ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/239938661

Origins of the supercontinent cycle

Article *in* Geoscience Frontiers · July 2013

DOI: 10.1016/j.gsf.2012.12.007

CITATIONS
105

READS
4,803

2 authors:

R. Damian Nance
Ohio University
252 PUBLICATIONS 9,670 CITATIONS

SEE PROFILE

J. Brendan Murphy
St. Francis Xavier University
310 PUBLICATIONS 12,137 CITATIONS

SEE PROFILE

Some of the authors of this publication are also working on these related projects:

Project Special Paper of the Geological Society of America View project

Project Supercontinent Cycle View project

All content following this page was uploaded by R. Damian Nance on 16 May 2014.

The user has requested enhancement of the downloaded file.

Geoscience Frontiers 4 (2013) 439–448

Contents lists available at SciVerse ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Focus paper

Origins of the supercontinent cycle

R. Damian Nance [a,*], J. Brendan Murphy [b]

[a] Department of Geological Sciences, 316 Clippinger Laboratories, Ohio University, Athens, OH 45701, USA
[b] Department of Earth Sciences, St. Francis Xavier University, Antigonish, Nova Scotia B2G 2W5, Canada

A R T I C L E I N F O

Article history:
Received 12 November 2012
Received in revised form
13 December 2012
Accepted 21 December 2012
Available online 8 January 2013

Keywords:
Supercontinent cycle
Plate tectonics
Tectonic episodicity
Secular trends

A B S T R A C T

The supercontinent cycle, by which Earth history is seen as having been punctuated by the episodic assembly and breakup of supercontinents, has influenced the rock record more than any other geologic phenomena, and its recognition is arguably the most important advance in Earth Science since plate tectonics. It documents fundamental aspects of the planet's interior dynamics and has charted the course of Earth's tectonic, climatic and biogeochemical evolution for billions of years. But while the widespread realization of the importance of supercontinents in Earth history is a relatively recent development, the supercontinent cycle was first proposed thirty years ago and episodicity in tectonic processes was recognized long before plate tectonics provided a potential explanation for its occurrence. With interest in the supercontinent cycle gaining momentum and the literature expanding rapidly, it is instructive to recall the historical context from which the concept developed. Here we examine the supercontinent cycle from this perspective by tracing its development from the early recognition of long-term episodicity in tectonic processes, through the identification of tectonic cycles following the advent of plate tectonics, to the first realization that these phenomena were the manifestation of episodic supercontinent assembly and breakup.

© 2013, China University of Geosciences (Beijing) and Peking University. Production and hosting by Elsevier B.V. All rights reserved.

1. Introduction

Although the existence of the supercontinent Pangea (Fig. 1) was first proposed a century ago (Wegener, 1912), the proposition that other supercontinents existed prior to Pangea (e.g., Valentine and Moores, 1970; Piper, 1974, 1975; Piper et al., 1976) has only become widely accepted over the past two decades (e.g., Hoffman, 1989, 1991; Dalziel, 1991, 1992, 1997; Williams et al., 1991; Stump, 1992; Powell et al., 1993; Powell, 1995). This has led, in recent years, to a rapidly widening recognition that much of Earth history has been punctuated by the episodic amalgamation and breakup of supercontinents (e.g., Zhao et al., 2002, 2004; Murphy and Nance, 2003, 2013; Rogers and Santosh, 2003, 2004; Santosh and Zhao, 2009; Condie, 2011; Yoshida and Santosh, 2011; Huston et al., 2012; Mitchell et al., 2012) with profound consequences to the Earth's geologic, climatic and biological records (e.g., Hoffman et al., 1998; Hoffman and Schrag, 2002; Lindsay and Brasier, 2002; Dewey, 2007; Condie et al., 2009, 2011; Goldfarb et al., 2010; Hawkesworth et al., 2010; Santosh, 2010a,b; Bradley, 2011; Hannisdal and Peters, 2011; Strand, 2012; Young, 2012a,b). This history of episodic supercontinent assembly and breakup, which constitutes the supercontinent cycle, has influenced the rock record more profoundly than any other geologic phenomenon (e.g., Condie, 2011). Its existence points to fundamental aspects of the Earth's interior dynamics (e.g., Condie, 2003; Evans, 2003; Zhong et al., 2007; Santosh et al., 2009; Zhang et al., 2009) and its recent recognition is arguably the most important advance in Earth Science since the advent of plate tectonics.

Yet the idea of a supercontinent cycle was first advanced thirty years ago, and the notion of episodicity in tectonic processes predates plate tectonics by decades. So while the widespread recognition of the significance of supercontinents in Earth history is a relatively recent phenomenon, a long history has led to this fundamental realization. In this paper, we provide an historical perspective to this important and rapidly growing development in Earth Science by tracing the history of the supercontinent cycle

* Corresponding author.
E-mail address: nance@ohio.edu (R. Damian Nance).

Peer-review under responsibility of China University of Geosciences (Beijing)

Production and hosting by Elsevier

1674-9871/$ – see front matter © 2013, China University of Geosciences (Beijing) and Peking University. Production and hosting by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.gsf.2012.12.007

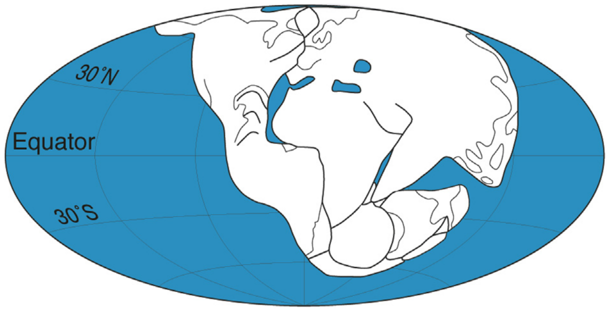


Figure 1. The late Paleozoic supercontinent Pangea as envisioned by Wegener (1922) (from Domeier et al., 2012).

from its beginnings in the many pre-plate tectonic ideas on episodicity in geologic processes to the first recognition that this episodicity was a manifestation of the assembly and breakup of supercontinents.

2. Episodicity prior to plate tectonics

Recognition of episodicity in tectonic processes occurred long before plate tectonics provided the framework to account for its occurrence. Of the many early advocates for such tectonic episodicity, one of the first, and certainly the most prescient, was the Dutch geologist Johannes Umbgrove who was arguing for periodicity in terrestrial processes more than two decades before the seminal papers on sea-floor spreading by Dietz (1961), Hess (1962) and Vine and Matthews (1963) ushered in the theory of plate tectonics (Umbgrove, 1940). In his remarkably modern book, “The Pulse of the Earth” Umbgrove (1947) complied a wealth of data in support of a ~250 m.y. periodicity in Phanerozoic sea level, orogeny, basin formation, climate and magmatic activity (Fig. 2). Consistent with the assembly and breakup of a supercontinent, he further argued that there were stages to this periodicity in which global sea level regression accompanied by increased crustal compression, continental erosion and climatic deterioration, was followed by orogeny, granitoid magmatism and glaciation, and finally, by mafic magmatism, global transgression and climatic amelioration.

Over the following two decades, tectonic episodicity was advocated by some of the foremost geologists of the day and was recognized in a wide variety of phenomena. For example, orogenic episodicity was recognized in Precambrian fold belts by Holmes (1951), Wilson et al. (1960) and Burwash (1969), and periodicity in the formation of continental crust was proposed by Holmes (1954) and further developed by Gastil (1960). Distinct peaks were also noticed in early radiometric age compilations (Voitkevich, 1958; Vinogradov and Tugarinov, 1962; Runcorn, 1962, 1965; Dearnly, 1966), and the notion of tectonic episodicity was inherent in the cratonic sequences recognized by Sloss (1963), whereby the late Precambrian to recent sedimentary record of the continental interior of North America was shown to comprise six major rock-stratigraphic units separated by regional unconformities.

But of all the early advocates for tectonic episodicity, it was Sutton (1963) who came closest to formulating a supercontinent cycle. His “chelogenic cycles”, or global-scale shield-forming events, called for the episodic clustering of continents. However, rather than producing a supercontinent, the chelogenic cycle resulted in the periodic recurrence of two antipodal continental clusters, the assembly and breakup of which were held to be responsible for the record of orogenic episodicity. The cycle was thought to occur because small subcontinental convection cells first resulted in continental clustering and orogeny in continental interiors, but then coalesced into larger cells that fostered continental breakup, orogenic quiescence, and the later regrouping of the rifted continental blocks into two new antipodal clusters. According to Sutton, the cycle had a periodicity of 750–1250 m.y. and had been repeated at least four times during Earth history.

3. Plate tectonics and tectonic cycles

Following the introduction of plate tectonics, the concept of tectonic episodicity was specifically advocated by Wilson (1966) in what are now known as the “Wilson cycles” of ocean opening and closure. The concept was also employed in regard to evolutionary biogenesis by Valentine and Moores (1970) and Hallam (1974) who showed how Phanerozoic marine diversity and sea level fluctuations could be related to patterns of continental fragmentation and reassembly with close correspondence to the observed geological record.

Episodicity was also observed in the pattern of Phanerozoic sedimentary cycling by Mackenzie and Pigott (1981), who argued that the cyclic nature of Phanerozoic sedimentary rock distribution and material transfer among sedimentary reservoirs were controlled by tectonic factors, and that a strong tectonically controlled correlation existed between the long-term cyclicity in the Phanerozoic global sea level curve and the distribution of carbon and sulfur among the major exogenic reservoirs.

Tectonic episodicity was also identified in the distribution of ore-forming processes through time by Meyer (1981), who linked such episodicity to characteristic peaks in the abundance of specific styles of metallic mineralization. Tectonic cycling was also recognized in the Phanerozoic record of strontium isotopes by Burke et al. (1982), whose curve for the variation of seawater $^{87}Sr/^{86}Sr$ with time was shown to be strongly influenced by the history of both plate interactions and sea-floor spreading. The episodicity in orogeny observed by earlier workers also found support in increasingly precise radiometric ages, most clearly illustrated in the compilation (Fig. 3) of Condie (1982).

The case for episodicity in geologic phenomena was brought to a culmination by Fischer (1981, 1984), who revived Umbgove's (1947) visionary model in a plate tectonic context. Using a geologic timescale 100 m.y. longer than that employed by Umbgrove, Fischer's compilation of the available data made a compelling case for two ~300 m.y. supercycles in the Phanerozoic record of climate, sea level and granitoid magmatism (Fig. 4). He interpreted the “greenhouse” to “ice house” climatic supercycles as reflecting variations in the levels of atmospheric CO_2 caused by changes in the pattern of mantle convection recorded in concordant variations in global sea level and the proxy record of felsic volcanism in the emplacement of granitoids. Fischer further linked oceanic aeration to periods of global cooling and showed that several major biotic crises coincided with the boundaries between climatic states.

4. Recognition of the supercontinent cycle

Despite compelling evidence for episodicity in geologic processes, it would be seventy years after Wegener's (1912) vision of moving continents, and more than forty years following Umbgrove's (1940, 1947) insightful claim for periodicity in terrestrial processes, that a case would be made that this long-recognized history of tectonic episodicity was the manifestation of a long-term cycle of supercontinent assembly and breakup. The case for such a supercontinent cycle was first put forward by Worsley et al. (1982, 1984).

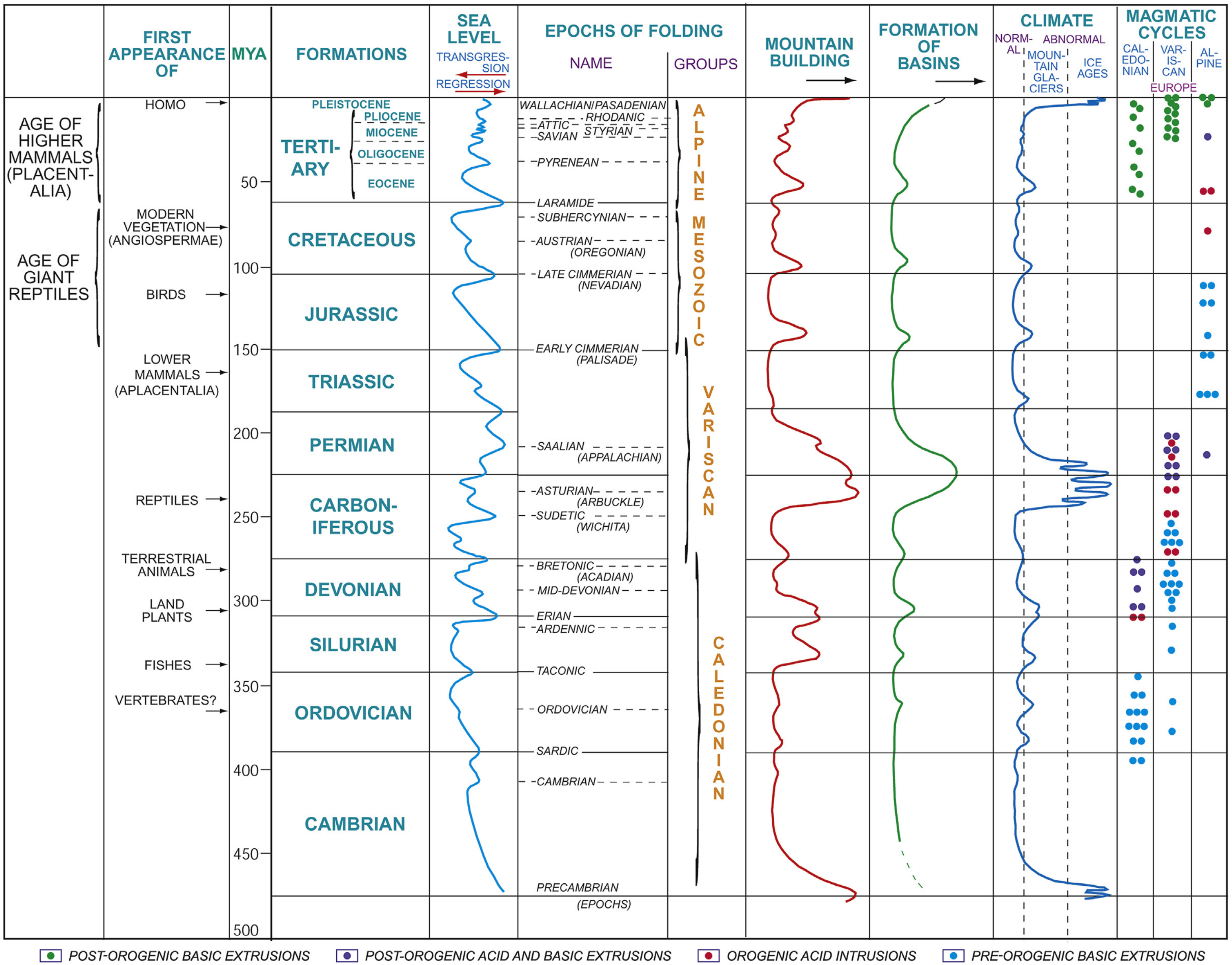


Figure 2. Summary of Umbgrove's (1947) ~250 m.y. "pulse" in the Phanerozoic history of sea level, mountain building, basin formation, climate and magmatic cycles.

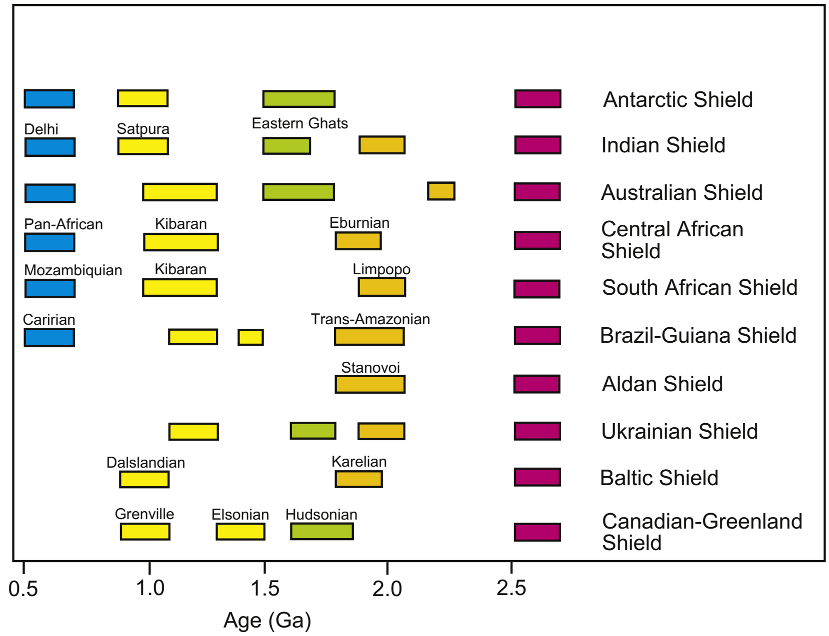


Figure 3. Compilation of radiometric ages (chiefly Rb/Sr) for periods of major orogenesis in Earth history (after Condie, 1982). These data were taken by Worsley et al. (1984) to document the "quasi-periodic" assembly of supercontinents.

4.1. A case presented

Since the amalgamation of supercontinents requires continents to collide, whereas supercontinent breakup requires them to rift, Worsley et al. (1984) argued that evidence of a supercontinent cycle would be documented in the geologic record by episodic peaks in collisional orogenesis and rift-related mafic dike swarms. Using the available age data for such events (chiefly Rb/Sr and K/Ar), then recently compiled by Condie (1976, 1982) and Windley (1977, 1984), they suggested that such peaks could be distinguished and that global episodes of orogenic activity lagged slightly by mafic dike swarms had punctuated Earth history at relatively regular intervals of about 500 m.y. for at least the past 2.5 billion years.

Based on these data, Worsley et al. (1984) predicted the existence of four, and later five (Worsley et al., 1985; Nance et al., 1986), pre-Pangean supercontinents at ca. 0.6, 1.1, 1.8–1.6, 2.0 and 2.6 Ga (Fig. 5). From this compilation, they additionally recognized an apparent coincidence of supercontinents with ice ages, and a correspondence of supercontinent breakup with major evolutionary events. This suggested a controlling connection between supercontinents, climate and biogenesis, which they suggested was a likely consequence of the profound effect of the supercontinent cycle on sea level.

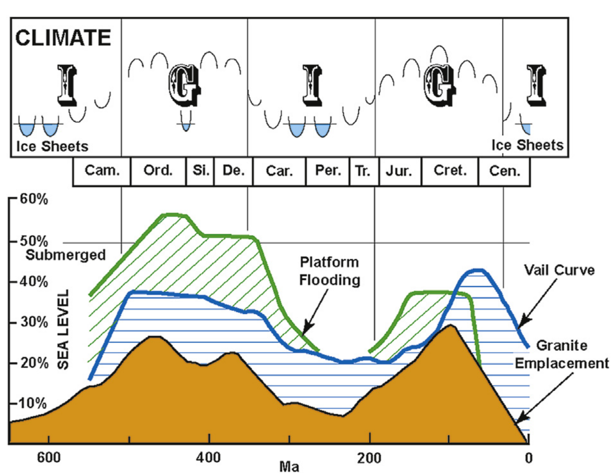


Figure 4. Outline of the two ~300 m.y. supercycles of Fischer (1981, 1884) in the Phanerozoic record of climate, sea level (after Vail et al., 1977) and granitoid magmatism (after Engel and Engel, 1964).

Worsley et al. (1984) attempted to model the cycle's effect on sea level by applying Parsons and Sclater's (1971) age-versus-depth relation for oceanic lithosphere to Berger and Winterer's (1974) calculations for the average age of the world's oceanic crust as a function of the breakup of Pangea. These calculations determined the changes in sea floor age and, hence, ocean volume, that would occur when an entirely "Pacific-type" world ocean bordered by active margins (i.e., supercontinentality) evolves toward one with a uniformly increasing proportion of "Atlantic-type" ocean bordered by passive margins (i.e., supercontinent dispersal). In this way, they were able to broadly quantify the changes in global sea level that might be expected to result from the supercontinent cycle's independent effects on ocean basin volume and continental elevation (Fig. 6).

For supercontinental breakup, their calculations suggested (like those of Heller and Angevine, 1985) that crustal extension and the formation of young ocean basins would first cause sea level to rise, only to fall as the floors of the new oceans aged. On the other hand, during supercontinent assembly, subduction of old oceanic lithosphere coupled with the crustal shortening associated with orogenesis would cause sea level to rise again.

In addition, drawing on Anderson's (1982) assertion that continental lithosphere should act as a thermal insulator to mantle heat flow, Worsley et al. (1984) argued that supercontinents would become epeirogenically uplifted as heat accumulated beneath them. They suggested a minimum figure of 400 m for this epeirogenic uplift based on available data (Hay and Southam, 1977; Harrison et al., 1981) for the present day thermal elevation of near-stationary Africa. The resulting model curve (Fig. 6) simply combined the sea floor and continental components.

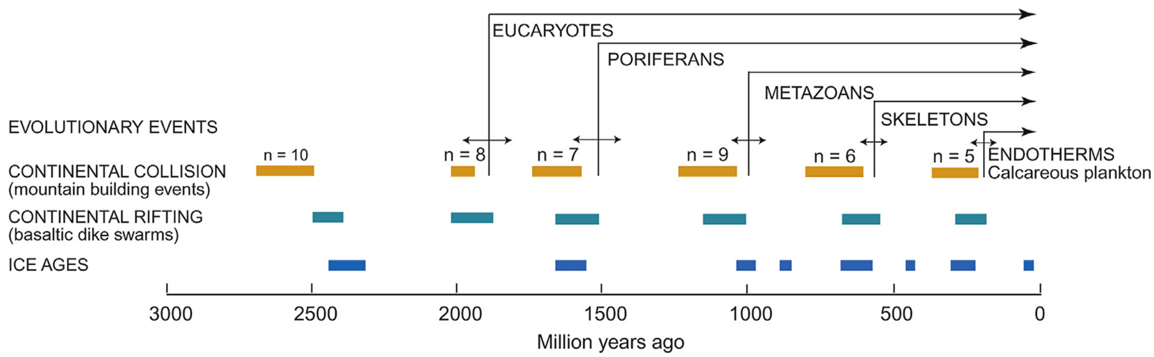


Figure 5. Summary of episodic events in Earth history linked to the supercontinent cycle by Worsley et al. (1984, 1985). Orogenic peaks (supercontinent assembly) from Condie (1976, 1982), lagging mafic dike swarms (supercontinent breakup) from Windley (1977), major evolutionary events from Cloud (1968a,b, 1976), and major glacial intervals from Frakes (1979) and Christie-Blick (1982).

Calibrated to the Phanerozoic using the known amalgamation and breakup ages for Pangea, Worsley et al. (1984) were able to show (Fig. 7) that their model sea level curve closely matched the first-order sea level curve of Vail et al. (1977). The supercontinent cycle so defined had a duration of about 440 m.y., and predicted amalgamation of the next supercontinent in roughly 150 m.y.

4.2. A potential mechanism proposed

Worsley et al. (1984) suggested a potential driving mechanism for the supercontinent cycle might be found in the counteracting influences of the insulating effect of supercontinents on mantle heat flow (Anderson, 1982), and the cooling effect of age on the buoyancy of oceanic lithosphere (Parsons and Sclater, 1971; Hynes, 1982). They argued that the former might be expected to lead to the eventual breakup of supercontinents as heat accumulated beneath them, whereas the latter might be expected to result in supercontinent assembly since it ensured that the new oceans created by supercontinent breakup would eventually close (Nance et al., 1988). This mechanism was based on the history of Pangea and has come to be known as introversion (Murphy and Nance, 2003), which Worsley et al. (1984) preferred over extroversion, by which supercontinents are assembled by the closure of the exterior ocean (e.g., Gurnis, 1988), since this required the interior oceans to age well beyond their maximum age in today's world of 180 m.y.

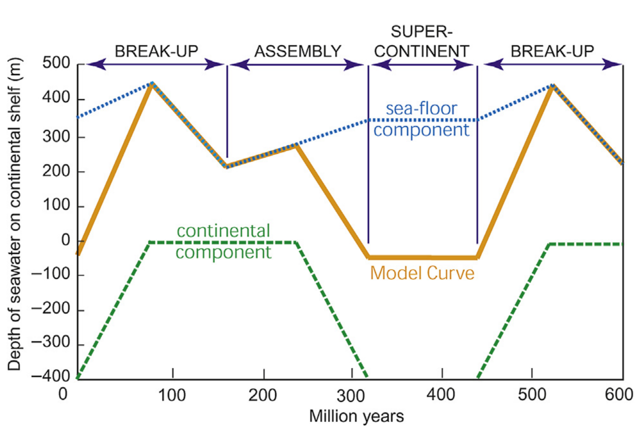


Figure 6. Tectonic components (ocean basin volume and continental elevation) of sea-level change for the three main phases of the supercontinent cycle (breakup, assembly, supercontinentality) and the model sea level curve obtained by their summation (Worsley et al., 1982, 1984).

4.3. Potential consequences examined

Worsley et al. (1985, 1986, 1991), Nance et al. (1986) and Worsley and Nance (1989) subsequently explored the potential influence of the supercontinent cycle on the Earth's tectonic, biogeochemical and paleoceanographic record (Fig. 8). Subdividing the cycle into three main phases – supercontinentality, breakup and dispersal, and supercontinent assembly – they identified a variety of trends in tectonic activity, platform sedimentation, climate, life, and the stable isotope record that might be expected to accompany each phase.

Among these trends, they argued that, during supercontinentality: (1) tectonic activity should be dominated by epeirogenic uplift as trapped mantle heat accumulates beneath the largely stationary supercontinent, (2) accretionary orogeny might be expected at the margins of the exterior (Panthalassic) ocean, now at its largest size, (3) with sea level at its lowest elevation, terrestrial deposition should be enhanced, (4) sequestering of isotopically light carbon in non-marine and organic-rich sediments, and heavy sulfur in evaporites, might be expected to produce a record of low $\delta^{13}C$ and $\delta^{34}S$ in the reciprocal marine platform reservoir, (5) massive extinctions might be expected to accompany loss of shallow marine habitat, and (6) cold climates (potentially leading to continental glaciation) might be expected to develop as CO_2 is removed from the atmosphere by the weathering of large areas of subaerially exposed continental crust.

During supercontinent breakup and dispersal, they argued that: (1) younging of the world ocean floor through rifting and the opening of new (interior) ocean basins, coupled with subsidence of dispersing continental fragments, should raise sea level to its maximum elevation, (2) collisional orogeny should be minimal, although accretionary orogeny and terrane accretion might be

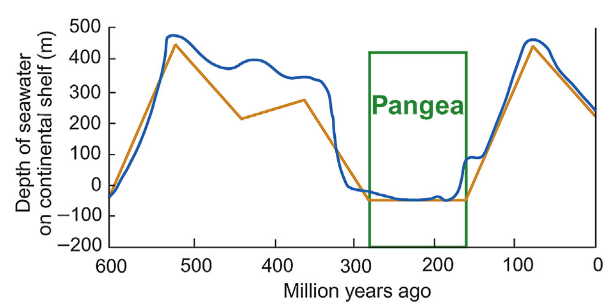


Figure 7. Comparison of the calculated effect of the supercontinent cycle on sea level (Worsley et al., 1982, 1984) with first-order eustasy (Vail et al., 1977) during the Phanerozoic.

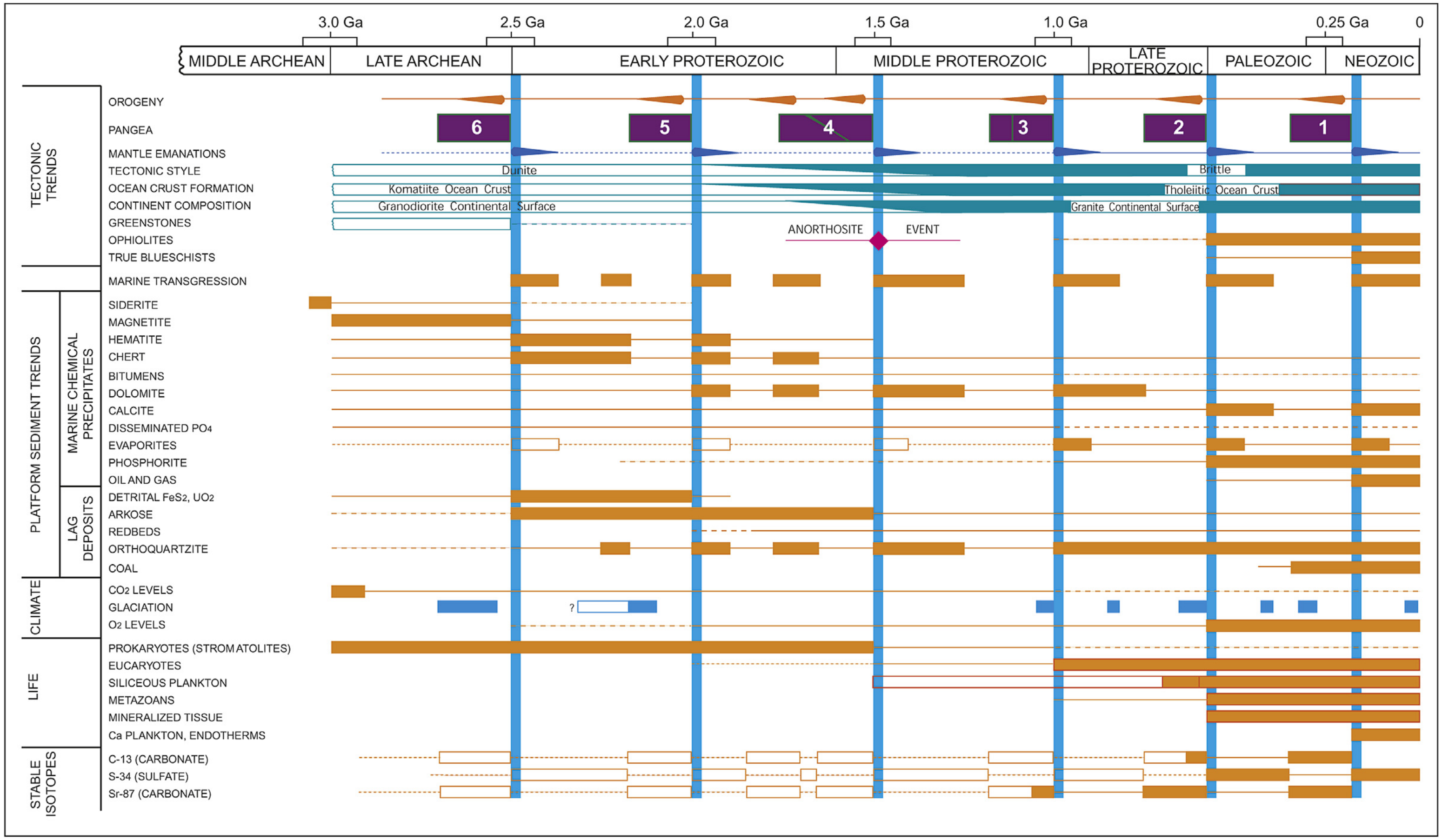


Figure 8. Qualitative summary (Worsley et al., 1985; Nance et al., 1986) of late Archean to present tectonic, platform sedimentary, climatic, biotic and stable isotope trends tuned within allowable dating errors to a quasi-periodic, ~0.5 b.y. supercontinent cycle. Trends: abundant, intense or heavy shown by solid bars (documented) and stippled bars (speculative); common or moderate shown by solid and dashed lines (documented) and dotted lines (speculative).

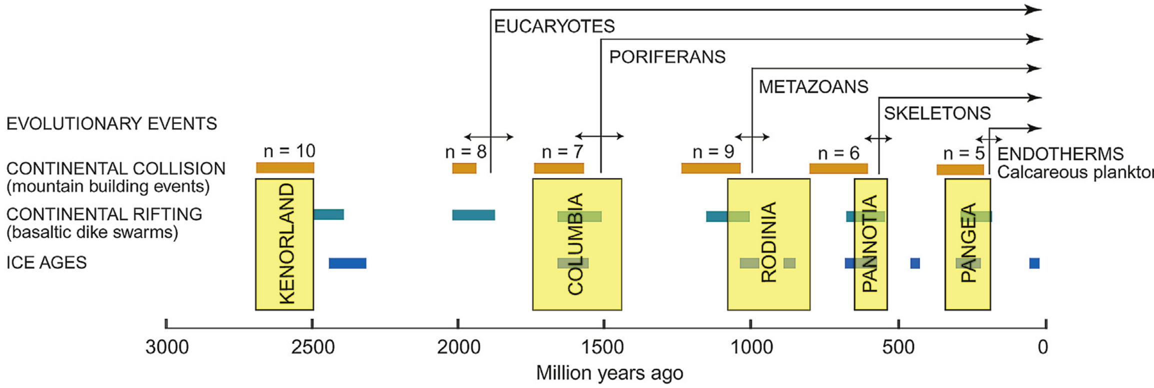


Figure 9. Comparison of episodic events in Earth history linked to the supercontinent cycle by Worsley et al. (1984, 1985) with the duration of supercontinents as they are presently known. See Fig. 5 for sources.

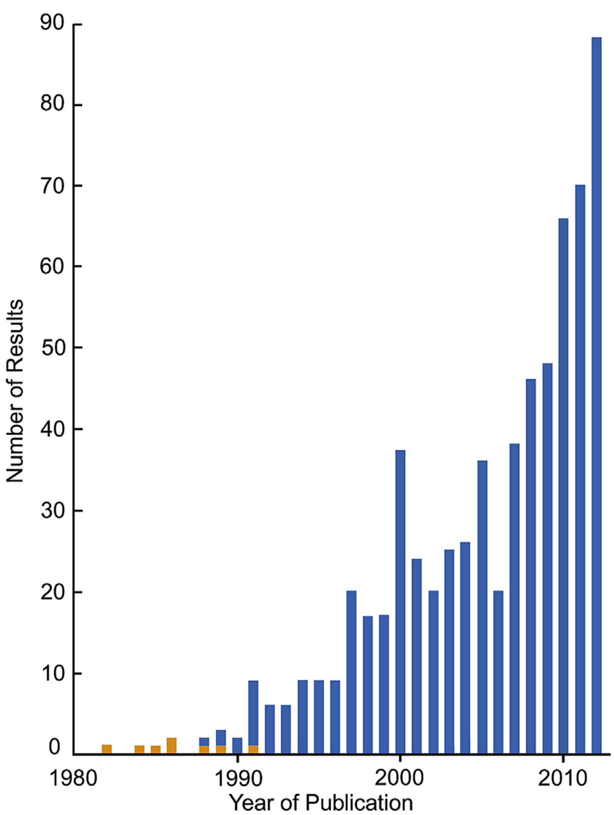


Figure 10. Histogram of data from Google Scholar showing the responses by year to a search using the keyword "supercontinent cycle". The pioneering position of the papers on the supercontinent cycle by T.R. Worsley and his co-authors are shown in orange.

expected on the exterior ocean margins, (3) rapid biotic diversification and enhanced preservation of platform sediments with increasing high values of $\delta^{13}C$ and $\delta^{34}S$ should accompany continental drowning, and (4) warm, equable climates should develop as continental flooding allows atmospheric CO_2 levels to build.

Finally, during supercontinent assembly, they argued that: (1) accretionary and collision orogenesis should increase to a maximum, (2) global sea level should first rise and then fall as subduction consumes first the old and then the young floor of the interior oceans (opening and then closing back-basins along their margins), (3) active margin sedimentation should increase, and (4) atmospheric CO_2 levels should fall, causing global climates to deteriorate.

5. Concluding remarks

Worsley et al. (1984) were by no means the first to suggest that supercontinents had formed prior to Pangea. On the contrary, the existence of a late Neoproterozoic supercontinent had already been proposed on the basis of paleomagnetic data (Morel and Irving, 1978), and had long since been implied on the basis of the fossil record (Valentine and Moores, 1970) and the history of continental rifting (Sawkins, 1976). Likewise, Piper (1974, 1975) had previously argued for the existence of a single supercontinent throughout much of the Proterozoic, although the evidence was disputed (McGlynn et al., 1975). The model of the supercontinent cycle proposed by Worsley et al.'s (1984) was also necessarily simplistic, and it is apparent from contemporary U-Pb age data (e.g., Hawkesworth et al., 2010; Condie et al., 2011) that the cycle is not as regular as the Rb/Sr data originally suggested (Fig. 9), assuming all pre-Pangean supercontinents have been identified. Likewise, the mechanism they proposed for its operation lacked any detailed knowledge of mantle tomography and the fate of subducting slabs (e.g., Condie, 2004; Maruyama et al., 2007; Murphy and Nance, 2008).

Nevertheless, Worsley et al. (1982, 1984) were the first to propose that the assembly and breakup of supercontinents had occurred episodically throughout much of geologic time with profound consequences to the course of Earth history. Of the five supercontinents they predicted, four are now recognized as corresponding to the amalgamation of Pannotia (Gondwana), Rodinia, Columbia (or Nuna) and Kenorland (Fig. 9). And while data in support of the proposed effects of the supercontinent cycle on sea level, climate and biogeochemical trends were limited at the time, many of the effects predicted by Worsley et al. (1985, 1986) have since been borne out by more sophisticated analyses of the contemporary database (e.g., Eriksson et al., 2005, 2012, 2013; Miller et al., 2005; Dewey, 2007; Bradley, 2008, 2011; Cogné and Humler, 2008; Young, 2012a,b).

The concept of the supercontinent cycle has evolved significantly in the thirty years since it was first proposed, largely as a result of developments in mantle tomography (e.g., Zhao et al., 2012) and significant advances in precise geochronology (e.g., Condie et al., 2009, 2011) and geophysical modeling (e.g., Yoshida and Santosh, 2011; Rolf et al., 2012). This has led to a rapidly widening interest in the supercontinent cycle and a near-exponential increase in the literature (Fig. 10). A list of the many milestones driving this trend would have to include: (i) the SWEAT connection of Moores (1991) and the papers by Hoffman (1991) and Dalziel (1991) that stemmed from this idea in the early 1990s; (ii) the interest in supercontinents generated by the Snowball Earth hypothesis (e.g., Hoffman et al., 1998; Kirschvink et al., 2000) in the late 1990s; (iii) Unrug and Powell's highly successful project (IGCP 440) on Rodinia Assembly and Breakup, which culminated in the consensus reconstruction of Li et al. (2008), and the investigation of earlier supercontinents championed by Rogers and Santosh (2003, 2004) in the early 2000s; and (iv) a steady stream of provocative papers throughout this period from Condie (1998, 2002, 2003).

With the rapidly emerging capability of using precisely dated and paleomagnetically constrained mafic dike swarms as piercing points for continental reconstructions (e.g., Ernst et al., 2011), and the newly developed ability to visualize and manipulate both plate tectonic reconstructions and the geological data on which they are based through geologic time with programs such as GPLATES (e.g., Boyden et al., 2011; Gurnis et al., 2012), we are, for the first time, close to developing reliable supercontinent reconstructions for the Proterozoic. Coupled with increasingly sophisticated geophysical modeling and increasingly sensitive seismic tomography, we also stand poised at a comprehensive understanding of mantle dynamics from which the mechanism of the supercontinent cycle will doubtless emerge.

Yet the original tenet of the supercontinent cycle that post-Archean Earth history has been punctuated by the episodic assembly and breakup of supercontinents with profound consequences to the geologic record has stood the test of time. In this respect, the supercontinent cycle as it is currently envisaged remains a prodigy (Fig. 10) of the pioneering contributions by Worsley et al. (1984, 1985, 1986) and those that came before.

Acknowledgments

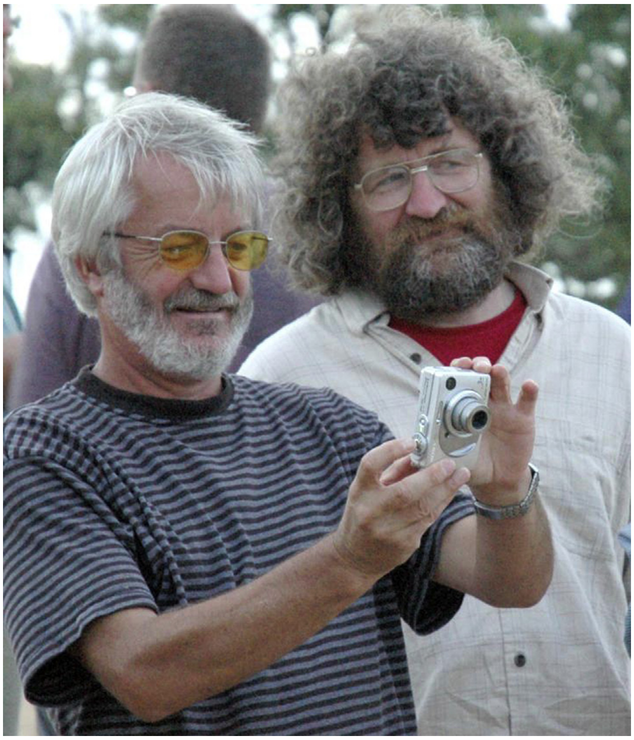
This contribution was significantly improved by the thoughtful comments of G.C. Zhao and an unknown reviewer. Their efforts on our behalf are greatly appreciated. R.D.N. acknowledges NSF Grant EAR-0308105, J.B.M. acknowledges N.S.E.R.C. (Canada) Discovery and Research Capacity grants for continuing support. This is a contribution to IGCP 597.

References

Anderson, D.L., 1982. Hotspots, polar wander, Mesozoic convection and the geoid. Nature 297, 391–393.
Berger, W.H., Winterer, E.L., 1974. Plate stratigraphy and the fluctuating carbonate line. In: Hsu, K.J., Jenkyns, H.C., Halam, A. (Eds.), Pelagic Sediments: In Land and under the Sea, vol. 1. Special Publication of the International Association of Sedimentology, pp. 11–48.
Boyden, J.A., Müller, R.D., Gurnis, M., Torsvik, T.H., Clark, J.A., Turner, M., Ivey-Law, H., Watson, R.J., Cannon, J.S., 2011. Next-generation plate-tectonic reconstructions using GPlates. In: Keller, G.R., Baru, C. (Eds.), Geoinformatics: Cyberinfrastructure for the Solid Earth Sciences. Cambridge University Press, Cambridge, pp. 95–114.
Bradley, D.C., 2011. Secular trends in the geologic record and the supercontinent cycle. Earth and Planetary Science Letters 108, 16–33.
Bradley, D.C., 2008. Passive margins through earth history. Earth-Science Reviews 91, 1–26.
Burke, W.H., Denison, R.E., Heatherington, E.A., Koepnick, R.B., Nelson, H.F., Otto, J.B., 1982. Variation of seawater $^{87}Sr/^{86}Sr$ through Phanerozoic time. Geology 10, 516–519.
Burwash, R.A., 1969. Comparative Precambrian geochronology of the North American, European, and Siberian shields. Canadian Journal of Earth Science 6, 357–365.
Christie-Blick, N., 1982. Pre-Pleistocene glaciation on Earth: implications for climatic history of Mars. Icarus 50, 423–443.
Cloud, P.E., 1968a. Atmospheric and hydrospheric evolution on the primitive Earth. Science 160, 729–736.
Cloud, P.E., 1968b. Pre-metazoan evolution and the origins of metazoa. In: Drake, E.T. (Ed.), Evolution and Environment. Yale University Press, New Haven, Connecticut, pp. 1–72.
Cloud, P.E., 1976. Beginnings of biospheric evolution and their biogeochemical consequences. Paleobiology 2, 351–387.
Cogné, J.-P., Humler, E., 2008. Global scale patterns of continental fragmentation: Wilson's cycles as a constraint for long-term sea-level changes. Earth and Planetary Science Letters 273, 251–259.
Condie, K.C., 1976. Plate Tectonics and Crustal Evolution. Pergamon Press, New York, 288 pp.
Condie, K.C., 1982. Plate Tectonics and Crustal Evolution, second ed. Pergamon Press, New York, 310 pp.
Condie, K.C., 1998. Episodic continental growth and supercontinents: a mantle avalanche connection? Earth and Planetary Science Letters 163, 97–108.
Condie, K.C., 2002. The supercontinent cycle: are there two patterns of cyclicity? Journal of African Earth Sciences 35, 179–183.
Condie, K.C., 2003. Supercontinents, Superplumes and Continental Growth: The Neoproterozoic Record, vol. 206. Geological Society of London Special Publications, pp. 1–21.
Condie, K.C., 2004. Supercontinents and superplume events: distinguishing signals in the geologic record. Physics of the Earth and Planetary Interiors 146, 319–332.
Condie, K.C., 2011. The supercontinent cycle. In: Earth as an Evolving Planetary System. Academic Press, New York, pp. 317–355 (Chapter 8).
Condie, K.C., Belousova, E., Griffin, W.L., Sircombe, K.N., 2009. Granitoid events in space and time: constraints from igneous and detrital zircon age spectra. Gondwana Research 15, 228–242.
Condie, K.C., Bickford, M.E., Aster, R.C., Belousova, E., Scholl, D.W., 2011. Episodic zircon ages. Hf isotopic composition and the preservation rate of continental crust. Geological Society Bulletin 123, 951–957.
Dalziel, I.W.D., 1991. Pacific margins of Laurentia and East Antarctica-Australia as a conjugate rift pair: evidence and implications for an Eocambrian supercontinent. Geology 19, 598–601.
Dalziel, I.W.D., 1992. On the organization of American plates in the Neoproterozoic and the breakout of Laurentia. GSA Today 2, 237–241.
Dalziel, I.W.D., 1997. Overview: Neoproterozoic-Paleozoic geography and tectonics: review, hypotheses and environmental speculations. Geological Society of America Bulletin 109, 16–42.
Dearnly, R., 1966. Orogenic fold-belts and a hypothesis of earth evolution. Physics and Chemistry of the Earth 7, 1–24.
Dewey, J.F., 2007. The secular evolution of plate tectonics and the continental crust: an outline. Geological Society of America Memoir 200, 1–7.
Dietz, R.S., 1961. Continent and ocean basin evolution by spreading of the sea floor. Nature 190, 854–857.
Domeier, M., Van der Voo, R., Torsvik, T.H., 2012. Paleomagnetism and Pangea: the road to reconciliation. Tectonophysics, 514–517, 14–43.
Ernst, E., Srivastava, R., Bleeker, W., Hamilton, M., 2011. Precambrian large igneous provinces (LIPs) and their dyke swarms: new insights from high-precision geochronology integrated with paleomagnetism and geochemistry. Precambrian Research 183, vii–xi.
Engel, A.E.J., Engel, C.B., 1964. Continental accretion and the evolution of North America. In: Subramaniam, A.P., Balakrishna, S. (Eds.), Advancing Frontiers in Geology and Geophysics. Indian Geophysical Union, Hyderabad, India, pp. 17–37.
Eriksson, P.G., Catuneanu, O., Sarkar, S., Tirsgaard, H., 2005. Patterns of sedimentation in the Precambrian. Sedimentary Geology 176, 17–42.
Eriksson, P.G., Catuneanu, O., Nelson, D.R., Rigby, M.J., Bandopadhyay, P.C., Altermann, W., 2012. Events in the Precambrian history of the Earth: challenges in discriminating their global significance. Marine and Petroleum Geology 33, 8–25.
Eriksson, P.G., Banerjee, S., Catuneanu, O., Corcoran, P.L., Eriksson, K.A., Hiatt, E.E., Laflamme, M., Lenhardt, N., Long, D.G.F., Miall, A.D., Mints, M.V., Pufahl, P.K., Sarkar, S., Simpson, E.L., Williams, G.E., 2013. Secular changes in sedimentation systems and sequence stratigraphy. Gondwana Research. http://dx.doi.org.scopeesprx.elsevier.com/10.1016/j.gr.2012.09.008.
Evans, D.A.D., 2003. True polar wander and supercontinents. Tectonophysics 362, 303–320.
Fischer, A.G., 1981. Climatic oscillations in the biosphere. In: Nitecki, M.H. (Ed.), Biotic Crises in Ecological and Evolutionary Time. Academic Press, New York, N.Y., pp. 103–131.
Fischer, A.G., 1984. The two Phanerozoic supercycles. In: Berggren, W.A., Van Couvering, J. (Eds.), Catastrophies and Earth History. Princeton Press, Princeton, N.J., pp. 129–150.
Frakes, L.A., 1979. Climates Through Geologic Time. Elsevier, Amsterdam, Netherlands, 310 pp.
Gastil, G., 1960. Continents and mobile belts in the light of mineral dating. In: 2. International Geological Congress (Pt.9), pp. 162–169.
Goldfarb, R.J., Bradley, D.C., Leach, D.L., 2010. Secular variation in economic geology. Economic Geology 105, 459–465.
Gurnis, M., 1988. Large-scale mantle convection and the aggregation and dispersal of supercontinents. Nature 332, 695–699.
Gurnis, M., Turner, M., Zahirovic, S., DiCaprio, L., Spasojevich, S., Müller, R.D., Boyden, J., Seton, M., Manea, V.C., Bower, D., 2012. Plate reconstructions with continuously closing plates. Computers and Geosciences 38, 35–42.
Hallam, A., 1974. Changing patterns of provinciality and diversity of fossil animals in relation to plate tectonics. Journal of Biogeography 1, 213–225.
Hannisdal, B., Peters, S.E., 2011. Phanerozoic Earth system evolution and marine biodiversity. Science 334, 1121–1124.
Harrison, C.G.A., Bass, G.W., Saltzman, E., Sloan II, J., Southam, J., Whitman, J.M., 1981. Sea level variations, global sedimentation rates and the hypsographic curve. Earth and Planetary Science Letters 54, 1–16.
Hawkesworth, C.J., Dhuime, B., Pietranik, A.B., Cawood, P.A., Kemp, A.I.S., Storey, C.D., 2010. The generation and evolution of the continental crust. Journal of the Geological Society, London 167, 229–248.
Hay, W.W., Southam, J.R., 1977. Modulations of marine sedimentation by the continental shelves. In: Anderson, N.R., Malahoff, A. (Eds.), The Fate of Fossil Fuel CO_2 in the Oceans. Plenum Press, New York, pp. 569–604.

Heller, P.L., Angevine, C.L., 1985. Sea-level cycles and the growth of Atlantic-type oceans. Earth and Planetary Science Letters 75, 417–426.
Hess, H.H., 1962. History of ocean basins. In: Engel, A.E.J., James, H.L., Leonard, B.F. (Eds.), Petrologic Studies: A Volume to Honor A.F. Buddington. Geological Society of America, Boulder, CO, pp. 599–620.
Hoffman, P.F., 1989. Speculations on Laurentia's first gigayear (2.0 to 1.0 Ga). Geology 17, 135–138.
Hoffman, P.F., 1991. Did the breakout of Laurentia turn Gondwanaland inside-out? Science 252, 1409–1412.
Hoffman, P.F., Schrag, D.P., 2002. The snowball Earth hypothesis: testing the limits of global change. Terra Nova 14, 129–155.
Hoffman, P.F., Kaufman, A.J., Halverson, G.P., Schrag, D.P., 1998. A Neoproterozoic snowball Earth. Science 281, 1342–1346.
Holmes, A., 1951. The sequence of Precambrian orogenic belts in south and central Africa. In: 18th International Geological Congress, London (1948), Part 14, pp. 254–269.
Holmes, A., 1954. Principles of Physical Geology. Thomas Nelson & Sons, 1288 pp.
Huston, D.L., Blewett, R.S., Champion, D.C., 2012. Australia through time: a summary of its tectonic and metallogenic evolution. Episodes 35 (1), 23–43.
Hynes, A., 1982. Stability of the oceanic tectosphere – a model for Proterozoic intracratonic orogeny. Earth and Planetary Science Letters 61, 333–345.
Kirschvink, J.L., Gaidos, E.J., Bertani, L.E., Beukes, N.J., Gutzmer, J., Maepa, L.N., Steinberger, R.E., 2000. Paleoproterozoic snowball Earth: extreme climatic and geochemical global change and its biological consequences. Proceedings of the National Academy of Science 97, 1400–1405.
Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkochub, D.P., Jacobs, J., Karlstrom, K.E., Lu, S., Natapov, L.M., Pease, V., Pisarevsky, S.A., Thrane, K., Vernikovsky, V., 2008. Assembly, configuration, and break-up history of Rodinia: a synthesis. Precambrian Research 160, 179–210.
Lindsay, J.F., Brasier, M.D., 2002. Did global tectonics drive early biosphere evolution? Carbon isotope record from 2.6 to 1.9 Ga carbonates of Western Australian basins. Precambrian Research 114, 1–34.
Mackenzie, F.T., Pigott, J.D., 1981. Tectonic controls of Phanerozoic sedimentary rock cycling. Journal of the Geological Society of London 138, 183–196.
Maruyama, S., Santosh, M., Zhao, D., 2007. Superplume, supercontinent, and post-perovskite: mantle dynamics and anti-plate tectonics on the Core–Mantle Boundary. Gondwana Research 11, 7–37.
McGlynn, J.C., Irving, E., Bell, K., Pullaiah, G., 1975. Palaeomagnetic poles and a Proterozoic supercontinent. Nature 255, 318–319.
Meyer, C., 1981. Ore-forming Processes in Geologic History. In: Economic Geology, 75th Anniversary Volume, pp. 6–41.
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., Pekar, S.F., 2005. The Phanerozoic record of global sea-level change. Science 310, 1293–1298.
Mitchell, R.N., Kilian, T.M., Evans, D.A.D., 2012. Supercontinent cycles and the calculation of absolute palaeolongitude in deep time. Nature 482, 208–212.
Moores, E.M., 1991. Southwest U.S.–East Antarctic (SWEAT) connection: a hypothesis. Geology 19, 425–428.
Morel, P., Irving, E.C., 1978. Tentative paleocontinental maps for the early Phanerozoic and Proterozoic. Journal of Geology 86, 535–561.
Murphy, J.B., Nance, R.D., 2003. Do supercontinents introvert or extrovert?: Sm–Nd isotopic evidence. Geology 31, 873–876.
Murphy, J.B., Nance, R.D., 2008. The Pangea conundrum. Geology 36, 703–706.
Murphy, J.B., Nance, R.D., 2013. Speculations on the mechanisms for the formation and breakup of supercontinents. Geoscience Frontiers 4, 185–194.
Nance, R.D., Worsley, T.R., Moody, J.B., 1986. Post-Archean biogeochemical cycles and long-term episodicity in tectonic processes. Geology 14, 514–518.
Nance, R.D., Worsley, T.R., Moody, J.B., 1988. The supercontinent cycle. Scientific American 256, 72–79.
Parsons, B., Sclater, J.G., 1971. An analysis of the variation of ocean floor bathymetry and heat flow with age. Journal of Geophysical Research 82, 803–827.
Piper, J.D.A., 1974. Proterozoic crustal distribution, mobile belts and apparent polar movements. Nature 251, 381–384.
Piper, J.D.A., 1975. Proterozoic supercontinent: time duration and the Grenville problem. Nature 256, 519–520.
Piper, J.D.A., Beckmann, G.E.J., Badham, J.P.N., 1976. Palaeomagnetic evidence for a Proterozoic super-continent [and discussion]. Philosophical Transactions of the Royal Society of London A 280, 469–490.
Powell, C.McA., 1995. Are Neoproterozoic glacial deposits preserved on the margins of Laurentia related to the fragmentation of two supercontinents? Comment. Geology 23, 1053–1054.
Powell, C.McA., Li, Z.X., McElhinny, M.W., Meert, J.G., Park, J.K., 1993. Paleomagnetic constraints on timing of the Neoproterozoic breakup of Rodinia and the Cambrian formation of Gondwana. Geology 21, 889–892.
Rogers, J.J.W., Santosh, M., 2003. Supercontinents in Earth history. Gondwana Research 6, 357–368.
Rogers, J.J.W., Santosh, M., 2004. Continents and Supercontinents. Oxford University Press, New York, p. 289.
Rolf, T., Coltice, N., Tackley, P.J., 2012. Linking continental drift, plate tectonics and the thermal state of the Earth's mantle. Earth and Planetary Science Letters, 351–352, 134–146.
Runcorn, S.K., 1962. Convection currents in the Earth's mantle. Nature 195, 1248–1249.
Runcorn, S.K., 1965. Changes in the convection pattern in the Earth's mantle and continental drift: evidence for a cold origin of the Earth. Philosophical Transactions of the Royal Society of London A 258, 228–251.
Santosh, M., 2010a. Supercontinent tectonics and biogeochemical cycle: a matter of 'life and death'. Geoscience Frontiers 1, 21–30.
Santosh, M., 2010b. A synopsis of recent conceptual models on supercontinent tectonics in relation to mantle dynamics, life evolution and surface environment. Journal of Geodynamics 50, 116–133.
Santosh, M., Zhao, G. (Eds.), 2009. Special issue: supercontinent dynamics. Gondwana Research 15, 225–470.
Santosh, M., Maruyama, S., Yamamoto, S., 2009. The making and breaking of supercontinents: some speculations based on superplumes, superdownwelling and the role of tectosphere. Gondwana Research 15, 324–341.
Sawkins, F.J., 1976. Widespread continental rifting: some considerations of timing and mechanism. Geology 4, 427–430.
Sloss, L.L., 1963. Sequences in the cratonic interior of North America. Geological Society of America Bulletin 74, 93–114.
Strand, K., 2012. Global and continental-scale glaciations on the Precambrian earth. Marine and Petroleum Geology 33, 69–79.
Stump, E., 1992. The Ross orogen of the Transantarctic Mountains in the light of the Laurentian-Gondwana split. GSA Today 2, 25–27. 30–33.
Sutton, J., 1963. Long-term cycles in the evolution of the continents. Nature 198, 731–735.
Umbgrove, J.H.F., 1940. Periodicity in terrestrial processes. American Journal of Science 238, 573–576.
Umbgrove, J.H.F., 1947. The Pulse of the Earth. Martinus Nijhoff, The Hague, Netherlands, 358 pp.
Vail, P.R., Mitchum Jr., R.M., Thompson III, S., 1977. Global cycles of relative changes of sea level. In: Payton, C.E. (Ed.), Seismic Stratigraphy – Applications to Hydrocarbon Explorations, vol. 26. American Association of Petroleum Geologists, Memoir, pp. 83–97.
Valentine, J.W., Moores, E.M., 1970. Plate tectonic regulation of faunal diversity and sea level. Nature 228, 657–659.
Vine, F.J., Matthews, D.H., 1963. Magnetic anomalies over ocean ridges. Nature 199, 947–949.
Vinogradov, A.P., Tugarinov, A.I., 1962. Problems of geochronology of the pre-Cambrian in eastern Asia. Geochimica et Cosmochimica Acta 26, 1283–1300.
Voitkevich, G.V., 1958. A unified time-scale for the Precambrian. Priroda 5, 77–79 (in Russian).
Wegener, A., 1912. Die Herausbildung der Grossformen der Erdrinde (Kontinente und Ozeane), auf geophysikalischer Grundlage. Petermanns Geographische Mitteilungen 58, 185–195. 253–256, 305–309.
Wegener, A., 1922. Die Entstehung der Kontinente und Ozeane (On the Origin of Continents and Oceans). In: Skerl, J.G.A. (Ed.), English translation of third ed. Methuen, London (1924) 212 pp.
Williams, H., Hoffman, P.F., Lewry, J.F., Monger, J.W.H., Rivers, T., 1991. Anatomy of North America: thematic portrayals of the continent. Tectonophysics 187, 117–134.
Wilson, A.F., Compston, W., Jeffery, P.M., Riley, G.H., 1960. Radiometric ages from the Precambrian rocks in Australia. Journal of the Geological Society of Australia 6, 179–195.
Wilson, J.T., 1966. Did the Atlantic Ocean close and then re-open? Nature 211, 676–681.
Windley, B.F., 1977. The Evolving Continents. John Wiley, New York, N.Y., 385 pp.
Windley, B.F., 1984. The Evolving Continents, second ed. John Wiley, New York, N.Y., 399 pp.
Worsley, T.R., Nance, R.D., 1989. Carbon redox and climate control through Earth history: a speculative reconstruction. Palaeogeography, Palaeoclimatology, Palaeoecology (Global and Planetary Change Section) 75, 259–282.
Worsley, T.R., Nance, R.D., Moody, J.B., 1982. Plate tectonic episodicity: a deterministic model for periodic "Pangeas". Eos, Transactions of the American Geophysical Union 65 (45), 1104.
Worsley, T.R., Nance, R.D., Moody, J.B., 1984. Global tectonics and eustasy for the past 2 billion years. Marine Geology 58, 373–400.
Worsley, T.R., Nance, R.D., Moody, J.B., 1985. Proterozoic to recent tectonic tuning of biogeochemical cycles. In: Sunquist, E.T., Broecker, W.S. (Eds.), The Carbon Cycle and Atmospheric CO_2: Natural Variations Archean to Present. Geophysical Monograph 32. American Geophysical Union, pp. 561–572.
Worsley, T.R., Nance, R.D., Moody, J.B., 1986. Tectonic cycles and the history of the Earth's biogeochemical and paleoceanographic record. Paleoceanography 1, 233–263.
Worsley, T.R., Nance, R.D., Moody, J.B., 1991. Tectonics, life and climate for the last three billion years: a unified system? In: Schneider, S.H., Boston, P.J. (Eds.), Scientists on Gaia. M.I.T. Press, Cambridge, MA, pp. 200–210.
Yoshida, M., Santosh, M., 2011. Supercontinents, mantle dynamics and plate tectonics: a perspective based on conceptual vs. numerical models. Earth-Science Reviews 105, 1–24.
Young, G.M., 2012a. Precambrian supercontinents, glaciations, atmospheric oxygenation, metazoan evolution and an impact that may have changed the second half of Earth history. Geoscience Frontiers 4, 247–261.
Young, G.M., 2012b. Secular changes at the Earth's surface; evidence from paleosols, some sedimentary rocks, and paleoclimatic perturbations of the Proterozoic Eon. Gondwana Research. http://dx.doi.org/10.1016/j.gr.2012.07.016.
Zhang, N., Zhong, S., McNarmara, A.K., 2009. Supercontinent formation from stochastic collision and mantle convection models. Gondwana Research 15, 267–275.

Zhao, D., Yamamoto, Y., Yanada, T., 2012. Global mantle heterogeneity and its influence on teleseismic regional tomography. Gondwana Research. http://dx.doi.org/10.1016/j.gr.2012.08.004.
Zhao, G.C., Cawood, P.A., Wilde, S.A., Sun, M., 2002. A review of the global 2.1–1.8 Ga orogens: implications for a pre-Rodinia supercontinent. Earth-Science Reviews 59, 125–162.
Zhao, G.C., Sun, M., Wilde, S.A., Li, S.Z., 2004. A Paleo-Mesoproterozoic supercontinent: assembly, growth and breakup. Earth-Science Reviews 67, 91–123.
Zhong, S., Zhang, N., Li, Z.-X., Roberts, J.H., 2007. Supercontinent cycles, true polar wander, and very long-wavelength mantle convection. Earth and Planetary Science Letters 261, 551–564.



Damian Nance (left): Distinguished Professor of Geological Sciences at Ohio University where he has been since 1980. He obtained his B.Sc. (Hons) degree from the University of Leicester, U.K., in 1972, and his Ph.D. from Cambridge University in 1978 after emigrating to Canada in 1976. He is science editor of *GSA Today* and Associate Editor of *Gondwana Research*, and his main research interests are in coupled structural geology/tectonics and isotopic studies, and their application to orogenic processes, plate reconstructions, palaeocontinental configurations and the assembly and breakup of supercontinents. He has published over 200 research papers, edited several memoir volumes and journal special issues, and is co-author (with Brendan Murphy) of the book ‘Earth Science Today’ (Brooks-Cole/Wadsworth, 1999).

Brendan Murphy (right): Professor in the Department of Earth Sciences at St. Francis Xavier University, Canada, where he has been since 1982. He obtained his B.Sc. degree from University College Dublin, Ireland, before emigrating to Canada in 1975. He acquired a M.Sc. from Acadia University in 1977 and a Ph.D. degree from McGill University in 1982. He is editor of *Geoscience Canada* and past editor of *GSA Bulletin*, and his main research interests are in understanding orogenic processes, the relationship between tectonics, magmatism and mineralization, mantle plumes and mountain building, and the use of isotopic systematics as tectonic tracers. He has published over 250 research papers, edited several memoir volumes and journal special issues, and is co-author (with Damian Nance) of the book ‘Earth Science Today’ (Brooks-Cole/Wadsworth, 1999).

View publication stats