GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G45294.1

Manuscript received 20 June 2018
Revised manuscript received 18 September 2018
Manuscript accepted 20 September 2018

Direct Mesoproterozoic connection of the Congo and Kalahari cratons in proto-Africa: Strange attractors across supercontinental cycles

Johanna Salminen[1], Richard Hanson[2], David A.D. Evans[3], Zheng Gong[3], Tierney Larson[3], Olivia Walker[3], Ashley Gumsley[4,5], Ulf Söderlund[4,6], and Richard Ernst[7,8]

[1]Department of Geosciences and Geography, University of Helsinki, 00014 University of Helsinki, Finland
[2]Department of Geological Sciences, Texas Christian University, Fort Worth, Texas 76129, USA
[3]Department of Geology & Geophysics, Yale University, New Haven, Connecticut 06520, USA
[4]Department of Geology, Lund University, Lund 223 62, Sweden
[5]Institute of Geophysics, Polish Academy of Sciences, Warsaw 01-452, Poland
[6]Department of Geosciences, Swedish Museum of Natural History, Stockholm 11418, Sweden
[7]Department of Earth Sciences, Carleton University, Ottawa, ON K1S 5B6, Canada
[8]Faculty of Geology and Geography, Tomsk State University, Tomsk 634050, Russia

ABSTRACT

Mobilistic plate-tectonic interpretation of Precambrian orogens requires that two conjoined crustal blocks may derive from distant portions of the globe. Nonetheless, many proposed Precambrian cratonic juxtapositions are broadly similar to those of younger times (so-called "strange attractors"), raising the specter of bias in their construction. We evaluated the possibility that the Congo and Kalahari cratons (Africa) were joined together prior to their amalgamation along the Damara-Lufilian-Zambezi orogen in Cambrian time by studying diabase dikes of the Huila-Epembe swarm and sills in the southern part of the Congo craton in Angola and in Namibia. We present geologic, U-Pb geochronologic, and paleomagnetic evidence showing that these two cratons were directly juxtaposed at ca. 1.1 Ga, but in a slightly modified relative orientation compared to today. Recurring persistence in cratonic connections, with slight variations from one supercontinent to the next, may signify a style of supercontinental transition similar to the northward motion of Gondwana fragments across the Tethys-Indian oceanic tract, reuniting in Eurasia.

INTRODUCTION

Efforts to reconstruct the paleogeographies of Precambrian landmasses have intensified in recent decades (summarized by Evans, 2013), although there is no consensus on the arrangements of cratons in supercontinents such as Rodinia (ca. 900–700 Ma) and Nuna (ca. 1600–1400 Ma). Methods of cratonic reconstruction include tectonostratigraphic comparisons, paleomagnetism, and matching fragments of large igneous provinces (LIPs) on now-separated crustal blocks (Bleeker and Ernst, 2006; Li et al., 2008). Ideally, a favored model would be supported by several independent lines of evidence.

Meert (2014) noted the frequent occurrence of hypothesized Precambrian cratonic connections that approximate those of Pangea. Calling such examples "strange attractors," he suggested the possibility that implicit bias might favor familiar reconstruction models over more exotic possibilities. An alternative explanation might be lack of plate-tectonic mobility for most of Precambrian time (e.g., Stern, 2005), but mobilistic interpretations are bolstered by many lines of evidence. This evidence includes paleomagnetic support for the independent lateral motion of lithospheric blocks, magmatic arc activity and associated ore deposits related to subduction of oceanic-type lithosphere, and well-documented ophiolites and eclogites back to at least ca. 2.0 Ga (Cawood et al., 2006; Boniface et al., 2012).

The Ediacaran–Cambrian Damara-Lufilian-Zambezi orogen (DLZO) in southern Africa has been interpreted variously to have formed by closure of a wide ocean basin (e.g., Goscombe et al., 2018) or at most a narrow oceanic seaway (Miller, 1983; Hanson, 2003). One argument in favor of the latter hypothesis comes from recent U-Pb dating of the Huila gabbronorite dikes (Congo craton), which provided a temporal match with the extensive Umkondo LIP (Kalahari craton) at ca. 1110 Ma (Ernst et al., 2013). Nonetheless, evidence in the Damara belt of full-fledged rifts and passive margins, and an accretionary prism and orogenic foreland basin (Hoffman and Halverson, 2008; Miller, 2008), testify to ocean opening and closure between 750 and 500 Ma. Can these observations be reconciled in a single tectonic model?

METHODS AND RESULTS

In order to constrain the relative positions of the Congo and Kalahari cratons, we conducted a paleomagnetic and U-Pb geochronologic investigation of the ca. 1.1 Ga Huila-Epembe (HE) dikes and related mafic rocks across the Congo craton in Angola and northernmost Namibia (Fig. 1), the results of which can be compared to the well-established paleomagnetic pole from the coeval Umkondo LIP from the Kalahari (Swanson-Hysell et al., 2015). Methods are fully described in the GSA Data Repository[1]. As part of a broader study on numerous dike swarms exposed in the area, we identified 25 sites (i.e., separate cooling units) in mafic igneous rocks that preserve either a shallow southwest or a

---

[1] GSA Data Repository item 2018386, methods and detailed results description, geochronology and paleomagnetic data tables, and additional data figures, is available online at http://www.geosociety.org/datarepository/2018/, or on request from editing@geosociety.org.

CITATION: Salminen, J., et al., 2018, Direct Mesoproterozoic connection of the Congo and Kalahari cratons in proto-Africa: Strange attractors across supercontinental cycles: Geology, v. 46, p. 1011–1014, https://doi.org/10.1130/G45294.1

Figure 1. Site locality map with Google Earth™ background. Eastern limit of Kaoko belt (Namibia) allochthons is from Goscombe et al. (2018). Inset abbreviations: DLZO—Damara-Lufilian-Zambezi orogen, Kala—Kalahari craton, SF—São Francisco craton, W.Afr.—West African craton. U-Pb baddeleyite age for site S1642 is from Ernst et al. (2013); other baddeleyite ages farther south are from this work.

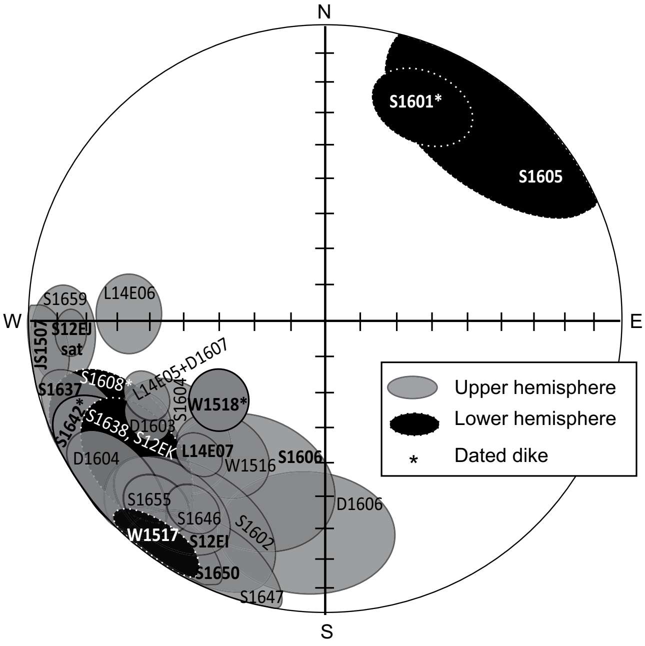

Figure 2. Equal-area projection of paleomagnetic results from studied mafic intrusions in Angola and Namibia (this study). Geochronologic data for the dated dikes are listed in Tables DR1 and DR2 (see footnote 1).

less-common northeast characteristic magnetic remanence vector (Fig. 2). Most of these sites are in the generally north-trending or NNW-trending Huila dikes, including the dike dated by Ernst et al. (2013), which yielded a U-Pb baddeleyite age of 1110 ± 3 Ma. We obtained three new isotope dilution–thermal ionization mass spectrometry (ID-TIMS) U-Pb baddeleyite ages (Fig. 3): one from our southernmost region, where dolerite dikes near Epembe trend northwest (1109 ± 10 Ma); one from a Huila dike, with a northeast-directed magnetic remanence vector (ca. 1104 Ma); and one from a mafic sill intruding red beds of the Chela Plateau (1127 ± 8 Ma). The Chela sill yielded a virtual geomagnetic pole that is similar to, but predates, our new ca. 1.1 Ga paleomagnetic pole from the HE dikes; the latter result (34.7°S, 256.5°E, K = 12.1, A_{95} = 8.7°) was demonstrated to be primary via a positive baked-contact test on a 100-m-wide Epembe dike intruded into host gneiss (Fig. DR3 in the Data Repository). In the baked-contact test, host rocks within 1–20 m of the contact show complete remagnetization at the time of dike intrusion, whereas host rocks 33–130 m from the contact exhibit a distinct stable magnetic remanence direction. Additional baked-contact tests were inconclusive (Fig. DR4). Sites in proximity to the Kaoko belt, which is contiguous with the Damara belt (Fig. 1), bear distinct WSW or northwest downward magnetic remanence directions, which we interpret as Ediacaran–Cambrian overprints by comparison to the Congo craton's apparent polar wander path from that time interval (Rapalini, 2018). The new HE pole fulfills all seven of the Van der Voo (1990) reliability criteria and can be called a paleomagnetic key pole (Buchan, 2014).

PALEOGEOGRAPHIC IMPLICATIONS

The HE paleomagnetic pole yields a relatively low latitude for the Congo craton at ca. 1.1 Ga and permits a direct connection between the Congo and Kalahari cratons (Fig. 4B), the latter of which remained in tropical low latitudes throughout late Mesoproterozoic time (Gose et al., 2013). Data presented by Ernst et al. (2013) and de Kock et al. (2014) showed that the Huila dikes are fractionated continental tholeiites with compositions similar to much of the Umkondo LIP, and those workers hypothesized that the dikes represent a radial arm of the LIP emanating from a focus in the Kalahari craton. Like the majority of published Umkondo paleomagnetic data, the HE remanence directions are southerly and upward, favoring the same-hemisphere polarity option for those two suites as shown in Figure 4B. Following Swanson-Hysell et al. (2015), we propose that south-seeking magnetic remanences represent normal polarity for the Congo and Kalahari data; this allows the ca. 1.1 Ga reconstruction to be more consistent with both the final arrival of Kalahari in

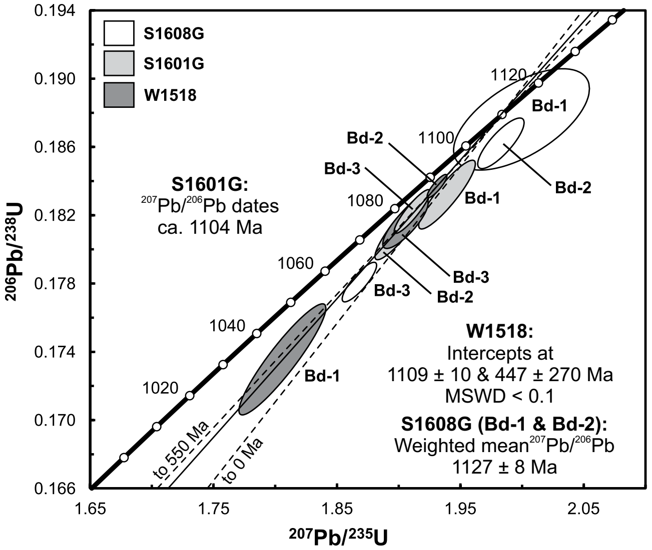

Figure 3. Wetherill U-Pb isotope dilution–thermal ionization mass spectrometry (ID-TIMS) concordia diagrams for analyzed baddeleyite from dikes S1601 (sample: S1601G) and W1518 (sample: W1518) and from sill S1608 (sample: S1608G) in Angola and Namibia, with error ellipses demarcating individual fractions analyzed at 2σ. For details, see Table DR1 (see footnote 1). MSWD—mean square of weighted deviates.

Rodinia (Swanson-Hysell et al., 2015; Kasbohm et al., 2016) and the derivation of Congo from the breakup of Nuna (Salminen et al., 2016). Based on the distribution of Umkondo igneous rocks in the Kalahari craton, including two well-constrained dike swarms, de Kock et al. (2014) inferred the existence of a major magmatic center for the LIP near the northwest edge of the craton. Significantly, the HE dikes point directly to that magmatic center in the reconstruction in Figure 4B, which was arrived at independently using our new paleomagnetic data.

The simplest possible kinematic evolution from the proposed ca. 1.1 Ga relative reconstruction of the Congo and Kalahari cratons to that of post-Damara time would be a ~45° pivot around a local Euler pole. If the reconstructed relative positions of Congo and Kalahari persisted through Rodinia breakup, then the Damaran evolution between the two cratons might be comparable to the evolution of the Pyrenees in the Cretaceous (Vissers and Meijer, 2012). This scenario would support models for the DLZO involving a narrow ocean basin (Miller, 1983; Hanson, 2003). We propose, however, that the two cratons became far separated after ca. 1.1 Ga. Kalahari converged toward Laurentia across a distance of ~6000 km to arrive in Rodinia by ca. 1.0 Ga (Loewy et al., 2011). Congo's post–1.1 Ga motion and eventual location relative to Rodinia are less clear, but its moderately high latitude at ca. 0.92 Ga (Evans et al., 2016) is incompatible with Kalahari's low-latitude position within Rodinia at that time. Such a scenario suggests a cause-and-effect relationship between emplacement of the Umkondo LIP and initial separation of the Congo and Kalahari cratons.

Our kinematic model through the Rodinia-Gondwana supercontinental cycle thus proposes that Congo and Kalahari were "strange attractors" in Meert's (2014) terminology; their relative positions were similar before and after a large separation across the globe. We consider the age overlap and paleomagnetic data from the HE dikes and Umkondo LIP, together with alignment of the HE dikes with a major focus of Umkondo igneous activity on the Kalahari craton, as compelling support for the proposed 1.1 Ga reconstruction. How can cratons separate over large distances in a mobilistic plate-tectonic scenario and then return to rejoin each other?

The reunion of Gondwana-derived terranes in Asia serves as an example of how such moderate reshuffling can occur from one supercontinent to the next, despite wide oceans having once intervened (e.g., Metcalfe, 2011). Figure 5 shows Arabia and Australia reconstructed in their positions relative to India during mid- to late Mesozoic time, utilizing the model of Seton et al. (2012). The difference between the ca. 160 Ma and present-day locations of Arabia might appear as a simple ~60° pivot around a local Euler pole, but the ca. 80 Ma reconstruction divulges a history of ocean widening and narrowing between Arabia and India. A more dramatic set of motions is demonstrated by Australia. If current convergence relative to Eurasia continues (e.g., DeMets et al., 1994), the Australian continent will collide with Korea and Japan ~80 m.y. into the future, and the ensuing positions of India and Australia will superficially resemble their Gondwanan ancestry. Depending on the degree of lateral escape of the once-intervening island arcs during collision, there may be scant evidence of the ~5000-km-wide ocean that currently separates those two landmasses.

A dynamic explanation for this process appeals to long-term stability of circum-supercontinental

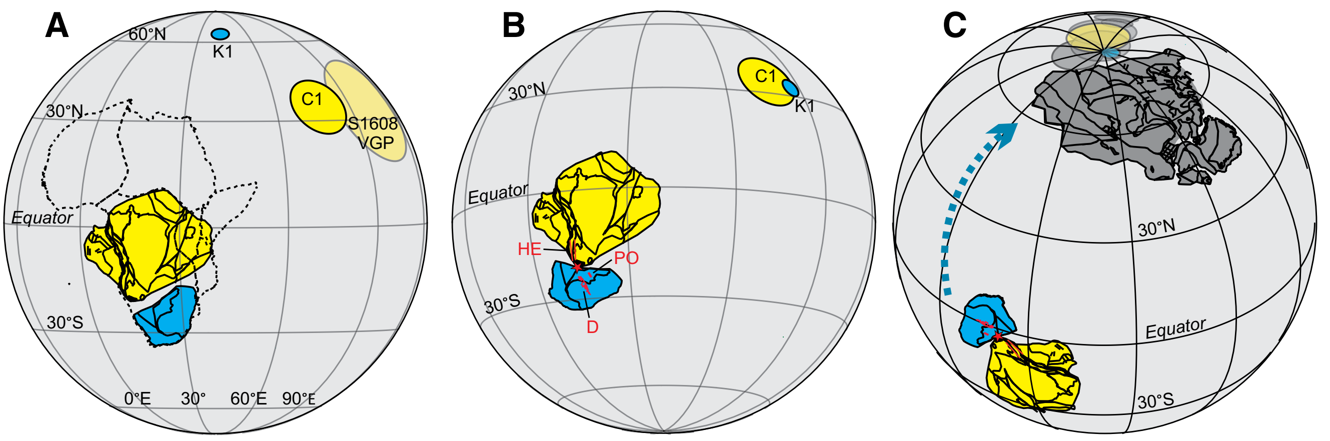

Figure 4. Paleogeographic relationships between Congo and Kalahari cratons (Africa). A: Present-day configuration with discordant paleomagnetic results from Huila-Epembe (HE) dikes (C1; this work) and Chela sill (S1608, this work) versus Umkondo large igneous province (LIP) (K1; Swanson-Hysell et al., 2015). VGP—virtual geomagnetic pole. B: Kalahari craton and Umkondo pole rotated to present-day Congo craton (Euler rotation –12.8°N, 019.0°E, –43.2°) in proposed relative configuration at 1.1 Ga. In this reconstruction, Huila-Epembe dikes on Congo craton (HE), and Dibete (D) and Proterozoic Okavango (PO) dikes on Kalahari craton (red lines) represent a radial arm of Umkondo LIP emanating from a focus near edge of Kalahari craton (red star) previously inferred by de Kock et al. (2014). C: 1.1 Ga paleogeographic reconstruction of Congo, Kalahari, and Laurentia (poles are listed in Table DR3 [see footnote 1]). Euler rotations: Congo to rotation axis (–05.7°N, 007.1°E, –124.2°) and Laurentia to rotation axis (49.7°N, 168.6°E, +66.2°). Blue arrow indicates relative motion of Kalahari craton toward its subsequent collision with Laurentia in Rodinia.

Figure 5. Reconstructed Gondwana-derived cratons in fixed-India reference frame, using rotation model of Seton et al. (2012). Orange—Arabia, purple—India, red—Australia.

subduction systems, with that surrounding Pangea as the best understood example (Richards and Engebretson, 1992). In a mantle reference frame, Australia's late Mesozoic motion had a significant eastward component. However, for the last 45 m.y., an abrupt change to northward motion along the ancient pan-Pacific subduction system suggests that it has become confined to that system (Yoshida, 2016). If, more generally, the fragments of supercontinents have motions that are similarly restricted to ~90° from the host landmass centroid, then one might expect only limited reshuffling of cratons through supercontinental cycles. Thus, the "strange attractor" phenomenon may have a plausible physical basis, even within a mobilistic, plate-tectonic conceptual framework.

ACKNOWLEDGMENTS

We thank editor Chris Clark, and Nick Swanson-Hysell and an anonymous reviewer for constructive comments, which improved our manuscript. Jorge Rosario, Jakes Smit, and Mario Sousa are thanked for their valuable help with the logistics during our 2016 field campaign in Angola. Salminen was funded by an Academy of Finland Research Fellow grant; Evans and Hanson were supported, respectively, by research grants from Yale University and Texas Christian University. Gumsley was funded by the Swedish Research Council. Ernst was partially supported by Russian Mega-Grant 14.Y26.31.0012. We thank Charlie Hoffmann and colleagues from the Geological Survey of Namibia for logistical support. This publication contributes to International Geoscience Programme (IGCP) 648 "Supercontinent Cycles and Global Geodynamics." Part of the funding for the geochronology came through the International Government-Industrial-Academic Program "Reconstruction of Supercontinents Back to 2.7 Ga Using the Large Igneous Province (LIP) Record, with Implications for Mineral Deposit Targeting, Hydrocarbon Resource Exploration, and Earth System Evolution" (www.supercontinent.org) and is publication 74 from that program (NSERC-CRD NSERC CRDPJ 419503–1).

REFERENCES CITED

Bleeker, W., and Ernst, R., 2006, Short-lived mantle generated magmatic events and their dyke swarms: The key unlocking Earth's paleogeographic record back to 2.6 Ga, *in* Hanski, E., et al., eds., Dyke Swarms—Time Markers of Crustal Evolution: London, Taylor and Francis, p. 3–26, https://doi.org/10.1201/NOE0415398992.ch1.

Boniface, N., Schenk, V., and Appel, P., 2012, Paleoproterozoic eclogites of MORB-type chemistry and three Proterozoic orogenic cycles in the Ubendian belt (Tanzania): Evidence from monazite and zircon geochronology, and geochemistry: Precambrian Research, v. 192–195, p. 16–33, https://doi.org/10.1016/j.precamres.2011.10.007.

Buchan, K.L., 2014, Reprint of "Key paleomagnetic poles and their use in Proterozoic continent and supercontinent reconstructions: A review": Precambrian Research, v. 244, p. 5–22, https://doi.org/10.1016/j.precamres.2014.01.010.

Cawood, P.A., Kröner, A., and Pisarevsky, S., 2006, Precambrian plate tectonics: Criteria and evidence: GSA Today, v. 16, no. 7, p. 4–11, https://doi.org/10.1130/GSAT01607.1.

de Kock, M.O., et al., 2014, Dykes of the 1.11 Ga Umkondo LIP, southern Africa: Clues to a complex plumbing system: Precambrian Research, v. 249, p. 129–143, https://doi.org/10.1016/j.precamres.2014.05.006.

DeMets, C., Gordon, R.G., Argus, D.F., and Stein, S., 1994, Effect of recent revisions to the geomagnetic reversal timescale on estimates of current plate motions: Geophysical Research Letters, v. 21, p. 2191–2194, https://doi.org/10.1029/94GL02118.

Ernst, R.E., Pereira, E., Hamilton, M.A., Pisarevsky, S.A., Rodriques, J., Tassinari, C.C.G., Teixeira, W., and Van-Dunem, V., 2013, Mesoproterozoic intraplate magmatic 'barcode' record of the Angola portion of the Congo craton: Newly dated magmatic events at 1505 and 1110 Ma and implications for Nuna (Columbia) supercontinent reconstructions: Precambrian Research, v. 230, p. 103–118, https://doi.org/10.1016/j.precamres.2013.01.010.

Evans, D.A.D., 2013, Reconstructing pre-Pangean supercontinents: Geological Society of America Bulletin, v. 125, p. 1735–1751, https://doi.org/10.1130/B30950.1.

Evans, D.A.D., Trindade, R.I.F., Catelani, E.L., D'Agrella-Filho, M.S., Heaman, L.M., Oliveira, E.P., Söderlund, U., Ernst, R.E., Smirnov, A.V., and Salminen, J.M., 2016, Return to Rodinia? Moderate to high paleolatitude of the São Francisco/Congo craton at 920 Ma, *in* Li, Z.X., et al., eds., Supercontinent Cycles through Earth History: Geological Society of London Special Publication 424, p. 167–190.

Goscombe, B., Foster, D.A., Gray, D., and Wade, B., 2018, The evolution of the Damara orogenic system: A record of West Gondwana assembly and crustal response, *in* Siegesmund, S., et al., eds., Geology of Southwest Gondwana: Berlin, Springer, p. 303–352, https://doi.org/10.1007/978-3-319-68920-3_12.

Gose, W.A., Hanson, R.E., Harmer, R.E., and Seidel, E.K., 2013, Reconnaissance paleomagnetic studies of Mesoproterozoic alkaline igneous complexes in the Kaapvaal craton, South Africa: Journal of African Earth Sciences, v. 85, p. 22–30, https://doi.org/10.1016/j.jafrearsci.2013.04.005.

Hanson, R.E., 2003, Proterozoic geochronology and tectonic evolution of southern Africa, *in* Yoshida, M., et al., eds., Proterozoic East Gondwana; Supercontinent Assembly and Breakup: Geological Society of London Special Publication 206, p. 427–463, https://doi.org/10.1144/GSL.SP.2003.206.01.20.

Hoffman, P.F., and Halverson, G.P., 2008, Otavi Group of the western Northern Platform, the Eastern Kaoko Zone and the western Northern Margin Zone, *in* Miller, R.McG., ed., The Geology of Namibia, Volume 2: Windhoek, Namibia, Geological Survey of Namibia, p. 69–136.

Kasbohm, J., Evans, D.A.D., Panzik, J.E., Hofmann, M., and Linneman, U., 2016, Palaeomagnetic and geochronologic data from late Mesoproterozoic redbed sedimentary rocks on the western margin of Kalahari craton, *in* Li, Z.X., et al., eds., Supercontinent Cycles through Earth History: Geological Society of London Special Publication 424, p. 145–165.

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., Dalziel, I.W.D., Pisarevsky, S., Connelly, J.N., Tait, J., Hanson, R.E., and Bullen, D., 2011, Coats Land crustal block, East Antarctica: A tectonic tracer for Laurentia?: Geology, v. 39, p. 859–862, https://doi.org/10.1130/G32029.1.

Meert, J.G., 2014, Strange attractors, spiritual interlopers and lonely wanderers: The search for pre-Pangean supercontinents: Geoscience Frontiers, v. 5, p. 155–166, https://doi.org/10.1016/j.gsf.2013.12.001.

Metcalfe, I., 2011, Palaeozoic–Mesozoic history of SE Asia, *in* Hall, R., et al., eds., The SE Asian Gateway: History and Tectonics of the Australia-Asia Collision: Geological Society of London Special Publication 355, p. 7–35.

Miller, R.McG., 1983, The Pan-African Damara orogen of Namibia, *in* Miller, R.McG., ed., Evolution of the Damara Orogen of South West Africa/Namibia: Geological Society of South Africa Special Publication 11, p. 431–515.

Miller, R.McG., 2008, Evolution of the Damara orogen, *in* Miller, R.McG., ed., The Geology of Namibia, Volume 2: Neoproterozoic to Early Palaeozoic: Windhoek, Namibia, Ministry of Mines and Energy, Geological Survey of Namibia, p. 13-390–13-410.

Rapalini, A.E., 2018, The assembly of western Gondwana: Reconstruction based on paleomagnetic data, *in* Siegesmund, S., et al., eds., Geology of Southwest Gondwana: Berlin, Springer, p. 3–18, https://doi.org/10.1007/978-3-319-68920-3_1.

Richards, M.A., and Engebretson, D.C., 1992, Large-scale mantle convection and the history of subduction: Nature, v. 355, p. 437–440, https://doi.org/10.1038/355437a0.

Salminen, J.M., Evans, D.A.D., Trindade, R.I.F., Olivera, E.P., Piispa, E.J., and Smirnov, A.V., 2016, Paleogeography of the Congo/São Francisco craton at 1.5 Ga: Expanding the core of Nuna supercontinent: Precambrian Research, v. 286, p. 195–212, https://doi.org/10.1016/j.precamres.2016.09.011.

Seton, M., et al., 2012, Global continental and ocean basin reconstructions since 200 Ma: Earth-Science Reviews, v. 113, p. 212–270, https://doi.org/10.1016/j.earscirev.2012.03.002.

Stern, R.J., 2005, Evidence from ophiolites, blueschists, and ultrahigh-pressure metamorphic terranes that the modern episode of subduction tectonics began in Neoproterozoic time: Geology, v. 33, p. 557–560, https://doi.org/10.1130/G21365.1.

Swanson-Hysell, N.L., Kilian, T.M., and Hanson, R.E., 2015, A new grand mean palaeomagnetic pole for the 1.11 Ga Umkondo large igneous province with implications for palaeogeography and the geomagnetic field: Geophysical Journal International, v. 203, p. 2237–2247, https://doi.org/10.1093/gji/ggv402.

Van der Voo, R., 1990, The reliability of paleomagnetic data: Tectonophysics, v. 184, p. 1–9, https://doi.org/10.1016/0040-1951(90)90116-P.

Vissers, R.L.M., and Meijer, P.Th., 2012, Mesozoic rotation of Iberia: Subduction in the Pyrenees?: Earth-Science Reviews, v. 110, p. 93–110, https://doi.org/10.1016/j.earscirev.2011.11.001.

Yoshida, M., 2016, Formation of a future supercontinent through plate motion–driven flow coupled with mantle downwelling flow: Geology, v. 44, p. 755–758, https://doi.org/10.1130/G38025.1.

Printed in USA