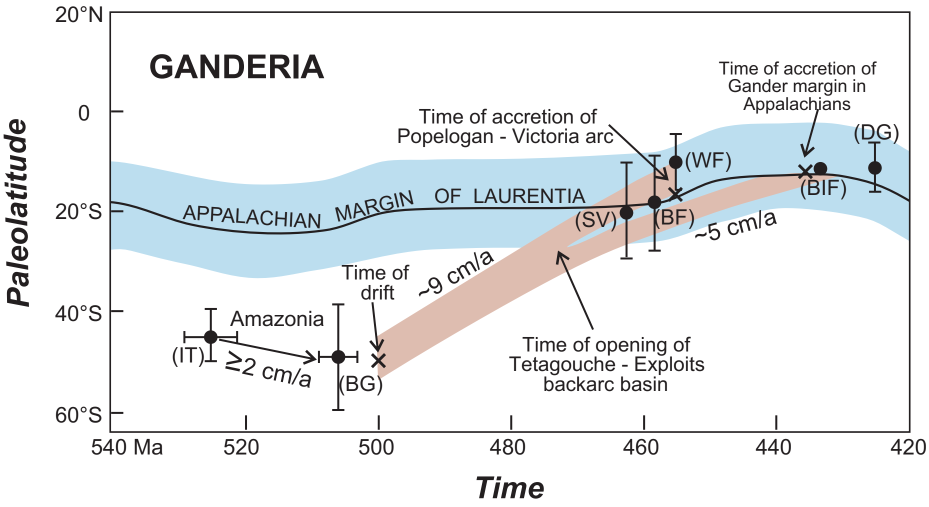

Figure 2. Early Paleozoic paleolatitudes and their errors (references in text) for Amazonia (IT—Itabaiana dikes) and Ganderian rocks in North America (BG—Bourinot Group; BF—Bluffer Pond Formation; BIF—Big Indian Pond Formation; WF—Winterville Formation; SV—Stacyville volcanics) and Ireland (DG—Dunquin Group), compared with predicted paleolatitudes of Appalachian margin of Laurentia (from MacNiocaill, 2000, and references therein). Errors on predicted paleolatitudes are ~10°. Errors of radiometric ages of rocks are indicated. Ages based on fossils have errors ≤5 m.y.

vening Tetagouche-Exploits backarc basin, which initiated ca. 475 Ma and culminated in the formation of oceanic lithosphere and widespread deposition of pelagic chert and shale by ca. 464 Ma (van Staal et al., 2009). The rate discrepancy suggests a half-spreading rate of ~2 cm/a in the Tetagouche-Exploits basin, which produced a 600–800-km-wide oceanic basin prior to the collision of the Popelogan-Victoria arc with Laurentia ca. 455 Ma.

TECTONIC IMPLICATIONS FOR THE PALEOGEOGRAPHIC EVOLUTION OF IAPETUS AND RHEIC OCEANS

Penobscot arc magmatism on Ganderia's leading edge overlapped with Ganderia rift-drift recorded on its trailing edge (Zagorevski et al., 2010), suggesting that the Rheic Ocean initially opened as a backarc basin. Avalonia rifted from Gondwana in the Arenig (ca. 479 Ma) (Murphy et al., 2004), opening the southern arm of the Rheic Ocean, following a long history of transcurrent southward motion along the Amazonian margin toward Africa (e.g., Satkoski et al., 2010). The opening of the Rheic Ocean appears to have been diachronous from paleonorth (505 Ma) to paleosouth (479 Ma; Fig. 1C). Using Ganderia as a proxy, parts of Amazonia had reached a latitude of ~50°S at 500 Ma, while Laurentia had a latitude of ~20°S at that time (Fig. 2), implying that the western segment of Iapetus had achieved a width of ~3300 km or less; this translates to a maximum spreading rate of ~5 cm/a. However, in addition to the uncertainties associated with the sparse paleomagnetic data of Amazonia, this rate is dependent on the exact time of opening of Iapetus, which is uncertain. The Rheic Ocean opened initially at ~9 cm/a, but appears to have decelerated after 470 Ma to ~5 cm/a, likely due to opening of the Tetagouche-Exploits backarc basin (Figs. 1B and 2). Hence rapid rollback of the Iapetus slab beneath the arc on Ganderia's leading edge was likely a critical factor in the opening and early expansion of the Rheic Ocean at the expense of the vanishing Iapetus Ocean. Slab rollback-driven movement with comparable velocities in the Mesozoic–Cenozoic arc terranes in the southwestern Pacific and Tethys Oceans are implied by the syntheses of Lallemand et al. (2005) and Hall (2011). The Rheic Ocean appears to terminate to the paleowest (Fig. 1B), because subduction of the Iapetus Ocean remained south dipping beneath a relatively stable proto-Andean margin, producing the Famatina arc, which extended from Peru to Argentina (Ramos, 2009). This setting allowed accretion of the Laurentia-derived Cuyania terrane (Fig. 1B) during the Ocloyic orogeny (Astini et al., 1995), while Ganderia was moving north toward Laurentia. These relationships suggest the presence of a major transform fault near the northern margin of Peru (Fig. 1B), which connected the Famatina system with a same-polarity subduction zone that accommodated convergence of Ganderia with Laurentia.

Placing Ganderia along the paleo-Caribbean margin of Amazonia prior to the Late Cambrian suggests that it was probably connected with the 18,000-km-long Terra Australis orogenic system (Cawood, 2005), which therefore nearly circumnavigated West Gondwana. In addition, considering that Ganderian arc activity is at least as old as 640 Ma, it is unlikely that Amazonia was connected to Baltica during the late Neoproterozoic.

DISCUSSION

Our interpretations imply that early opening of the Iapetus and Rheic oceans was largely driven by far-field stresses induced by slab pull and slab rollback, respectively. Opening of the Iapetus Ocean between Laurentia and the proto-Andean margin of Gondwana was dynamically linked (slab pull) to closure of the Puncoviscana Ocean, which led to reaccretion of Arequipa-Antofalla to Amazonia during the Pampean (530–525 Ma) orogeny (Escayola et al., 2011). Stepping back of the Pampean subduction zone into the Iapetus Ocean behind accreted Arequipa-Antofalla created the Famatina arc at the latitude of Peru and further south. The correlative Penobscot arc on Ganderia (Fig. 1C) rifted from Amazonia by 505 Ma, which led to opening of the northern arm of the Rheic Ocean as a backarc basin. The Rheic Ocean grew at the expense of a progressively diminishing segment of Iapetus that faced Ganderia, while Laurentia and West Gondwana remained relatively stationary. The available data indicate that Ganderia remained on the upper plate until the Late Ordovician, implying that slab rollback was largely responsible for the rapid transfer of arc ribbons such as Ganderia from Gondwana toward Laurentia. However, our analysis also identifies potential geodynamic problems that remain to be resolved. In the context of a narrowing Iapetus Ocean, the age of the subducting lithosphere would have decreased progressively. A concomitant progressive decrease in the rate of slab rollback would be expected, but this is not clear in the data. In addition, following opening of the Tetagouche-Exploits basin and the accretion of the Popelogan-Victoria arc, the geodynamic forces driving its trailing margin and Avalonia toward Laurentia remain enigmatic. Their movement was driven at least in part by slab pull of the downgoing oceanic slabs of the intervening basins (e.g., Tetagouche-Exploits basin), but probably also by ridge push at the Rheic spreading center.

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REFERENCES CITED

Astini, R.A., Benedetto, J.L., and Vaccari, N.E., 1995, The early Paleozoic evolution of the Argentine Precordillera as a Laurentian rifted, drifted and collided terrane: A geodynamic model: Geological Society of America Bulletin, v. 107, p. 253–273, doi:10.1130/0016-7606(1995)107<0253:TEPEOT>2.3.CO;2.

Barr, S.M., Davis, D.W., Kamo, S., and White, C.E., 2003, Significance of U-Pb detrital zircon ages in quartzite from peri-Gondwanan terranes, New Brunswick and Nova Scotia, Canada: Precambrian Research, v. 126, p. 123–145, doi:10.1016/S0301-9268(03)00192-X.

Cardona, A., Cordani, U.G., Valencia, V.A., Armstrong, R., Chew, D., Nutman, A., and Sanchez, A.W., 2009, U-Pb zircon geochronology and Nd isotopic signatures of the pre-Mesozoic metamorphic basement of the eastern Peruvian Andes: Growth and provenance of a late Neoproterozoic to Carboniferous accretionary orogen on the northwest margin of Gondwana: Journal of Geology, v. 117, p. 285–305, doi:10.1086/597472.

Cawood, P., 2005, Terra Australis orogen: Rodinia breakup and development of the Pacific and Iapetus margins of Gondwana during the Neoproterozoic and Paleozoic: Earth-Science Reviews, v. 69, p. 249–279, doi:10.1016/j.earscirev.2004.09.001.

Chew, D.M., Magna, T., Kirkland, C.L., Miskovic, A., Cardona, A., Spikings, R., and Schaltegger, U., 2008, Detrital fingerprint of the Proto-Andes: Evidence for a Neoproterozoic active margin: Precambrian Research, v. 167, p. 186–200, doi:10.1016/j.precamres.2008.08.002.

Cordani, U.G., Cardona, A., Jimenez, D.M., Liu, D., and Nutman, A.P., 2005, Geochronology of Proterozoic basement inliers in the Colombian Andes: Tectonic history of remnants of a fragmented Grenville belt, *in* Vaughan, A.P.M., et al., eds., Terrane processes at the margins of Gondwana: Geological Society of London Special Publication 246, p. 329–346.

Escayola, M.P., van Staal, C.R., and Davis, W., 2011, The age and tectonic setting of the Puncoviscana Formation in northwestern Argentina: An accretionary complex related to Early Cambrian closure of the Puncoviscana Ocean and accretion of the Arequipa-Antofalla block: Journal of South American Earth Sciences, v. 32, p. 438–459, doi:10.1016/j.jsames.2011.04.013.

Fyffe, L.R., Barr, S.M., Johnson, S.C., McLeod, M.J., McNicoll, V., Valverde-Vaquero, P., van Staal, C.R., and White, C.E., 2009, Detrital zircon ages from Neoproterozoic and early Paleozoic conglomerate and sandstone units of New Brunswick and coastal Maine: Implications for the tectonic evolution of Ganderia: Atlantic Geology, v. 45, p. 110–144, doi:10.4138/atlgeol.2009.006.

Hall, R., 2011, Australia-SE Asia collision: Plate tectonics and crustal flow, *in* Hall, R., et al., eds., The SE Asian gateway: History and tectonics of the Australian-Asia Collision: Geological Society of London Special Publication 355, p. 75–109, doi:10.1144/SP355.5.

Hibbard, J.P., van Staal, C.R., and Rankin, D.W., 2007, Links among Carolinia, Avalonia, and Ganderia in the Appalachian peri-Gondwanan realm, *in* Sears et al., eds., Whence the mountains? Inquiries into the evolution of orogenic systems: Geological Society of America Special Paper 433, p. 291–311, doi:10.1130/2007.2433(14).

Johnson, R.J.E., and van der Voo, R., 1985, Middle Cambrian paleomagnetism of the Avalon terrane in Cape Breton Island, Nova Scotia: Tectonics, v. 4, p. 629–651, doi:10.1029/TC004i007p00629.

Lallemand, S., Heuret, A., and Boutelier, D., 2005, On the relationships between slab dip, back-arc stress, upper plate absolute motion and crustal nature in subduction zones: Geochemistry Geophysics Geosystems, v. 6, Q09006, doi:10.1029/2005GC000917.

Loewy, S.L., Connelly, J.N., Dalziel, I.W.D., and Gower, C.F., 2003, Eastern Laurentia in Rodinia: Constraints from whole-rock Pb and U/Pb geochronology: Tectonophysics, v. 375, p. 169–197, doi:10.1016/S0040-1951(03)00338-X.

Mac Niocaill, C., 2000, A new Silurian paleolatitude for eastern Avalonia and evidence for crustal rotations in the Avalonian margin of southwestern Ireland: Geophysical Journal International, v. 141, p. 661–671, doi:10.1046/j.1365-246x.2000.00101.x.

Murphy, J.B., Pisarevsky, S.A., Nance, R.D., and Keppie, J.D., 2004, Neoproterozoic–early Paleozoic configuration of peri-Gondwanan terranes: Implications for Laurentia-Gondwanan connections: International Journal of Earth Sciences, v. 93, p. 659–682, doi:10.1007/s00531-004-0412-9.

Potts, S.S., van der Pluijm, B.A., and van der Voo, R., 1995, Paleomagnetism of the Pennington Mountain terrane: A near-Laurentian back arc basin in the Maine Appalachians: Journal of Geophysical Research, v. 100, p. 10,003–10,011, doi:10.1029/94JB03013.

Ramos, V.A., 2009, Anatomy and global context of the Andes: Main geologic features and the Andean orogenic cycle, *in* Kay, S.M., et al., eds., Backbone of the Americas: Shallow subduction, plateau uplift, and ridge and terrane collision: Geological Society of America Memoir 204, p. 31–65, doi:10.1130/2009.1204(02).

Rushton, A.W.A., 1963, Paradoxides from Colombia: Geological Magazine, v. 100, p. 255–257, doi:10.1017/S0016756800055199.

Satkoski, A.M., Barr, S.M., and Samson, S.D., 2010, Provenance of late Neoproterozoic and Cambrian sediments in Avalonia: Constraints from detrital zircon ages and Sm-Nd isotopic compositions in southern New Brunswick, Canada: Journal of Geology, v. 118, p. 187–200, doi:10.1086/649818.

Schultz, K.J., and Ayuso, R.A., 2003, Lithogeochemistry and paleotectonic setting of the Bald Mountain massive sulfide deposit, northern Maine, *in* Goodfellow, W.D., et al., eds., Massive sulfide deposits of the Bathurst Mining Camp, New Brunswick and northern Maine: Society of Economic Geologists Monograph 11, p. 79–110.

Schulz, K.J., Stewart, D.B., Tucker, R.D., Pollock, J.C., and Ayuso, R.A., 2008, The Ellsworth terrane, coastal Maine. Geochronology, geochemistry, and Nd-Pb isotopic compositions—Implications for the rifting of Ganderia: Geological Society of America Bulletin, v. 120, p. 1134–1158, doi:10.1130/B26336.1.

Smethurst, M.A., and McEnroe, S.A., 2003, The palaeolatitude controversy in the Silurian of Newfoundland resolved: New palaeomagnetic results from the central mobile belt: Tectonophysics, v. 362, p. 83–104, doi:10.1016/S0040-1951(02)00632-7.

Tesfai, F.G., 2011, Petrology and Ti-P-V potential of the Lower Coverdale plutonic suite, southeastern New Brunswick, Canada [M.S. thesis]: Wolfville, Nova Scotia, Canada, Acadia University, 234 p.

Thompson, M.D., Grunow, A.M., and Ramezani, J., 2010, Cambro-Ordovician paleogeography of the southeastern New England Avalon zone; implications for Gondwana breakup: Geological Society of America Bulletin, v. 122, p. 76–88, doi:10.1130/B26581.1.

Trindade, R.I.F., D'Arella-Filho, M.S., Epof, I., and Brito Neves, B.B., 2006, Paleomagnetism of Early Cambrian mafic dikes (NE Brazil) and the final assembly of Gondwana: Earth and Planetary Science Letters, v. 244, p. 361–377, doi:10.1016/j.epsl.2005.12.039.

van Staal, C.R., Sullivan, R.W., and Whalen, J.B., 1996, Provenance and tectonic history of the Gander Margin in the Caledonian/Appalachian Orogen: Implications for the origin and assembly of Avalonia, *in* Nance, R.D., and Thompson, M.D., eds., Avalonian and related Peri-Gondwanan terranes of the Circum-North Atlantic: Geological Society of America Special Paper 304, p. 347–367, doi:10.1130/0-8137-2304-3.347.

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, *in* Murphy, J.B., et al., eds., Ancient orogens and modern analogues: Geological Society of London Special Publication 327, p. 271–316.

Waldron, J.W.F., and van Staal, C.R., 2001, Taconic orogeny and the accretion of the Dashwoods block: A peri-Laurentian microcontinent in the Iapetus Ocean: Geology, v. 29, p. 811–814, doi:10.1130/0091-7613(2001)029<0811:TOATAO>2.0.CO;2.

White, C.E., Barr, S.M., Bevier, M.L., and Kamo, S., 1994, A revised interpretation of Cambrian and Ordovician rocks in the Bourinot belt of central Cape Breton Island, Nova Scotia: Atlantic Geology, v. 30, p. 123–142.

Zagorevski, A., van Staal, C.R., McNicoll, V., Rogers, N., and Valverde-Vaquero, P., 2008, Tectonic architecture of an arc-arc collision zone, Newfoundland Appalachians, *in* Draut, A., et al., eds., Formation and applications of the sedimentary record in arc-collision zones: Geological Society of America Special Paper 346, p. 309–333, doi:10.1130/2008.2436(14).

Zagorevski, A., van Staal, C.R., Rogers, N., McNicoll, V., Dunning, G.R., and Pollock, J.C., 2010, Middle Cambrian to Ordovician arc-backarc development on the leading edge of Ganderia, Newfoundland Appalachians, *in* Tollo, R.P., et al., eds., From Rodinia to Pangea: The lithotectonic record of the Appalachian region: Geological Society of America Memoir 206, p. 367–396, doi:10.1130/2010.1206(16).

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