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RESEARCH FOCUS

Whither the supercontinent cycle?

J. Brendan Murphy
Department of Earth Sciences, St. Francis Xavier University, Antigonish, Nova Scotia B2G 2W5, Canada

The concept of episodicity in tectonic processes pre-dates acceptance of the plate tectonic paradigm (e.g., Umbgrove, 1940; Holmes, 1951; Sutton, 1963). It was specifically advocated by Wilson (1966) when he made the case that ocean basins repeatedly opened and closed, a process now known as "Wilson cycles" (Dewey and Burke, 1974). The relationship between tectonic episodicity and the supercontinent cycle was first proposed by Worsley et al. (1982, 1984), who argued that episodic peaks in the number of continental collisions reflect supercontinent amalgamation, and that episodes of rift-related mafic dike swarms record supercontinent breakup. These authors identified trends in tectonic activity, platform development, climate, life and stable isotopes that accompanied supercontinent amalgamation, breakup and dispersal (Nance et al. 2013). Although not universal (e.g., Stern, 2008), a broad consensus has emerged over the past 30 years that repeated cycles of supercontinent amalgamation and dispersal occurred since the late Archean, with profound effect on the evolution of the Earth's geosphere, hydrosphere, atmosphere and biosphere. Statistical peaks in the age distributions of orogenic granites and detrital zircons, as well as negative ε_{Hf} excursions in zircons may match the timing of supercontinent amalgamation. As Hf is the more incompatible element, Lu/Hf is lower in the crust and higher in the depleted mantle relative to the bulk earth, and the crust therefore evolves towards negative εHf values. Whether these εHf data imply episodicity, a preservational bias, or a combination of both phenomena is debated (e.g., Roberts, 2012; Cawood et al., 2013; Nance et al., 2013).

The mechanisms potentially responsible for the supercontinent cycle remain controversial, with paleocontinental reconstructions interpreted in different ways. For example, continental reconstructions for the ca. 800–650 Ma breakup of Rodinia (e.g., Hoffman, 1991; Li et al., 2008) imply that Gondwana (part of Pannotia; see Dalziel, 2013) was assembled by preferential subduction of relatively old oceanic lithosphere around Rodinia (the exterior ocean of Murphy and Nance, 2003), whereas Paleozoic (545-245 Ma) continental reconstructions (e.g., Stampfli and Borel, 2002; Scotese, 2007) imply that Pangea was formed by preferential subduction of the relatively young oceanic lithosphere formed by the breakup of Pannotia (the interior oceans of Murphy and Nance, 2003).

Two papers in this issue of *Geology* (Spencer et al., 2013, p. 795; Van Kranendonk and Kirkland, 2013, p. 735) add to the increasing evidence that no two supercontinents form in the same manner, and that the processes responsible for their formation have changed with time (e.g., Bradley, 2011; Condie, 2011; Nance et al., 2013). Both use isotopic proxy methods in an effort to understand the behavior of continental margins during supercontinent amalgamation: Spencer et al. compare the amalgamation of Rodinia and Gondwana, van Kranendonk and Kirkland focus on amalgamation of Rodinia and Grenville orogenesis.

Spencer et al. describe marked differences in seawater Sr and zircon Hf isotopic signatures during the 750–550 Ma amalgamation of Gondwana, and the 1250–980 Ma amalgamation of Rodinia (Cawood et al., 2013). Variations in the initial $^{87}Sr/^{86}Sr$ ratios of seawater through time provide a record of the influences of enhanced continental weathering accompanying orogenesis (high initial Sr) relative to ocean ridge spreading and increased hydrothermal activity (low initial Sr), and thus are sensitive supercontinent amalgamation and breakup (respectively). Sr initial ratios during the Late Neoproterozoic–Early Cambrian were higher than at any time in the past 1.0 g.y. (Veizer et al., 1999), which has been related to enhanced continental weathering during and following Gondwanan collisions. A pronounced negative excursion in the ε_{Hf} (zircon) data suggests that the weathered material was predominantly recycled ancient continental crust (Belousova et al., 2010; Collins et al., 2011).

But amalgamation of Rodinia is hard to decipher from either proxy record. Initial Sr values started to decrease at ca. 1.8 Ga, and maintained this decline until ca. 750 Ma, whereas ε_{Hf} (zircon) values remained close to those of CHUR (Chondritic Uniform Reservoir) from ca. 1.6–0.7 Ga (with the exception of modest, ca. 20-50 m.y. excursions). Given the unprecedented scale of orogenesis associated with the assembly of Rodinia (Beaumont et al., 2010), the lack of significant changes in the Sr seawater and ε_{Hf} (zircon) suggests that relatively juvenile crust was recycled during its amalgamation, compatible with evidence that the eastern flank (modern coordinates) of Laurentia was a Pacific-type margin for nearly 0.8 g.y. prior to collision, and produced abundant juvenile crust between 1.7 and 1.3 Ga (e.g., Åhäll, and Gower, 1997; Dickin, 2000).

These contrasting signatures are interpreted to reflect ocean closure by way of single-sided (Gondwana) versus two-sided (Rodinia) subduction zones. The former leads to collision between a passive margin and juvenile continental arc, the latter between crust generated by two juvenile arc systems.

An important corollary of this study is that it reaffirms the status of Gondwana (or Gondwana plus Laurentia = Pannotia; Dalziel, 2013) as a supercontinent. The proxy data clearly indicate that the amalgamation of Gondwana produced very strong, global signals. The Early Paleozoic development of the Iapetus ocean has been assigned to "the final breakup of Rodinia" (e.g., Li et al., 2008; Bradley 2011), but this masks the importance of Gondwana assembly for global Late Neoproterozoic events, including an explosion in biological activity, and dramatic climate swings (e.g., Hoffman et al., 1998; Knoll, 2013). The proxy records for the Early Paleozoic breakup that led to the development of the Iapetus and Rheic oceans are characterized by decreasing initial Sr and increasing ε_{Hf} (zircon), consistent with enhanced ocean ridge activity, and show a very different signal than earlier phases of Rodinia breakup. These trends are matched by the formation of passive margins (Bond et al., 1984), and a sharp rise in sea level (e.g., Miller et al., 2005) during the Early Paleozoic, when continental subsidence and the formation of youthful (and more elevated) ocean floor resulted in progressively less relative contribution from continental weathering.

Secular differences between Archean and Phanerozoic terranes (e.g., higher abundance of komatiites, tonalite–trondhjemite–granodiorite [TTG] intrusions, and banded iron formations in Archean terranes; blueschists only in Phanerozoic terranes, etc.) were accommodated within the original concept of Worsley et al. (1984), and are generally attributed to higher mantle temperatures and an oxygen-poor atmosphere in the Archean (e.g., Brown, 2008; Campbell and Allen, 2008). In contrast, van Kranendonk and Kirkland propose that the amalgamation of Rodinia occurred during a limited time window when Earth was characterized by a Goldilocks combination of "thicker plates on a warmer Earth, with more rapid continental drift relative to modern Earth." Contributing to rapid continental drift is the enhanced slab pull of a thicker oceanic lithosphere. In their view, this "Goldilocks" scenario can explain the unprecedented level of crustal recycling, as indicated by the global $\delta^{18}O$ zircon database, and the enormous scale of Grenvillian orogens. The scenario envisaged

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prior to Rodinia's amalgamation is one of tectonic switching (Collins, 2002) between juvenile crustal formation during episodes of roll-back, and crustal recycling/accretion during episodes of compression. This scenario is broadly compatible with that envisaged by Spencer et al. who indicate that recycled and subducted material was predominantly juvenile.

Clearly, there has been much recent progress in understanding the configuration of supercontinents, the timing of their amalgamation and breakup, as well as their relation to the evolution of the hydrosphere, atmosphere and biosphere. The two papers in this issue provide further evidence that no two supercontinents form in the same way, and that the mechanisms responsible for their amalgamation and breakup remain elusive.

A possible way forward would be to integrate the geological constraints provided by proxy records with numeric models. Since the pioneering work of Gurnis (1988) there have been significant advances in numerical modeling to simulate supercontinent amalgamation and breakup at realistic timescales (e.g., Zhang et al., 2009; Yoshida and Santosh, 2011). It would be interesting indeed to know whether and how these models could be tweaked to allow supercontinents to form in the manner implied by proxy data sets.

REFERENCES CITED

Åhäll, K.-I., and Gower, C.F., 1997, The Gothian and Labradorian orogens: Variations in accretionary tectonism along late Paleoproterozoic Laurentia-Baltica margin: GFF, v. 119, p. 181–191, doi:10.1080/11035899709546475.

Beaumont, C., Jamieson, R., and Nguyen, M., 2010, Models of large, hot orogens containing a collage of reworked and accreted terranes: Canadian Journal of Earth Sciences, v. 47, p. 485–515, doi:10.1139/E10-002.

Belousova, E.A., Kostitsyn, Y.A., Griffin, W.L., Begg, G.C., O'Reilly, S.Y., and Pearson, N.J., 2010, The growth of continental crust: Constraints from Hf-isotope data: Lithos, v. 119, p. 457–466, doi:10.1016/j.lithos.2010.07.024.

Bond, G.C., Nickeson, P.A., and Kominz, M.A., 1984, Breakup of a supercontinent between 625 Ma and 555 Ma: New evidence and implications for continental histories: Earth and Planetary Science Letters, v. 70, p. 325–345, doi:10.1016/0012-821X(84)90017-7.

Dewey, J.F., and Burke, K., 1974, Hot spots and continental breakup: implications for collisional orogeny: Geology, v. 2, p. 57–60, doi:10.1130/0091-7613(1974)2<57:HSACBI>2.0.CO;2.

Bradley, D.C., 2011, Secular trends in the geologic record and the supercontinent cycle: Earth and Planetary Science Letters, v. 108, p. 16–33.

Brown, M., 2008, Characteristic thermal regimes of plate tectonics and their metamorphic imprint throughout Earth history: When did Earth first adopt a plate tectonics mode of behavior? *in* Condie, K.C., and Pease, V., eds., When Did Plate Tectonics Begin on Earth?: Geological Society of America Special Paper, 440, pp. 97–128.

Campbell, I.H., and Allen, C.M., 2008, Formation of supercontinents linked to increases in atmospheric oxygen: Nature Geoscience, v. 1, p. 554–558, doi:10.1038/ngeo259.

Cawood, P.A., Hawkesworth, C.J., and Dhuime, B., 2013, The continental record and the generation of continental crust: Geological Society of America Bulletin, v. 125, p. 14–32, doi:10.1130/B30722.1.

Collins, W.J., 2002, Hot orogens, tectonic switching, and creation of continental crust: Geology, v. 30, p. 535–538, doi:10.1130/0091-7613(2002)030<0535:HOTSAC>2.0.CO;2.

Collins, W.J., Belousova, E.A., Kemp, A.I.S., and Murphy, J.B., 2011, Two contrasting Phanerozoic orogenic systems revealed by Hf isotope data: Nature Geoscience, v. 4, p. 333–337, doi:10.1038/ngeo1127.

Condie, K.C., 2011, The supercontinent cycle. Earth as an Evolving Planetary System, New York, Academic Press, p. 317–355 (Chapter 8).

Dalziel, I.W.D., 2013, Antarctica and supercontinent evolution: clues and puzzles: Earth and Environmental Transactions of the Royal Society of Edinburgh (in press).

Dickin, A.P., 2000, Crustal formation in the Grenville province: Nd isotopic evidence: Canadian Journal of Earth Sciences, v. 37, p. 165–181, doi:10.1139/e99-039.

Gurnis, M., 1988, Large-scale mantle convection and the aggregation and dispersal of supercontinents: Nature, v. 332, p. 695–699, doi:10.1038/332695a0.

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

Hoffman, P.F., Kaufman, A.J., Halverson, G.P., and Schrag, D.P., 1998, A Neoproterozoic Snowball Earth: Science, v. 281, p. 1342–1346, doi:10.1126/science.281.5381.1342.

Holmes, A., 1951, The sequence of Precambrian orogenic belts in south and central Africa: 18th International Geological Congress, London (1948), Part 14, p. 254–269.

Knoll, A.H., 2013, Systems paleobiology: Geological Society of America Bulletin, v. 125, p. 3–13, doi:10.1130/B30685.1.

Li, Z.X., an 16 others, 2008, Assembly, configuration, and break-up history of Rodinia: A synthesis: Precambrian Research, v. 160, p. 179–210, doi:10.1016/j.precamres.2007.04.021.

Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., and Pekar, S.F., 2005, The Phanerozoic record of global sea-level change: Science, v. 310, p. 1293–1298, doi:10.1126/science.1116412.

Murphy, J.B., and Nance, R.D., 2003, Do supercontinents introvert or extrovert?: Sm–Nd isotopic evidence: Geology, v. 31, p. 873–876, doi:10.1130/G19668.1.

Nance, R.D., Murphy, J.B., and Santosh, M., 2013, The supercontinent cycle: A retrospective essay: Gondwana Research, doi:10.1016/j.gr.2012.12.026, (in press).

Roberts, N.M.W., 2012, Increased loss of continental crust during supercontinent amalgamation: Gondwana Research, v. 21, p. 994–1000, doi:10.1016/j.gr.2011.08.001.

Scotese, C.R., 2007, PALEOMAP Project: http://www.scotese.com/future2.htm.

Spencer, C.J., Hawkesworth, C., Cawood, P.A., and Dhuime, B., 2013, Not all supercontinents are created equal: Gondwana-Rodinia case study: Geology, v. 41, p. 795–798, doi:10.1130/G34520.1.

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 isochrones: Earth and Planetary Science Letters, v. 196, p. 17–33, doi:10.1016/S0012-821X(01)00588-X.

Stern, R.J., 2008, Modern-style plate tectonics began in Neoproterozoic time: An alternative interpretation of Earth's tectonic history, *in* Condie, K.C., and Pease, V., eds., When did plate tectonics begin on Earth?: Geological Society of America Special Paper, 440, pp. 265–280, doi:10.1130/2008.2440(13).

Sutton, J., 1963, Long-term cycles in the evolution of the continents: Nature, v. 198, p. 731–735, doi:10.1038/198731b0.

Umbgrove, J.H.F., 1940, Periodicity in terrestrial processes: American Journal of Science, v. 238, p. 573–576, doi:10.2475/ajs.238.8.573.

Van Kranendonk, M.J., and Kirkland, C.L., 2013, Orogenic climax of Earth: The 1.2–1.1 Ga Grenvillian superevent: Geology, v. 41, p. 735–738, doi:10.1130/G34243.1.

Veizer, J., et al., 1999, $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$, $\delta^{13}\mathrm{C}$ and $\delta^{18}\mathrm{O}$ evolution of Phanerozoic seawater: Chemical Geology, v. 161, p. 59–88, doi:10.1016/S0009-2541(99)00081-9.

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

Worsley, T.R., Nance, R.D., and Moody, J.B., 1982, Plate tectonic episodicity: a deterministic model for periodic "Pangeas": Eos [Transactions, American Geophysical Union], v. 65, no. 45, p. 1104.

Worsley, T.R., Nance, R.D., and Moody, J.B., 1984, Global tectonics and eustasy for the past 2 billion years: Marine Geology, v. 58, p. 373–400, doi:10.1016/0025-3227(84)90209-3.

Yoshida, M., and Santosh, M., 2011, Supercontinents, mantle dynamics and plate tectonics: A perspective based on conceptual vs. numerical models: Earth-Science Reviews, v. 105, p. 1–24, doi:10.1016/j.earscirev.2010.12.002.

Zhang, N., Zhong, S., and McNamara, A.K., 2009, Supercontinent formation from stochastic collision and mantle convection models: Gondwana Research, v. 15, p. 267–275, doi:10.1016/j.gr.2008.10.002.

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