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Iapetan Oceans: An analog of Tethys?

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ABSTRACT

The Iapetus Ocean opened during the breakup of Rodinia by the separation of the major continental blocks of Laurentia (LA), Baltica, and Amazonia (AM). Relics of protracted continental extension to rifting from 750 to 530 Ma are observed along those continental margins, including two distinct phases of rifting: (1) at 750–680 Ma, and (2) at 615–550 Ma. Conventionally, the second phase is thought to have led to the opening of the Iapetus, while the first phase marked a failed rifting attempt. We challenge this concept on the basis of a new review of the geological observations from those margins and propose the successive opening of two "Iapetan" ocean basins. First, a "Paleo-Iapetus" opened between LA and AM at ca. 700 Ma, followed by the opening of the "Neo-Iapetus" at 600 Ma, which led to the final disaggregation of the supercontinent Rodinia. This scenario better explains the absence of the second rifting phase in western AM, as well as an otherwise enigmatic late Neoproterozoic detrital zircon age fraction in Phanerozoic sediments along that margin. We further propose that the opening of the Neo-Iapetus led to the detachment of small terranes from LA and their drift toward AM, following subduction of the Paleo-Iapetus mid-ocean ridge and the arrival of a mantle plume around 615 Ma. This could be a direct, deep-time analog of the opening of the Neo-Tethys Ocean in the late Paleozoic.

INTRODUCTION

In 1966, J. Tuzo Wilson famously posed the question "Did the Atlantic close and then re-open?" (Wilson, 1966). This established the conceptual groundwork for the idea of a cyclical opening and closing of ocean basins that has now become central to plate tectonics (the Wilson cycle). The monumental leap forward that Wilson presented was that some other ocean had closed before the Atlantic opened—the ocean we now know as the Iapetus (Harland and Gayer, 1972).

The Iapetus formed during the breakup of Rodinia, the geometry of which is still debated (see the review in Merdith et al. [2017]). In the most accepted configuration of Rodinia, the Iapetus opened by the three-way separation of the continents of Laurentia (LA), Baltica (BA), and Amazonia (AM) and marked the terminal stage of breakup of the supercontinent (Fig. 1; Hoffman, 1991; Li et al., 2008). Prevailing conceptual models of that opening envision the breakup of all three continents over the time interval 615–550 Ma by the formation of a ridge-ridge-ridge triple junction, possibly instigated by a plume (Tegner et al., 2019). One ridge axis formed between LA and BA, another formed between LA and AM, and the third axis opened the Tornquist Sea between BA and AM. However, that model struggles to explain several significant observations that we argue instead suggest the successive opening of two "Iapetan" ocean basins, starting at ca. 700 Ma.

MULTIPLE PHASES OF RIFTING IN LAURENTIA

Along eastern LA (present-day coordinates), Neoproterozoic magmatism that has been attributed to predrift rifting stretches over 200 m.y., from ca. 750 to 550 Ma, but it appears to be restricted to two pulses: one from ca. 750 to 680 Ma, and a younger phase from ca. 615 to 550 Ma (Fig. 1; e.g., Aleinikoff et al., 1995). A rift-to-drift transition marked by the replacement of synrift clastic sequences by passive-margin successions is only known from the Cambrian (Williams and Hiscott, 1987), so it has commonly been assumed that the earlier phase of magmatism was the expression of a failed rift attempt (Aleinikoff et al., 1995). However, the Cambrian timing of the rift-to-drift transition along eastern LA does not seem likely to have marked the opening of the Iapetus itself, as paleomagnetic data suggest that LA, AM, and BA must have already been significantly separated by the start of the Cambrian (Cawood et al., 2001; Robert et al., 2018). Cawood et al. (2001) proposed that continental separation had already occurred by ca. 570 Ma, perhaps instigated by the eruption of the Central Iapetus magmatic province (CIMP) at 615 Ma (Tegner et al., 2019). The continuation of rifting into the earliest Cambrian and the eventual rift-to-drift transition that is preserved along eastern LA were therefore reinterpreted as marking the opening of a narrow seaway between LA and a continental ribbon, called Dashwoods (Cawood et al., 2001; Waldron and van Staal, 2001). Some tens of millions of years after that seaway opened, it collapsed—re-accreting the Dashwoods ribbon continent to the Laurentian autochthon during the Taconic orogeny. If the establishment of the Cambrian passive margin of eastern LA marked the opening of a narrow seaway, and not the rift-to-drift transition associated with the birth of the main Iapetus Ocean (and no earlier passive-margin deposits are known), how do we really know the age of Iapetus Ocean opening? Could the earlier 750–680 Ma magmatic pulse along LA have been successful after all?

BALTICA-LAURENTIA CONNECTIONS

The margins of Scotland-Ireland (which were part of northeast LA prior to Atlantic opening) and west BA (present-day coordinates) are considered to have been conjugate margins before Iapetus opening, according to conventional reconstructions of Rodinia (Hoffman, 1991). Accordingly, those margins display a similar geological evolution from ca. 750 to 600 Ma, characterized by the deposition of thick siliciclastic successions in the Cryogenian–Ediacaran (e.g., Seve Nappe Complex in Norway and Sweden, and the Dalradian Supergroup in Scotland-Ireland) and the appearance of rift-related magmatism in the early to mid-Ediacaran (ca. 620–590 Ma; Stephenson et al., 2013; Kjøll et al., 2019). Together with sparse paleomagnetic constraints (Murthy et al., 1992; Walderhaug et al., 2007), the common

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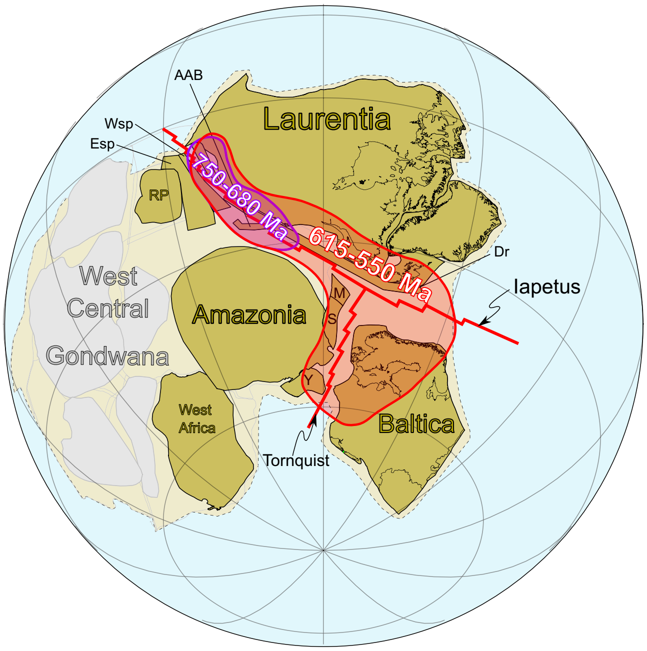

Figure 1. Delimitation of rift-related magmatic pulses at 750–680 Ma (purple) and 615–550 Ma (red) in Laurentia (LA), Amazonia (AM), and Baltica (BA). See Figure S1 (see footnote 1) for a detailed compilation of magmatic events. Reconstruction of Rodinia is slightly modified from Li et al. (2008); AM and BA are moved slightly southward to take into account the pre-Scandian extent of west BA, and to include the small terranes between LA and AM. Esp—Eastern Sierras Pampeanas; Wsp—Western Sierras Pampeanas; AAB—Arequipa-Antofalla block; RP—Rio de la Plata; Dr—Dashwoods ribbon; Y—Yucatan; S—Sierra Madre; M—Mixteca Oaxaca.

geological evolution of northeast LA and west BA are consistent with those continents having remained connected until a 615–600 Ma breakup with the arrival of the CIMP.

EVIDENCE OF RIFTING ALONG WEST AMAZONIA

Cryogenian to early Ediacaran ties between eastern LA and western AM (present-day coordinates) are not clear. In fact, Cryogenian to early Ediacaran rocks are virtually unknown from the western part of the AM craton (Fig. 1). However, to the west of the craton proper, basement inliers of late Mesoproterozoic–early Neoproterozoic age (1.2–0.9 Ga) that have been correlated with the 1.2–0.9 Ga Sunsas Province of AM are found in the Eastern Cordillera of Peru, suggesting direct ties to the AM craton (Mišković et al., 2009). The Eastern Cordillera also hosts Neoproterozoic granitoids (ca. 750–690 Ma) that have been identified as A-type, anorogenic granitoids related to continental breakup (Mišković et al., 2009). In the same area of the Eastern Cordillera, isolated metamorphosed ultramafic bodies (718 ± 47 Ma) have been interpreted as dismembered ophiolitic slices (Tassinari et al., 2011).

To the south of the Eastern Cordillera of Peru, distinct Precambrian massifs of the Arequipa-Antofalla block (AAB) of southern Peru, western Bolivia, and northern Chile host Neoproterozoic volcanic-volcaniclastic rocks and ca. 635 Ma dacite dikes (Loewy et al., 2004). The Precambrian relationship between the AAB and the AM craton remains uncertain. On the basis of their differing Paleoproterozoic histories, Loewy et al. (2004) argued that the AAB was not affiliated with AM at 2.0–1.8 Ga. However, the block must have been proximal to western Gondwana at least by the early Paleozoic because the late Cambrian–Silurian Famatinian volcanic arc crosses through both the Antofalla and Arequipa Massifs, tying them to the active margin of proto–South America by that time (Ramos, 2018).

CLUES FROM DETRITAL ZIRCONS

The metamorphic rocks that comprise the bulk of the Eastern Cordillera of Peru, collectively referred to as the Marañon Complex, were previously thought to represent exposures of Precambrian basement, but detrital zircon studies have indicated that they were mostly deposited during the Ordovician and Carboniferous (although poor upper age constraints on the oldest units allow for the possibility that they could be Cambrian or Neoproterozoic; Cardona et al., 2009). The detrital zircon (DZ) populations of those metamorphic rocks and other Paleozoic sedimentary rocks of the Eastern Cordillera have a characteristic age distribution with prominent peaks at 1.3–0.9 Ga and 650–450 Ma (Chew et al., 2008). A similar distribution has also been reported from Paleozoic metasedimentary rocks in the Central and Eastern Cordillera of Colombia and the Mérida Andes of Venezuela (Fig. 2), which also host Precambrian basement inliers that are thought to be correlative with the AM craton. As noted by Chew et al. (2008), the older of those two age fractions likely was derived from the Sunsas province of the AM craton. Likewise, the 500–450 Ma zircons can be easily explained as products of the subduction-related Famatinian magmatic belt that spanned the proto-Andean margin in late Cambrian to Silurian time (Ramos, 2018). However, the 650–500 Ma population is unexpected because it has no obvious source in western AM. Chew et al. (2008) entertained three possibilities to explain that age fraction: (1) it was derived from local, rift-related magmatism; (2) it was sourced from the Brasiliano orogenic system, which was active at that time on the opposite side of the AM craton, and in particular the Brasília belt, which contains 0.9–0.48 Ga magmatic rocks (Fig. 2B; Pimentel et al., 1999); or (3) it was generated from a local (west Amazonian) active margin (Fig. 2C).

CRYOGENIAN LAURENTIA-AMAZONIA BREAKUP?

The possibility that the late Neoproterozoic zircons were generated by magmatism associated with an Ediacaran rifting event between LA and AM is problematic because no in situ remnants of such magmatism have been reported from west AM. Moreover, rift-related magmatism is usually dominated by compositionally basic products that do not produce abundant zircon (Cawood et al., 2012); therefore, this scenario is unlikely.

In the second scenario (Fig. 2B), sediment transport likely traversed wide swaths of the AM craton and would be expected to reflect such a provenance. However, the DZ data set only shows a minor age fraction corresponding to the AM craton, in particular, from the Central Amazonian Province (older than 2.3 Ga). That incongruity could invalidate this scenario, unless the AM craton was a peneplain at that time, or the drainage networks skirted the craton (Chew et al., 2008). Another challenge to this second scenario is presented by the observation that the DZ age populations of some Ordovician–Silurian sediments deposited in close proximity to the then-active Famatinian volcanic arc are dominated by the late Neoproterozoic age fraction (Chew et al., 2008). It is striking that the late Neoproterozoic age fraction is often more pronounced than those corresponding to the then-active arc—especially if the former was distally sourced, and the latter was proximal.

Further problems arise if scenario 2 is considered in the greater paleogeographic context of the conventional LA-AM breakup model (Cawood et al., 2001). Because Brasiliano orogenesis ended in the Cambrian (Pimentel et al., 1999), and the Famatinian volcanic arc initiated in the latest Cambrian–earliest Ordovician (Ramos, 2018), the regional topography likely had opposing drainage from east to west (present-day coordinates) from that time. The occurrence of the late Neoproterozoic zircons within Ordovician and younger rocks, therefore, almost certainly required recycling of older, local sedimentary rocks, rather than a direct transport of material from the Brasiliano system. However, such re-sedimentation would require that the volume of sediment that was shed westwards prior to the erection of the Famatinian arc must have been substantial, given that Ordovician and Silurian deposits near the Famatinian arc remained dominated by those recycled materials

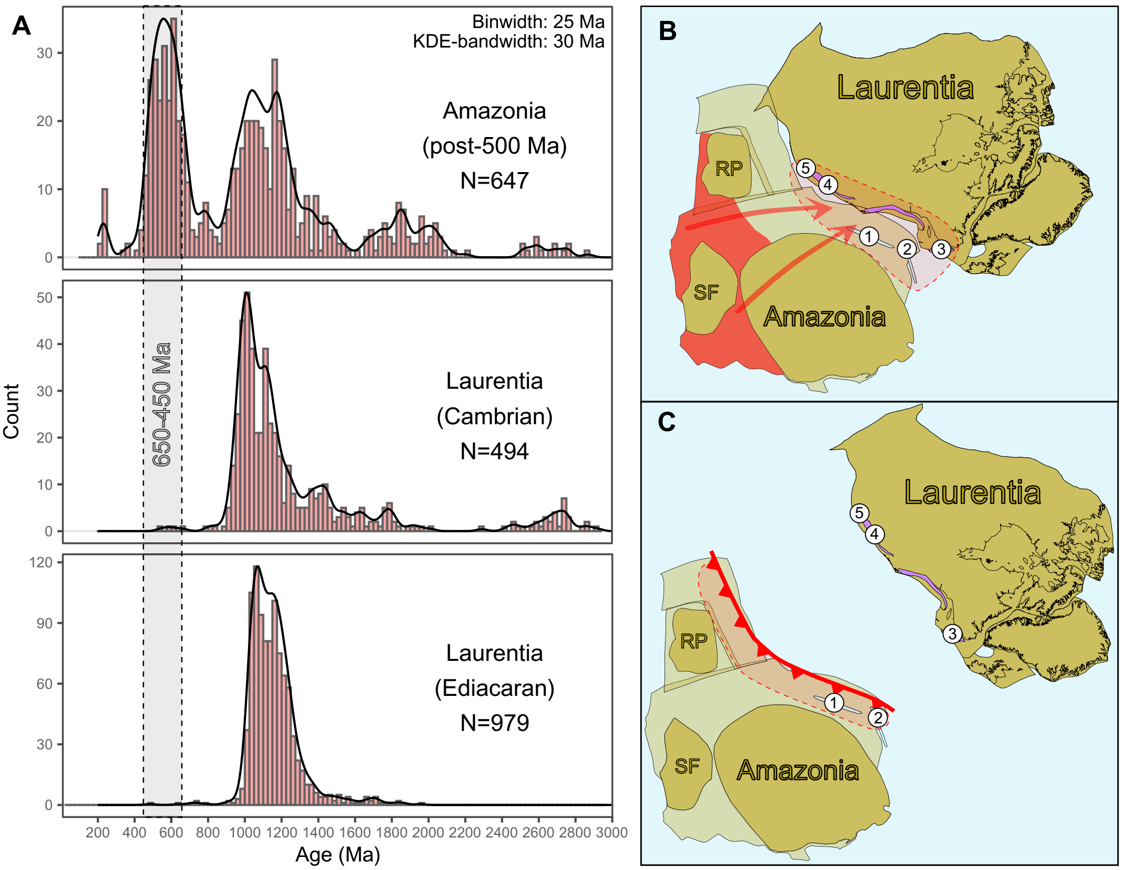

Figure 2. (A) Histograms and kernel density estimates of detrital zircon U-Pb ages of (top) post–500 Ma metasedimentary rocks (including inherited zircons in magmatic rocks) from the Eastern Cordillera of Peru and Cordillera Real of Ecuador (Chew et al., 2008), and (middle and bottom) early Cambrian and Ediacaran synrift sediments along eastern Laurentia (Eriksson et al., 2004; Thomas et al., 2004; Allen, 2009; Chakraborty et al., 2012). KDE—kernel density estimation. (B–C) Two alternative scenarios that may explain the provenance of 650–500 Ma zircons along west Amazonia: Neoproterozoic–early Cambrian Brasiliano belts (B), or continuous continental arc along proto-Andean margin (C). Sampling sites: 1—Marañon Complex; 2—Cordillera Real of Ecuador; 3—Humber zone in Newfoundland; 4—Blue Ridge inlier; 5—Birmingham basement graben system. RP—Rio de la Plata; SF—São Francisco.

(Chew et al., 2008). Consequently, if the westward transport of such abundant detritus was already occurring before the proposed breakup of LA and AM, a similar age fraction could be expected in eastern LA. Brasiliano detritus could have spread across the AM craton following collision of AM and São Francisco at ca. 630 Ma (Pimentel et al., 1999; a much younger collision of those blocks in the Cambrian has been proposed, but remains controversial—Trindade et al., 2006). That would allow ~30–60 m.y. for zircons to be liberated and transported westward before continental breakup at 600–570 Ma. Yet, the DZ records of Ediacaran–Cambrian sedimentary rocks from eastern North America do not exhibit a significant late Neoproterozoic age fraction (Fig. 2A). One interpretation of that absence is that LA and AM broke apart prior to 600–570 Ma. In that case, the occurrence of ca. 750–690 Ma rift-related magmatism observed in both LA and AM could reflect their breakup in the Tonian–early Cryogenian, with some early relics of that extension being preserved as ca. 718 Ma ophiolitic slices in west AM.

EDIACARAN SUBDUCTION AND A SECOND "IAPETAN" OPENING: A TETHYAN ANALOG?

A separation of LA and AM at ca. 700 Ma would have allowed ample time for the continents to drift far apart before the initiation of a subduction zone along AM by ca. 650 Ma, as in scenario 3 (Fig. 2C). Nevertheless, this solution is problematic because no in situ evidence of a local late Neoproterozoic arc has been recognized along western AM from 650 to 500 Ma. On the other hand, the South American margin was active through most of the Phanerozoic, and the Neoproterozoic geological record could have been destroyed by subduction-erosion and/or buried by younger foreland basin deposits. The temporal restriction of the late Neoproterozoic DZ age population, and its dominance over other age fractions among Paleozoic sedimentary rocks of west AM, is moreover better explained by a magmatic arc active along western AM from 650 to 500 Ma than the long-lived evolution of the Brasiliano system from 900 to 480 Ma (Pimentel et al., 1999).

If the western margin of AM were active during the Ediacaran, it is interesting to note that that subduction system would have put the eastern margin of LA into a state of tension, following subduction of the intervening Paleo-Iapetan ridge. Such a far-field pull could have acted to detach continental slivers from the margin of LA, analogous to the regime in which the Cimmerian terranes were dislodged from the northern margin of Gondwana by subduction beneath Eurasia (Fig. 3; Stampfli and Borel, 2002). The emplacement of CIMP along the eastern margin of LA (Tegner et al., 2019) may have additionally played an important role in the opening of Neo-Iapetus by weakening the continental lithosphere that was already under tension, comparable to the role the Panjal Traps in India may have played in facilitating the opening of Neo-Tethys. The terranes that were dislodged from the eastern margin of LA possibly included the AAB, which experienced diking ca. 635 Ma (Loewy et al., 2004), as well as the Western Sierras Pampeanas, which shares a similar 2.0–1.8 Ga basement with the AAB (Casquet et al., 2012) and was intruded by a rift-related syenite-carbonatite ca. 570 Ma (Casquet et al., 2008).

We contend that the observations and arguments summarized here are most compatible with ca. 700 Ma breakup between LA and AM that opened a Paleo-Iapetus Ocean, followed by renewed rifting in the Ediacaran that led to the opening of a Neo-Iapetus Ocean. However, as the assembled arguments are indirect and based on a conventional reconstruction of Rodinia, paleomagnetic data are of key importance to testing this hypothesis. Reliable paleomagnetic data are unfortunately sparse from 750 to 600 Ma (see the Supplemental Material[1]), precluding a

[1]Supplemental Material. The Cryogenian to Ediacaran rift-related magmatism distribution along east Laurentia, west Baltica, and west Amazonia, and a discussion about the paleomagnetic data from 750 to 600 Ma. Please visit https://doi.org/10.1130/GEOL.S.12331145 to access the supplemental material, and contact editing@geosociety.org with any questions.

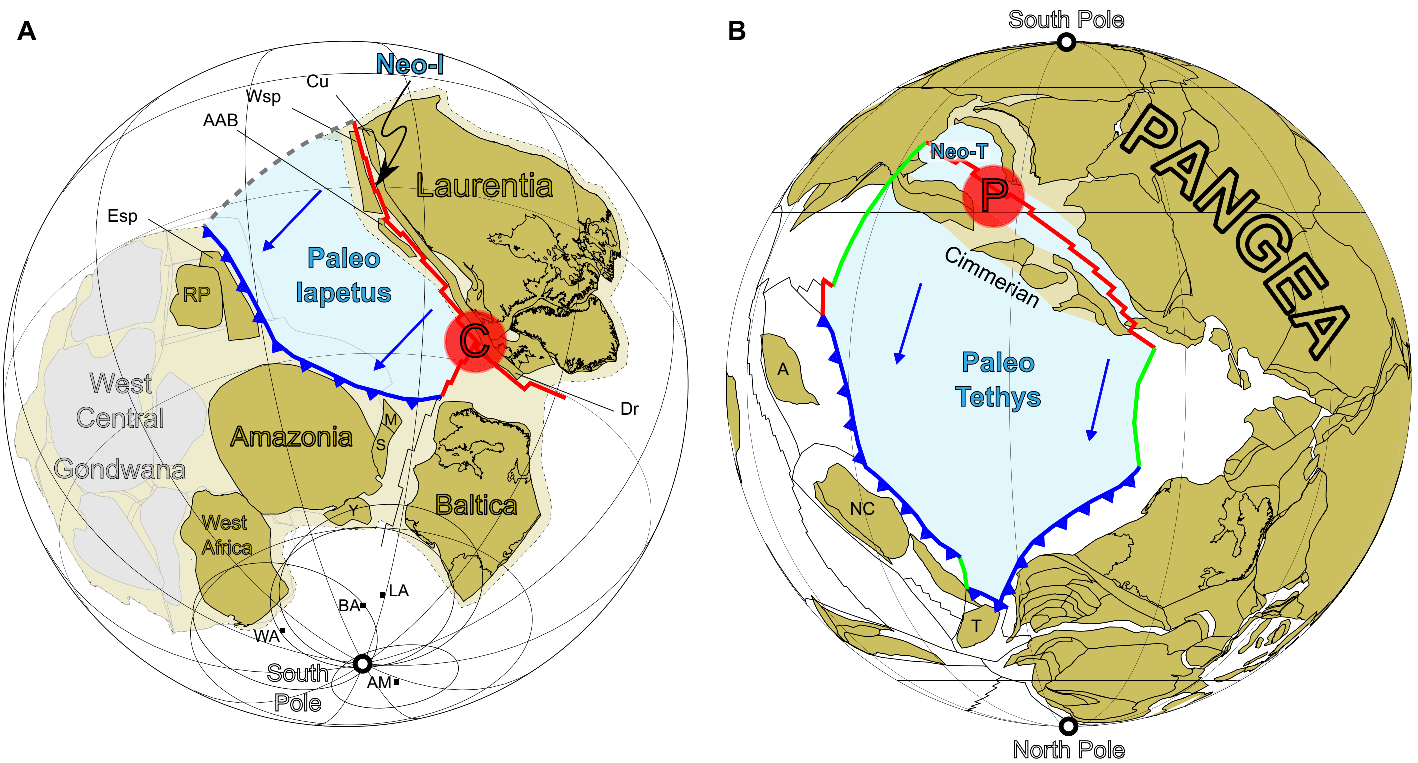

Figure 3. (A) Paleogeographic reconstruction at 615 Ma displaying the opening of Neo-Iapetus (Neo-I) following subduction of the Paleo-Iapetus mid-ocean ridge and emplacement of the Central Iapetus magmatic province (red C; Tegner et al., 2019). Continent abbreviations are as in Figure 1. Paleomagnetic poles and their A95 circle of confidence for Laurentia (LA), Baltica (BA), West Africa (WA), and Amazonia (AM) are given in the Supplemental Material (see footnote 1). (B) Opening of Neo-Tethys (Neo-T) at ca. 270 Ma following subduction of the Paleo-Tethys mid-ocean ridge and emplacement of the Panjal Traps (red P; Torsvik et al., 2014). Note the orientation of the globe is inverted. Reconstruction is after Domeier and Torsvik (2014). NC—North China; T—Tarim; A—Amuria; Cu—Cuyania.

rigorous test of our preferred model, but we note that the data available at 615 Ma are consistent with this reconstruction (Fig. 3A).

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REFERENCES CITED

Aleinikoff, J.N., Zartman, R.E., Walter, M., Rankin, D.W., Lyttle, P.T., and Burton, W.C., 1995, U-Pb ages of metarhyolites of the Catoctin and Mount Rogers formations, Central and Southern Appalachians: Evidence for two pulses of Iapetan rifting: American Journal of Science, v. 295, p. 428–454, https://doi.org/10.2475/ajs.295.4.428.

Allen, J.S., 2009, Paleogeographic Reconstruction of the St. Lawrence Promontory, Western Newfoundland [Ph.D. thesis]: Lexington, Kentucky, University of Kentucky, 310 p.

Cardona, A., Cordani, U.G., Ruiz, J., 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: The Journal of Geology, v. 117, p. 285–305, https://doi.org/10.1086/597472.

Casquet, C., Pankhurst, R.J., Galindo, C., Rapela, C., Fanning, C.M., Baldo, E., Dahlquist, J., González Casado, J.M., and Colombo, F., 2008, A deformed alkaline igneous rock–carbonatite complex from the Western Sierras Pampeanas, Argentina: Evidence for late Neoproterozoic opening of the Clymene Ocean?: Precambrian Research, v. 165, p. 205–220, https://doi.org/10.1016/j.precamres.2008.06.011.

Casquet, C., Rapela, C.W., Pankhurst, R.J., Baldo, E.G., Galindo, C., Fanning, C.M., Dahlquist, J.A., and Saavedra, J., 2012, A history of Proterozoic terranes in southern South America: From Rodinia to Gondwana: Geoscience Frontiers, v. 3, p. 137–145, https://doi.org/10.1016/j.gsf.2011.11.004.

Cawood, P.A., McCausland, P.J.A., and Dunning, G.R., 2001, Opening Iapetus: Constraints from the Laurentian margin in Newfoundland: Geological Society of America Bulletin, v. 113, p. 443–453, https://doi.org/10.1130/0016-7606(2001)113<0443:oicftl>2.0.co;2.

Cawood, P.A., Hawkesworth, C.J., and Dhuime, B., 2012, Detrital zircon record and tectonic setting: Geology, v. 40, p. 875–878, https://doi.org/10.1130/G32945.1.

Chakraborty, S., Moecher, D.P., and Samson, S.D., 2012, Provenance of the Lower Ocoee Supergroup, eastern Great Smoky Mountains: Geological Society of America Bulletin, v. 124, p. 1278–1292, https://doi.org/10.1130/B30578.1.

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

Domeier, M., and Torsvik, T.H., 2014, Plate tectonics in the late Paleozoic: Geoscience Frontiers, v. 5, p. 303–350, https://doi.org/10.1016/j.gsf.2014.01.002.

Eriksson, K.A., Campbell, I.H., Michael Palin, J., Allen, C.M., and Bock, B., 2004, Evidence for multiple recycling in Neoproterozoic through Pennsylvanian sedimentary rocks of the central Appalachian Basin: The Journal of Geology, v. 112, p. 261–276, https://doi.org/10.1086/382758.

Harland, W.B., and Gayer, R.A., 1972, The Arctic Caledonides and earlier oceans: Geological Magazine, v. 109, p. 289–314, https://doi.org/10.1017/S0016756800037717.

Hoffman, P.F., 1991, Did the breakout of Laurentia turn Gondwanaland inside-out?: Science, v. 252, p. 1409–1412, https://doi.org/10.1126/science.252.5011.1409.

Kjøll, H.J., Andersen, T.B., Corfu, F., Labrousse, L., Tegner, C., Abdelmalak, M.M., and Planke, S., 2019, Timing of breakup and thermal evolution of a pre-Caledonian Neoproterozoic exhumed magma-rich rifted margin: Tectonics, v. 38, p. 1843–1862, https://doi.org/10.1029/2018TC005375.

Li, Z.X., et al., 2008, Assembly, configuration, and break-up history of Rodinia: A synthesis: Precambrian Research, v. 160, p. 179–210, https://doi.org/10.1016/j.precamres.2007.04.021.

Loewy, S.L., Connelly, J.N., and Dalziel, I.W.D., 2004, An orphaned basement block: The Arequipa-Antofalla basement of the central Andean margin of South America: Geological Society of America Bulletin, v. 116, p. 171–187, https://doi.org/10.1130/B25226.1.

Merdith, A.S., et al., 2017, A full-plate global reconstruction of the Neoproterozoic:

Gondwana Research, v. 50, p. 84–134, https://doi.org/10.1016/j.gr.2017.04.001.

Mišković, A., Spikings, R.A., Chew, D.M., Košler, J., Ulianov, A., and Schaltegger, U., 2009, Tectonomagmatic evolution of Western Amazonia: Geochemical characterization and zircon U-Pb geochronologic constraints from the Peruvian Eastern Cordilleran granitoids: Geological Society of America Bulletin, v. 121, p. 1298–1324, https://doi.org/10.1130/B26488.1.

Murthy, G., Gower, C., Tubrett, M., and Pätzold, R., 1992, Paleomagnetism of Eocambrian Long Range dykes and Double Mer Formation from Labrador, Canada: Canadian Journal of Earth Sciences, v. 29, p. 1224–1234, https://doi.org/10.1139/e92-098.

Pimentel, M.M., Fuck, R.A., and Botelho, N.F., 1999, Granites and the geodynamic history of the Neoproterozoic Brasília belt, central Brazil: A review: Lithos, v. 46, p. 463–483, https://doi.org/10.1016/S0024-4937(98)00078-4.

Ramos, V.A., 2018, The Famatinian orogen along the protomargin of western Gondwana: Evidence for a nearly continuous Ordovician magmatic arc between Venezuela and Argentina, *in* Folguera, A., et al., eds., The Evolution of the Chilean-Argentinean Andes: Cham, Switzerland, Springer International, p. 133–161, https://doi.org/10.1007/978-3-319-67774-3_6.

Robert, B., Greff-Lefftz, M., and Besse, J., 2018, True polar wander: A key indicator for plate configuration and mantle convection during the late Neoproterozoic: Geochemistry Geophysics Geosystems, v. 19, p. 3478–3495, https://doi.org/10.1029/2018GC007490.

Stampfli, G.M., and Borel, G.D., 2002, A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons: Earth and Planetary Science Letters, v. 196, p. 17–33, https://doi.org/10.1016/S0012-821X(01)00588-X.

Stephenson, D., Mendum, J.R., Fettes, D.J., and Graham Leslie, A., 2013, The Dalradian rocks of Scotland: An introduction: Proceedings of the Geologists' Association, v. 124, p. 3–82, https://doi.org/10.1016/j.pgeola.2012.06.002.

Tassinari, C.C.G., Castroviejo, R., Rodrigues, J.F., Acosta, J., and Pereira, E., 2011, A Neoproterozoic age for the chromitite and gabbro of the Tapo ultramafic massif, Eastern Cordillera, central Peru, and its tectonic implications: Journal of South American Earth Sciences, v. 32, p. 429–437, https://doi.org/10.1016/j.jsames.2011.03.008.

Tegner, C., Andersen, T.B., Kjøll, H.J., Brown, E.L., Hagen-Peter, G., Corfu, F., Planke, S., and Torsvik, T.H., 2019, A mantle plume origin for the Scandinavian dyke complex: A "piercing point" for 615 Ma plate reconstruction of Baltica?: Geochemistry Geophysics Geosystems, v. 20, p. 1075–1094, https://doi.org/10.1029/2018GC007941.

Thomas, W.A., Astini, R.A., Mueller, P.A., Gehrels, G.E., and Wooden, J.L., 2004, Transfer of the Argentine Precordillera terrane from Laurentia: Constraints from detrital-zircon geochronology: Geology, v. 32, p. 965–968, https://doi.org/10.1130/G20727.1.

Torsvik, T.H., van der Voo, R., Doubrovine, P.V., Burke, K., Steinberger, B., Ashwal, L.D., Trønnes, R.G., Webb, S.J., and Bull, A.L., 2014, Deep mantle structure as a reference frame for movements in and on the Earth: Proceedings of the National Academy of Sciences of the United States of America, v. 111, p. 8735–8740, https://doi.org/10.1073/pnas.1318135111.

Trindade, R., Dagrellafilho, M., Epof, I., and Britoneves, B., 2006, Paleomagnetism of early Cambrian Itabaiana mafic dikes (NE Brazil) and the final assembly of Gondwana: Earth and Planetary Science Letters, v. 244, p. 361–377, https://doi.org/10.1016/j.epsl.2005.12.039.

Walderhaug, H.J., Torsvik, T.H., and Halvorsen, E., 2007, The Egersund dykes (SW Norway): A robust early Ediacaran (Vendian) palaeomagnetic pole from Baltica: Geophysical Journal International, v. 168, p. 935–948, https://doi.org/10.1111/j.1365-246X.2006.03265.x.

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

Williams, H., and Hiscott, R.N., 1987, Definition of the Iapetus rift-drift transition in western Newfoundland: Geology, v. 15, p. 1044–1047, https://doi.org/10.1130/0091-7613(1987)15<1044:dotlrt>2.0.co;2.

Wilson, J.T., 1966, Did the Atlantic close and then re-open?: Nature, v. 211, p. 676–681, https://doi.org/10.1038/211676a0.

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