Geoscience Frontiers 5 (2014) 155–166

Contents lists available at ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

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

Focus paper

Strange attractors, spiritual interlopers and lonely wanderers: The search for pre-Pangean supercontinents

Joseph G. Meert*

Department of Geological Sciences, 355 Williamson Hall, University of Florida, Gainesville, FL 32611, USA

A R T I C L E I N F O

Article history:
Received 17 October 2013
Received in revised form
2 December 2013
Accepted 4 December 2013
Available online 15 December 2013

Keywords:
Columbia
Rodinia
Pangea
Supercontinent
Tectonics

A B S T R A C T

The observation is made that there are very strong similarities between the supercontinents Columbia, Rodinia and Pangea. If plate tectonics was operating over the past 2.5 billion years of Earth history, and dominated by extroversion and introversion of ocean basins, it would be unusual for three supercontinents to resemble one another so closely. The term 'strange attractor' is applied to landmasses that form a coherent geometry in all three supercontinents. Baltica, Laurentia and Siberia form a group of 'strange attractors' as do the elements of East Gondwana (India, Australia, Antarctica, Madagascar). The elements of "West Gondwana" are positioned as a slightly looser amalgam of cratonic blocks in all three supercontinents and are referred to as 'spiritual interlopers'. Relatively few landmasses (the South China, North China, Kalahari and perhaps Tarim cratons) are positioned in distinct locations within each of the three supercontinents and these are referred to as 'lonely wanderers'.

There may be several explanations for why these supercontinents show such remarkable similarities. One possibility is that modern-style plate tectonics did not begin until the late Neoproterozoic and horizontal motions were restricted and a vertical style of 'lid tectonics' dominated. If motions were limited for most of the Proterozoic, it would explain the remarkable similarities seen in the Columbia and Rodinia supercontinents, but would still require the strange attractors to rift, drift and return to approximately the same geometry within Pangea.

A second possibility is that our views of older supercontinents are shaped by well-known connections documented for the most recent supercontinent, Pangea. It is intriguing that three of the four 'lonely wanderers' (Tarim, North China, South China) did not unite until just before, or slightly after the breakup of Pangea. The fourth 'lonely wanderer', the Kalahari (and core Kaapvaal) craton has a somewhat unique Archean-age geology compared to its nearest neighbors in Gondwana, but very similar to that in western Australia.

1. Introduction

The search for pre-Pangean supercontinents began around the same time as the plate-tectonic revolution (Gastil, 1960; Runcorn, 1962; Sutton, 1963). Runcorn (1962) and Sutton (1963) proposed several cycles of orogenesis based on a compilation of available geochronological data. Hawkesworth et al. (2010) provided a more recent compilation of U-Pb crystallization ages (Fig. 1) that they used to sketch out the intervals of global continental amalgamation and growth (see also Campbell and Allen, 2008; Cawood et al., 2013). Additional musings on the existence of pre-Pangean supercontinents can be found in the geological literature (Valentine and Moores, 1970, 1972; Burke and Dewey, 1973; Irving et al., 1974; Piper, 1976; Sawkins, 1976; McMenamin and McMenamin, 1990; Dalziel, 1991; Hoffman, 1991; Moores, 1991; Powell et al., 1993; Torsvik et al., 1996; Weil et al., 1998; Meert, 2002; Rogers and Santosh, 2002; Meert and Torsvik, 2003; Li et al., 2008; Meert, 2012 and references within those publications). The most commonly cited names for these supercontinents (Fig. 2a–c) are *Rodinia* (Neoproterozoic supercontinent; McMenamin and

* Tel.: +1 352 846 2414; fax: +1 352 392 9294.
E-mail address: jmeert@ufl.edu.

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

Production and hosting by Elsevier

1674-9871/$ – see front matter © 2014, 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.2013.12.001

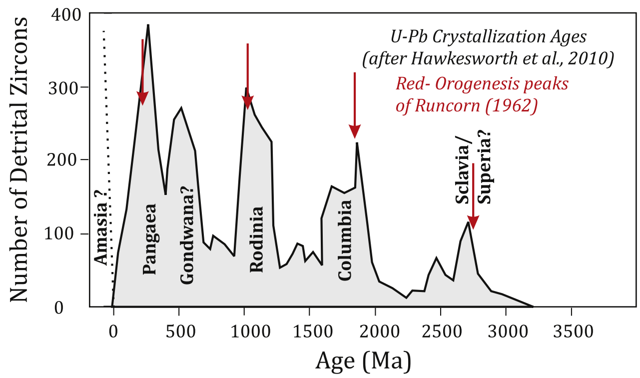

Figure 1. Detrital zircon spectra as given in Hawkesworth et al. (2010) and a comparison to the orogenesis peaks in the paper by Runcorn (1962) along with the names of the supercontinents associated with each peak.

McMenamin, 1990) and *Columbia* (Paleo-Mesoproterozoic supercontinent; Rogers and Santosh, 2002; Reddy and Evans, 2009; Meert, 2012). In addition, Piper (1976, 2000, 2007) proposed the names "*ProtoPangea*" and "*PaleoPangea*" for Archean and Paleoproterozoic–Neoproterozoic supercontinents respectively. Meert (2012) provided a history on the nomenclature of the various supercontinents proposed in the past 50 or so years.

The evidence is convincing that most of the Earth's landmasses were together in some pre-Pangean configuration, but the exact makeup of any particular supercontinent is poorly constrained (Torsvik et al., 1996; Weil et al., 1998; Zhao et al., 2002a,b, 2003, 2004; Meert and Torsvik, 2003; Pesonen et al., 2003; Piper, 2004, 2007; Hou et al., 2008; Li et al., 2008; Reddy and Evans, 2009; Rogers and Santosh, 2009; Betts et al., 2011; Meert et al., 2011). This short review focuses on some unusual aspects of the proposed configurations of Columbia, Rodinia and, to a lesser extent, Pangea. In particular, I emphasize remarkable similarities between the proposed configurations of certain cratonic elements (strange attractors); those elements that maintain a quasi-familiar relationship (spiritual interlopers); and elements that appear more randomly distributed in the various supercontinental reconstructions (lonely wanderers). The question posed in this paper is whether or not these relationships reflect some fundamental tectonic processes or are merely the result of a Pangean bias in thinking about the tectonic evolution of the planet.

2. Tools for reconstructing past supercontinents

Any attempts to reconstruct past supercontinental histories rely on several lines of evidence. Chief among these are paleomagnetism, alignment of orogenic features, geochronology, detrital zircon geochronology, 'barcodes' of Large Igneous Provinces (LIP's), paleontology, matching of conjugate margins and seafloor magnetic

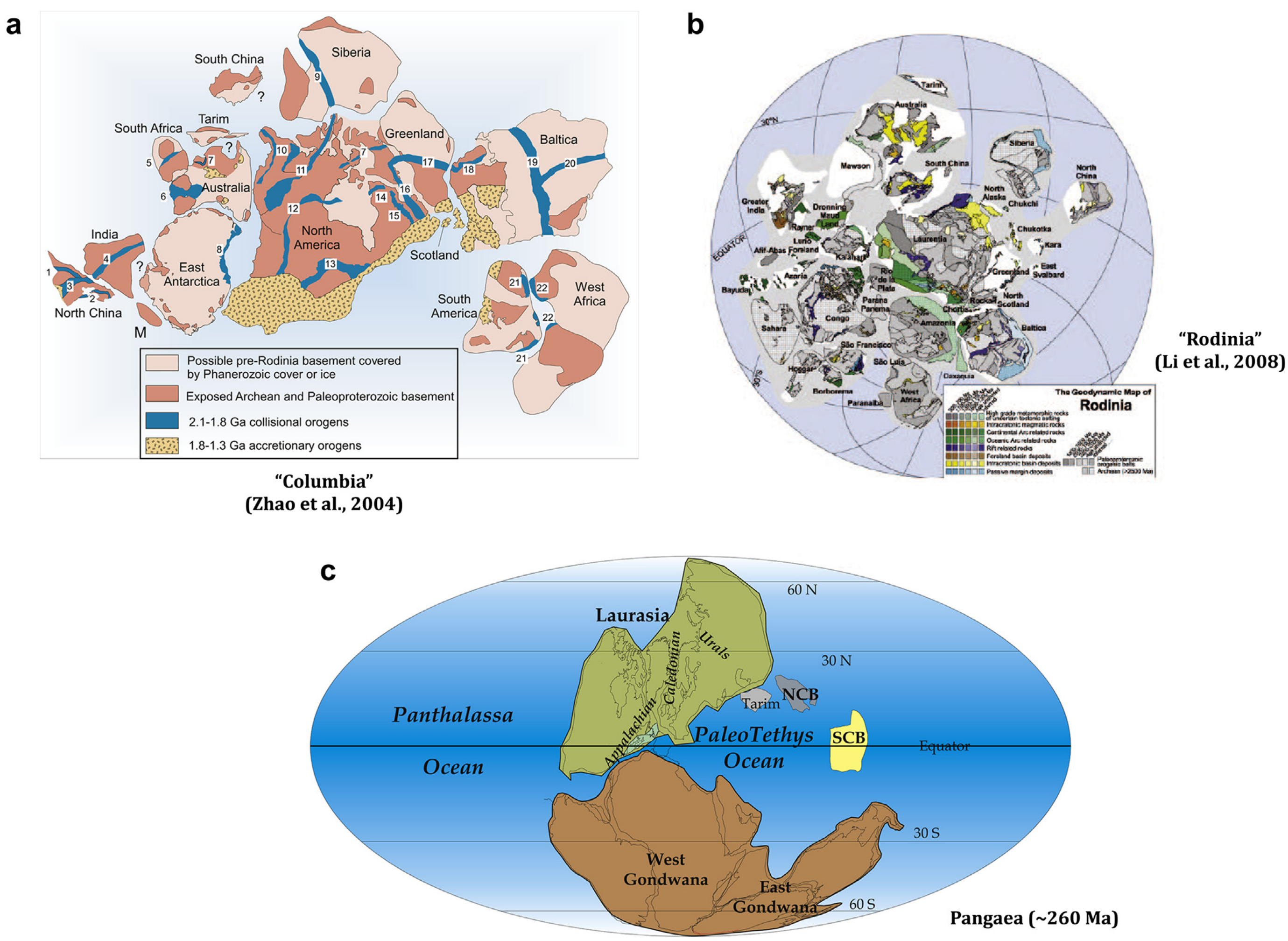

Figure 2. The supercontinents: (a) Columbia (Rogers and Santosh, 2002; Zhao et al., 2004), (b) Rodinia (Li et al., 2008) and (c) Pangea (Meert, 2012).

anomalies. In the case of Proterozoic supercontinents, signals from seafloor magnetic anomalies are absent and paleontological information is muted or non-existent. The remaining information is (wisely) integrated to provide the best picture of geometric relationships between the various blocks, but all suffer from ambiguities.

2.1. Paleomagnetism

Paleomagnetic studies are deemed the only 'quantitative method' for assessing the relative positions (latitude and orientation) of continental blocks in the past. Reconstructions that make use of lengthy segments of apparent polar wander paths (APWP's) are more robust than those that use only individual poles. Unfortunately, there are ambiguities in paleomagnetic data that can lead to critical errors in reconstructions. One of the major issues is the well-known hemispheric ambiguity resulting from the dipolar nature of the geomagnetic field (Fig. 3a,b; Buchan et al., 2001; Meert and Torsvik, 2003). If a continent is located near the equator, the hemispheric ambiguity is less critical since the choice of polarity option results in a mirror-image of the continent across the equator (Fig. 3c). As the paleolatitude increases, the assignment of hemisphere becomes more critical when trying to match craton to craton (Fig. 3d). One potential solution is to establish a temporal sequence of paleomagnetic poles from two (or more) different continents (APWP's). If the APWP's from the two blocks conform to the same basic shape and length, then they can be superimposed and used to establish relative paleolongitudinal differences between the two blocks. The problem in the Precambrian is that APWP's may rely on paleomagnetic poles that differ by 100 Ma or more. With such poor temporal resolution, details in the APWP's are lost and polarity choices can be made to force two APWP's into conformity (where in fact conformity may not have existed; Meert and Torsvik, 2003). An alternative solution is to take several widely separated (temporally and spatially) poles from two cratonic nuclei and document that coeval poles conform to a fixed reconstruction (see example in Salminen et al., 2013).

Additional problems related to paleomagnetic studies in Precambrian rocks are unrecognized secondary magnetizations and inclination shallowing in fine-grained sedimentary rocks (Tauxe and Kent, 2004; Meert et al., 2013).

2.2. Orogenic belts

The Columbia supercontinent was constructed largely on the basis of aligning the 2.1–1.8 Ga orogenic belts that traverse many continental blocks (see listing in Fig. 5). Evidence for Rodinia assembly is based, in part, on the presence of 1.1–0.9 Ga orogenic belts (Hoffman, 1991). In both cases (assembly of Rodinia and Columbia), the orogens are thought to have developed during the formation of the supercontinents. The orogens are linear or curvilinear features (Fig. 4a) that can be aligned in many non-unique and potentially incorrect ways. A simple illustration of problems associated with aligning orogenic belts of similar age is shown in Fig. 4. Examples of some problems using geological/orogenic features to orient/align cratonic blocks can be gleaned from the myriad orientations of Siberia with Laurentia in the Rodinia supercontinent (see summary in Meert and Torsvik, 2003).

A more detailed illustration of the non-uniqueness problem in using orogenic features to 'match margins' is exemplified by the variety of fits proposed for the North China craton (NCC) in Columbia. Condie (2002) proposed a NCC-northeastern Siberia connection in Columbia. Condie's (2002) reconstruction aligned the Trans-North China orogenic belt with the Akitkan orogenic belt in Siberia. Kusky and Li (2003) and Kusky et al. (2007) placed the North Hebei Orogen (NHO) against the Volhyn-Central Russia orogenic (southwestern Siberia) and the western side of the NCC adjacent to the Transamazonian orogeny of Amazonia. Chen et al. (2013) indicated that the NCC and Siberia were joined in a Columbia configuration outlined by Li et al. (1996).

Other Columbia models align the NCC orogenic belts with Baltica or India. Qian and Chen (1987) proposed that Baltica and the NCC were neighbors within Columbia based on lithological and geochronological correlations. Their hypothesis was used to align ~1.8 Ga collision zones in the NCC (Zhao et al., 2001) with the 1.9–1.8 Ga Kola-Karelian Orogen in Baltica (Berthelsen and Marker, 1986; Wilde et al., 2002). Kröner et al. (1998) suggested that the eastern block of the NCC connected with the southern block of India because both experienced crustal accretion in the period of 2.6–2.5 Ga. Similarities in geological evolution (such as coeval granitoid intrusive and metamorphic events with anticlockwise P-T paths) may indicate that both comprised a single major active continental margin and experienced an Archean crust-forming event together (Kröner et al., 1998). Zhao et al. (2002a) argued that the Trans-North China Orogen and the Central India Tectonic Zone (CITZ) evolved together. In their model, it was suggested that the Eastern and Western blocks of the NCC were connected with the Southern Indian block and North Indian block respectively until they coalesced along the CITZ. Peng et al. (2005) have also connected the NCC with the Dharwar craton in India according to the geometry of coeval dykes on both blocks at ~1780 Ma. However, Hou et al. (2008) argued the eastern India should lie to the south of the NCC as a better fit between the mafic dyke swarms.

A more complicated problem is defining the tectonic setting of ancient orogenic belts (Sizova et al., 2013). Did the orogenic belt form during the closure of a major ocean basin, accretionary tectonism or via ensialic processes? The idea of an ensialic orogeny was favored for many of the Proterozoic mobile belts during the 1980's (Baer, 1983; Kroner, 1983), but has largely fallen out of favor (Hoffman, 1989; Calvert et al., 1995; Cawood et al., 2006; Frisch et al., 2011). Nevertheless, the presence of large intracontinental shear zones associated with tectonic escape due to the Himalayan orogeny shows that large areas of continental crust can be deformed without the closure of an intervening ocean basin; although the 'escape' in this case did require collisional tectonism in a region distal from the shear zones (Tapponnier and Molnar, 1976; Hand and Sandiford, 1999; Yin and Harrison, 2000; Giles et al., 2002; Yang and Liu, 2002; Pacheco Neves and Mariano, 2004). Aitken et al. (2013) stressed the importance of intraplate tectonics in modern and ancient orogenic systems.

Lastly, it is important to note that just because there are orogenic events occurring during the 2.1–1.8 Ga interval, there is no *a priori* reason that all of the mountain building in that interval resulted from supercontinent formation. Using the most recent 300 Ma of the Phanerozoic as an example, there are a host of orogenic belts that are not necessarily related to the formation of the same supercontinent or, in some cases, the formation of any supercontinent. For example, the Alleghenian-Hercynian-Variscan (~325–260 Ma) and the latter stages of the Uralian-Mongol orogenies resulted in the formation of Pangea during the late Paleozoic. The Alpine and Himalayan-Tibetan orogenies (Mesozoic–Cenozoic) happened well after Pangea breakup and are perhaps related to the assembly of the next supercontinent, Amasia (Yin and Harrison, 2000). The Andean Orogenic cycle (Jurassic–present day) is the product of Pacific plate subduction beneath South America (Allmendinger et al., 1997). The Laramide and Sevier orogenies (Cretaceous–Paleogene) in North America were caused by the subduction of the Farallon plate (DeCelles, 2004). Changes in plate geometry following the Laramide and Sevier Orogenies led to considerable post-orogenic extension (Rio

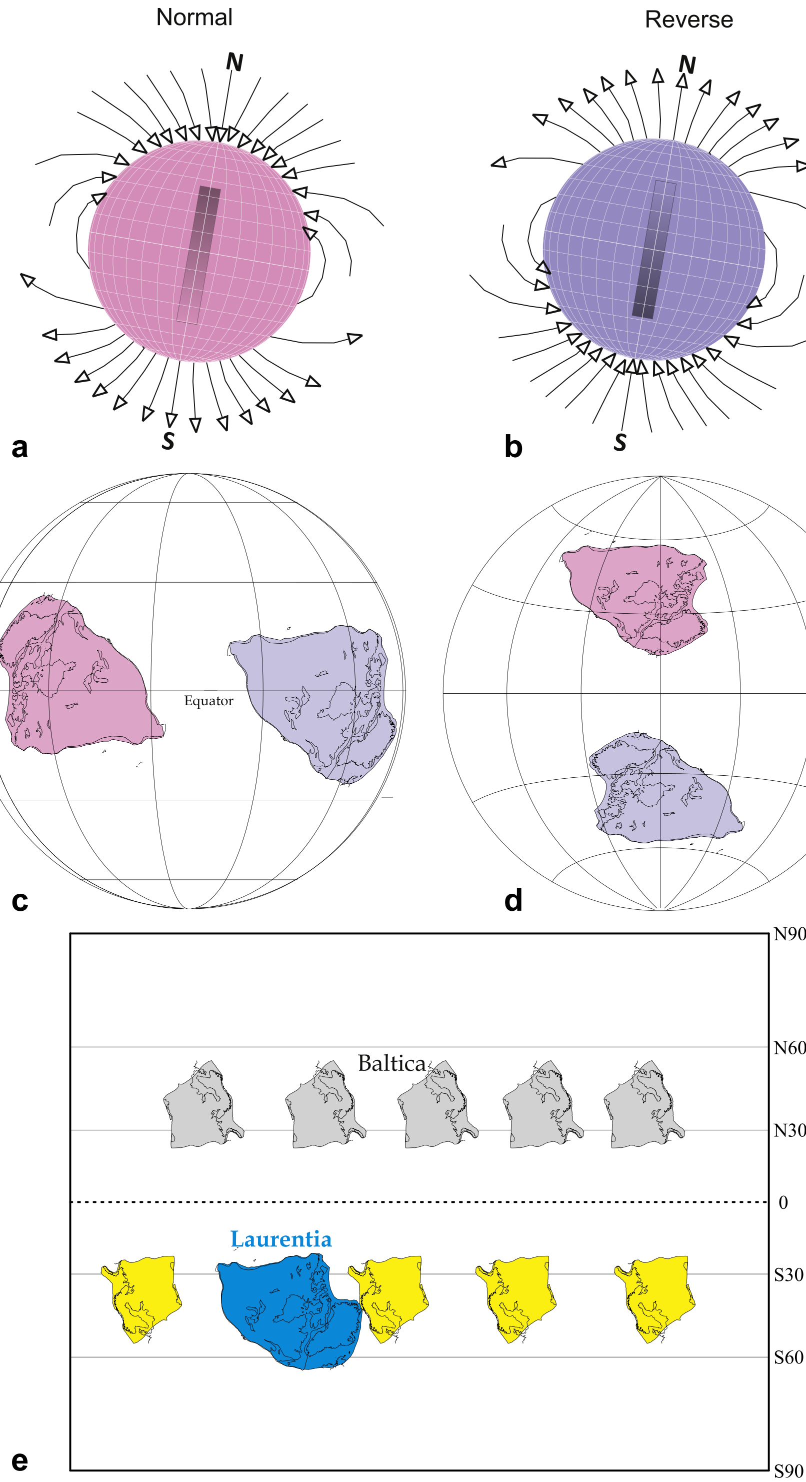

Figure 3. Cartoon structure of magnetic field lines in a "Normal" polarity field (a), a "Reverse" magnetic field (b), example of a reconstructed North America using the normal polarity option (pink shading) and reverse polarity option (blue shading) using synthetic 'low-latitude' data (c), and synthetic 'moderate-latitude' data (d), the 'longitude' and 'polarity' non-uniqueness problem in paleomagnetism (e). Laurentia (blue) is held fixed and Baltica (polarity option 1-yellow) is positioned in various longitudinal positions; polarity option 2-gray shows Baltica at various longitudinal options.

Grande Rift and Basin and Range Provinces; Wells et al., 2012) and a lengthy segment of western North America is now dominated by strike-slip motion. Thus, in the past 300 Ma, a wide variety of mountain building episodes took place (including a large number of accretionary orogens) that are not related to the formation of a *single* supercontinent.

2.3. *Detrital zircons*

In recent years, detrital zircon studies have been used to identify potential conjugate pairs in the Proterozoic (Rainbird et al., 1998; Cawood et al., 2007; Wu et al., 2010; Kuznetsov et al., 2014; Turner et al., 2014). The idea is that if 'foreign' zircons (i.e. those

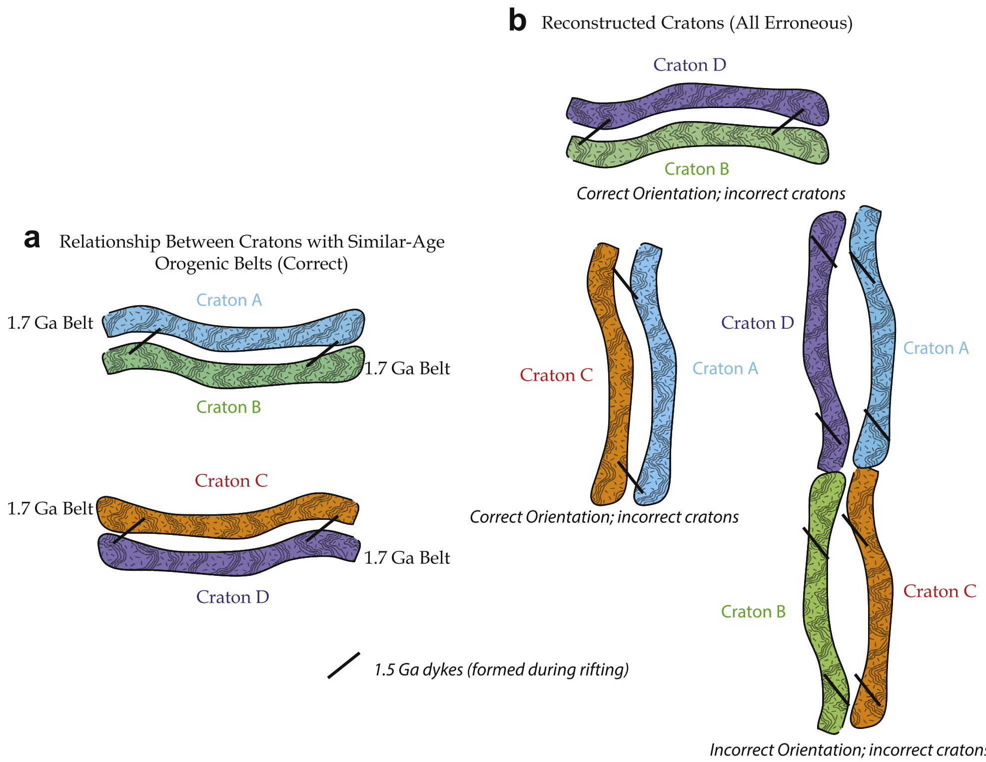

Figure 4. The orogenic belt problem. (a) Two orogenic belts that formed at 1.7 Ga along the margins of cratons A and B, and a second belt formed along the margins of cratons C and D. (b) Incorrect 'reconstructions' resulting from linking similar-aged orogenic belts.

not found in proximal regions to the sampled rocks) can be used to trace the missing piece (Fedo et al., 2003). Andersen (2014) takes a proper cautionary stance by noting that detrital zircon suites from southern Africa, Australia, Fennoscandia and eastern Laurentia cannot be distinguished from one another (Ireland et al., 1998; Lahtinen et al., 2002; Rino et al., 2004; Kuznetsov et al., 2014). This is somewhat disconcerting given that South Africa/Australia are not shown in proximity to Fennoscandia or eastern Laurentia in any of the supercontinental reconstructions (Figs. 5–8). Furthermore, Andersen (2014) argues that detrital zircon studies lack statistical rigor required to properly discern true differences between the populations. While the latter statement may be a bit strong, it would appear that differences in detrital zircon suites currently lack proper resolution for separating/uniting particular landmasses in supercontinental reconstructions.

2.4. LIP barcodes/mafic dyke swarms

Ernst et al. (2008, 2010) made the case that the ages of eruptive/intrusive products of large igneous provinces (LIPs) provide a unique 'bar-code' signature for any particular crustal blocks. Comparison of barcodes for different crustal blocks may reveal similar (or dissimilar) patterns that may indicate contiguity of those crustal segments in the former case or discontinuity of crustal blocks in the latter case.

In some cases the mafic dyke swarms associated with the LIPs may form a radiating pattern that may be used to identify the source region (mantle plume head). If the swarm is large enough, it can theoretically traverse several nearby continental blocks (Ernst and Srivastava, 2008; Ernst et al., 2008). Geochemical fingerprinting of the LIPs may also provide trace element comparisons that can be used to identify igneous products across now widely separated blocks.

The bar-code approach holds promise and new geochronological data along with paleomagnetic and geochemical data from the dyke swarms may provide new insights into past supercontinental reconstructions (Ernst and Srivastava, 2008; Ernst et al., 2013).

2.5. Jigsaw fit/paleontological information

Alternatives to the conventional Rodinia and Columbia models exist (Evans, 2009; Kaur and Chaudhri, 2014), but most represent relatively minor adjustments of individual cratons along the same conjugate margins as the archetypal reconstruction (Burrett and Berry, 2000; Hartz and Torsvik, 2002; Wingate et al., 2002; Meert and Torsvik, 2003; Bispos-Santos et al., 2013). Because the shape of the continents in Proterozoic and even Neoproterozoic time can be quite distinct from their modern outlines, jigsaw fits are less useful in reconstructing Proterozoic supercontinents. Paleontological information is commonly used in reconstructing Phanerozoic paleogeography (references), but due to both the limited nature of the Proterozoic fossil record and the lack of a well-established fossil zonation for the Proterozoic, very few attempts have been made to use fossils in Proterozoic plate reconstructions (Meert and Lieberman, 2004, 2008).

3. Strange attractors, spiritual interlopers and lonely wanderers

3.1. The Strange attractors (Siberia, Laurentia, Baltica; "East Gondwana")

Fig. 5a–c shows the proposed configurations of Siberia, Baltica and Laurentia in the Columbia, Rodinia and Pangea supercontinents. Slightly different configurations have been proposed for Paleo-Pangea (Sears and Price, 2002; Piper, 2007) wherein Siberia is placed along the present-day western margin of Laurentia. In

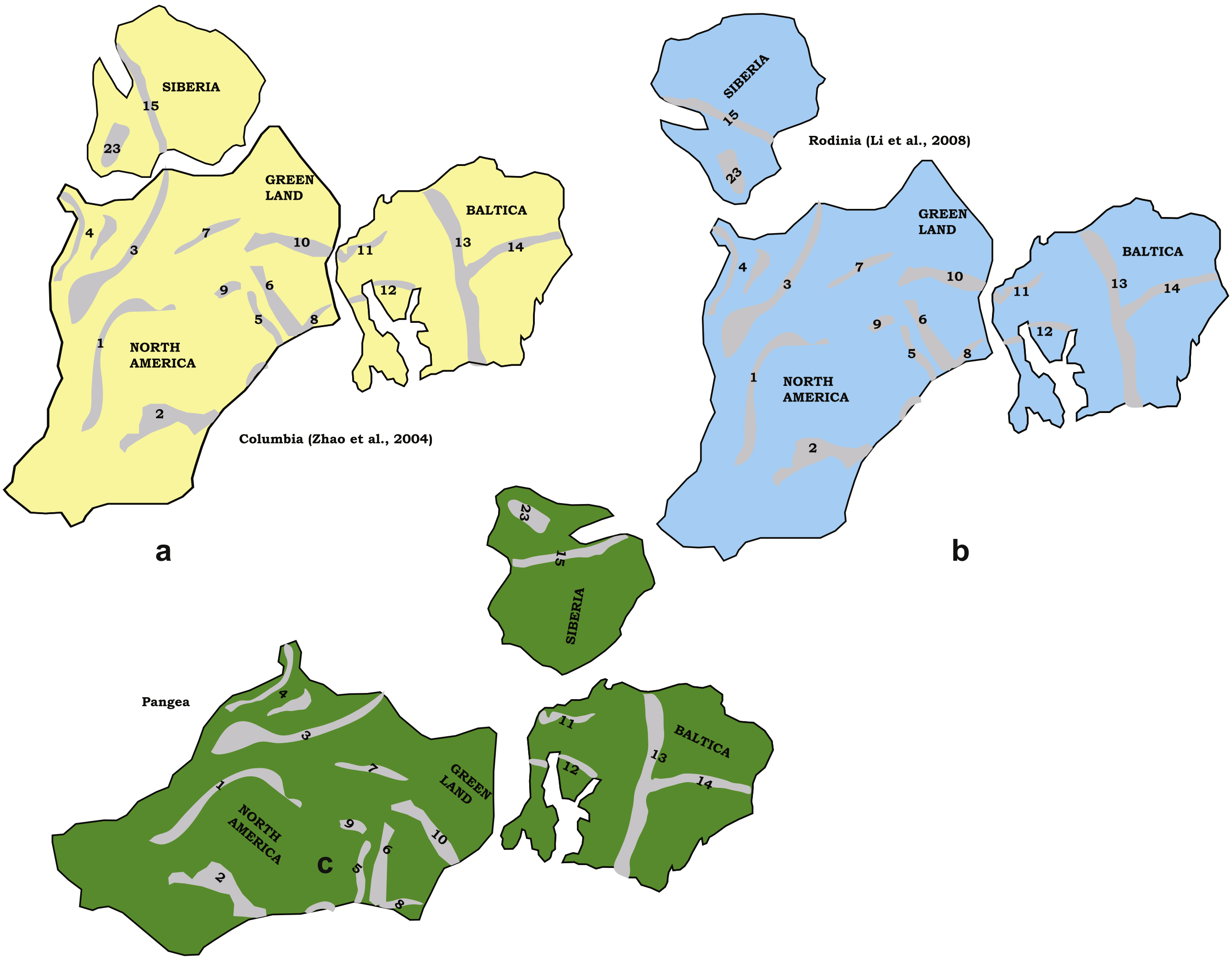

Figure 5. The strange attractors (Northern). (a) Siberia, Baltica and Laurentia in the archetypal “Columbia” supercontinent. Note that 2.1–1.8 Ga orogenic belts (gray-shading) are numbered according to the convention in Zhao et al. (2004); (b) Siberia, Baltica and Laurentia in the “Rodinia” configuration according to Li et al. (2008); (c) Pangea fit of Laurentia, Baltica and Siberia. Key to the gray-shaded 2.1–1.8 Ga orogens; 1–Trans-Hudson Orogen; 2–Penokean Orogen; 3–Taltson-Thelon Orogen; 4–Wopmay Orogen; 5–New Quebec Orogen; 6–Torngat Orogen; 7–Foxe Orogen; 8–Makkovik–Ketilidian Orogen; 9–Ungava Orogen; 10–Nugssugtoqidian Orogen; 11–Kola-Karelian Orogen; 12–Svecofennian Orogen; 13–Volhyn-Central Russian Orogen; 14–Pachelma Orogen; 15–Akitkan Orogen; 16–Transantarctic Orogen; 17–Capricorn Orogen; 18–Limpopo Belt; 19–Transamazonian Orogen; 20–Eburnean Orogen; 21–Trans-North China Orogen; 22–Central Indian Tectonic Zone; 23–Central Aldan Orogen; 24–Scotland.

‘archetypal’ Columbia, Rodinia, PaleoPangea and Pangea reconstructions; Baltica is placed at, or near, the Greenland margin of Laurentia. One alternative hypothesis for the position of Baltica within Rodinia positions it adjacent to the Greenland margin, but in an inverted position (Hartz and Torsvik, 2002). Each of these reconstructions are based on slightly different datasets, but the inescapable conclusion is that the evolution from Columbia-Rodinia-Pangea involved very little change in the relative positions of these three landmasses once assembled into the supercontinents.

East Gondwana (India, Madagascar, Australia, Antarctica, Sri Lanka) is depicted in Columbia, Rodinia and Pangea as a united landmass (Fig. 6a–c). Very few, if any, changes can be seen between these blocks in the ‘archetypal’ reconstructions of those supercontinents.

3.2. The spiritual interlopers (West Africa-Congo-Sao Francisco, Rio de la Plata, Tarim)

Landmasses of the Cambrian-age Gondwana continent include cratonic elements of South America, Africa, Madagascar, Sri Lanka, India, Australia and East Antarctica. The Rodinia and Columbia models show remarkable similarities in the placement of the western Gondwana blocks (Congo, Sao-Francisco, Rio de la Plata and West Africa) during the Proterozoic with some differences in their orientations (Fig. 7a–b; Zhao et al., 2002a,b; Li et al., 2008). If the Rodinia model is reasonable, then the transition from Rodinia to Gondwana involved large horizontal motions of the crust in order to bring the “West” Gondwana elements (West Africa, Congo, Kalahari, Sao Francisco and Rio de la Plata) adjacent to “East” Gondwana (India, Madagascar, Sri Lanka, East Antarctica, India and Australia) in the 750–550 Ma interval. The supercontinent Pangea maintains the coherence of the western and eastern Gondwana blocks until its breakup in the Mesozoic (Fig. 7c). Johansson (2009) argued for a nearly one billion year-long association between Amazonia and Baltica in the Proterozoic.

The Tarim microcontinent maintains a position near NW Australia in both the Columbia and Rodinia models (Fig. 7a–b), but is positioned to the East of Eurasia in Pangean reconstructions (Fig. 7c) and thus Tarim represents a ‘hybrid’ between a lonely wanderer and a spiritual interloper.

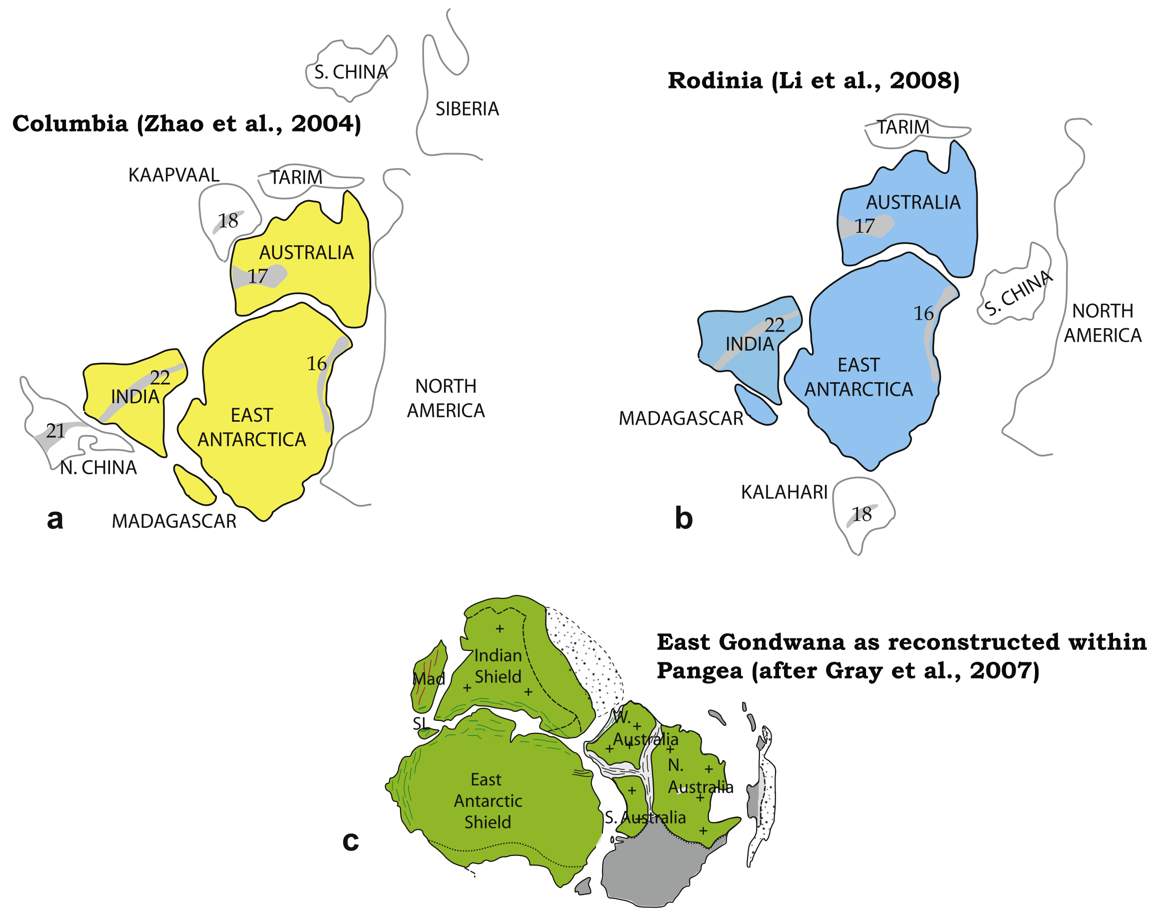

Figure 6. The strange attractors (East Gondwana). (a) The "Columbia" configuration according to Zhao et al. (2004) with a more or less traditional East Gondwana fit between India-Madagascar-East Antarctica and Australia. Sri Lanka was not included in the Columbia configuration; (b) the "Rodinia" configuration according to Li et al. (2008) showing a near-identical fit between the East Gondwana elements in Columbia and (c) East Gondwana as it existed during the time of Pangea after Gray et al. (2008). Gray orogenic belts as in Fig. 2.

3.3. The lonely wanderers (North China, South China, Kalahari/Kaapvaal, Tarim)

Drastic differences in the relative positions of South China, North China, Tarim and the Kalahari (Kaapvaal) nuclei can be seen in the reconstructions of Columbia, Rodinia and Pangea. In the Columbia configuration (Zhao et al., 2004), the Kaapvaal/Zimbabwe combined nucleus is placed adjacent to the Pilbara craton of western Australia (Fig. 8a). Rodinia models (Li et al., 2008), the Kalahari craton has migrated to a position geometrically similar to its African position within Gondwana; although the Kalahari is linked to the East Gondwana elements rather than to Africa proper (Fig. 8b). In Pangea, the Kalahari nucleus is considered part of West Gondwana (Fig. 8c).

South China in the Columbia model is sandwiched between Kaapvaal/Zimbabwe/Australia/Tarim and Siberia along the present-day NW-Arctic margin of Laurentia (Fig. 8a). Li et al. (2008) positioned South China between the Cordilleran margin of Laurentia and the Tasman line of eastern Australia (Fig. 8b). Reconstructions of Pangea place the South China block within the Paleotethyan Ocean away from 'mainland' Pangea (Fig. 8c).

The North China block is linked to India in the reconstruction of Zhao et al. (2004; Fig. 8a) and migrates to a position near Siberia and northernmost Greenland in the Rodinia supercontinent (Li et al., 2008; Fig. 8b). A myriad of other proposals for positioning the North China craton within Columbia were discussed in Section 2 of this paper. North China is located within the Paleo-Tethyan realm in Pangea reconstructions near to (but separated from) both Tarim and South China (Fig. 8c).

4. Discussion

Given the inconsistencies and weaknesses of the paleomagnetic database, the extraordinary parallels (strange attractors and spiritual interlopers) between Columbia, Rodinia and Pangea begs the question as to why this should be the case. The following is not meant to be an exhaustive analysis of this question, but merely offer some 'food for thought' as research moves forward in understanding plate dynamics in the Precambrian.

4.1. Minimal horizontal plate motion

There is considerable debate about the timing of the onset of horizontal plate tectonics (Moores, 2002; Hamilton, 2003, 2011; Cawood, 2005; Stern, 2005, 2008; Cawood et al., 2009; Condie and Aster, 2010; Kusky et al., 2013; Moore and Webb, 2013; Piper, 2013a; Sizova et al., 2013). In spite of the debate, there is either a tacit (or stated) assumption that Columbia formed, broke apart and most elements were re-assembled in a Rodinia configuration (Evans and Mitchell, 2011; Mitchell et al., 2012). Similarly, Rodinia breakup led to the assembly of Gondwana during the early Paleozoic and Pangea in the late Paleozoic (Powell and Pisarevsky, 2002; Meert, 2003, 2012). This mode of thought requires horizontal plate motions and therefore the essentials of modern-style plate tectonics are considered valid.

The plate tectonic model is not without its critics. As an example, Piper (2007, 2010, 2013a,b) made the argument that the similarities in the Paleoproterozoic and Neoproterozoic

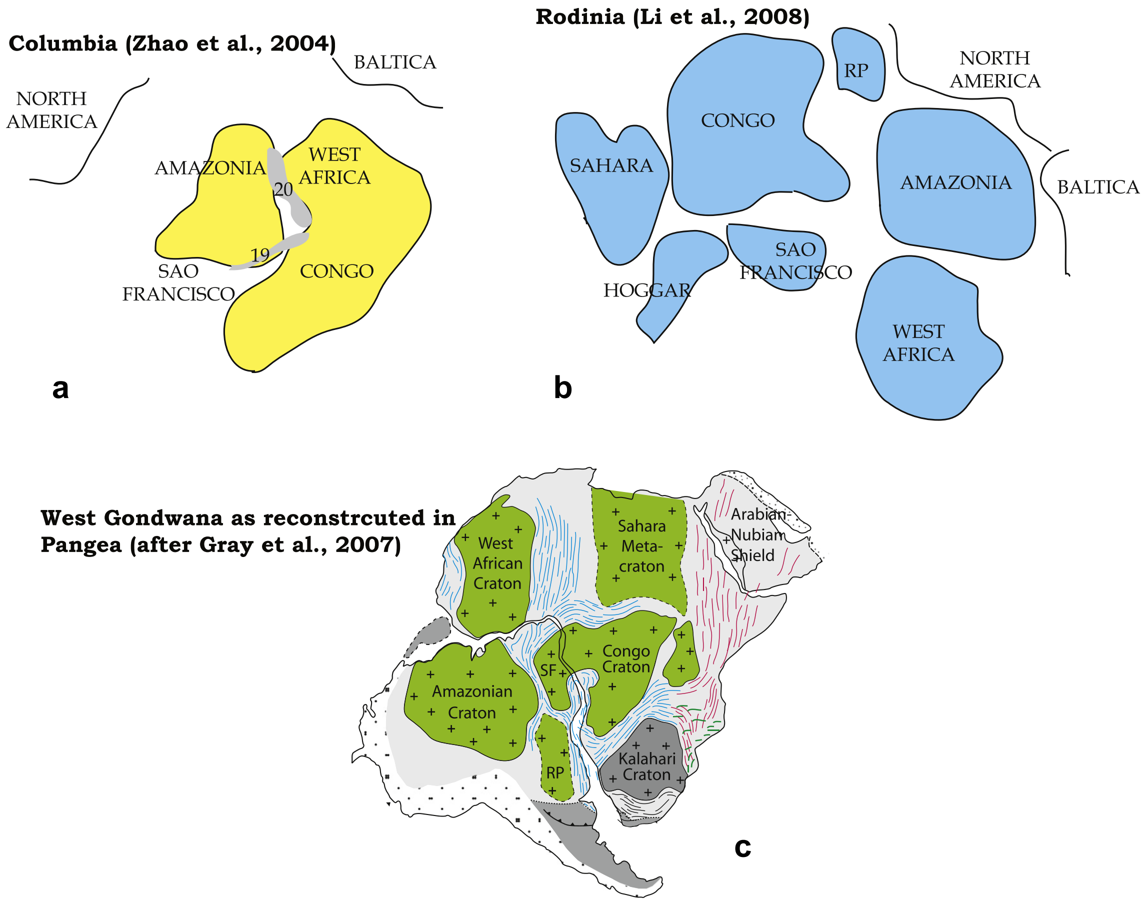

Figure 7. The spiritual interlopers (South America/Africa). (a) The "Columbia" configuration according to Zhao et al. (2004) showing a close relationship between Amazonia-Sao Francisco-Congo and West African cratons. The Sahara meta-craton and Rio de la Plata craton are not included in "Columbia"; (b) the "Rodinia" configuration according to Li et al. (2008) a slightly modified fit between Congo-Sao Francisco versus Amazonia and West Africa as compared to the Columbia model. Rodinia also include Hoggar, Sahara and Rio de la Plata (RP). Although the orientations are slightly different, these blocks maintained proximity to one another and to the eastern margin of Laurentia and the southern margin of Baltica in both Rodinia and Columbia (c) West Gondwana as it existed during the time of Pangea after Gray et al. (2008). Orogenic belts as in Fig. 2.

supercontinents are due to the fact that the Earth's crust was quasi-rigid and there was little relative motion between cratonic elements during most of the Proterozoic. In his models, modern-style plate tectonics does not begin until the very late Neoproterozoic. Piper's models rely heavily on paleomagnetic data. His approach was criticized and numerous flaws in his interpretations of the paleomagnetic data can be found throughout the literature (Van der Voo and Meert, 1991; Meert and Torsvik, 2004; Li et al., 2008; Meert and Lieberman, 2008). In spite of the paleomagnetic flaws in Piper's analysis, his model does posit very little change in continental configurations during the Paleoproterozoic (although his reconstructions are different from the more widely cited Columbia and Rodinia reconstructions).

Roberts (2013) also noted the rather minimal changes associated with the Columbia-Rodinia transition and argues (as did Piper, 2013a,b) that a style of 'lid tectonics' was more prevalent than modern-style plate tectonics during the Paleo–Mesoproterozoic interval. Roberts rejects the more extreme view of Piper (2013a,b) by noting the numerous 2.1–1.3 Ga accretionary belts including those such as the Trans-Hudson that hosted apparent subduction complexes (Corrigan et al., 2009). Moore and Webb (2013) discussed the possibility that what may appear to be subduction in ancient 'orogenic belts' may in fact relate to downward advection of cold thick lithosphere with minimal horizontal motion. It is possible that the Proterozoic interval was a time of transitional tectonism with aspects of both 'lid tectonics' and horizontal tectonics.

There are also proposals that speculate on a dominant cycle of true polar wander in the Precambrian and early Phanerozoic (Evans, 2003; Li et al., 2004; Li and Zhong, 2009). In true polar wander, much of the horizontal motion detectable using paleomagnetic data is ascribed to motion of the entire lithosphere as a single block. The central concept is that large landmasses regulate mass distribution in the mantle via cold downwellings (subduction) along their margins and warm upwellings (plumes) near their center. These resultant mass imbalances can result in large-scale true polar wander (Li et al., 2004; Li and Zhong, 2009). Although subduction zones imply modern-style plate tectonics, large-scale true polar wander of the supercontinent may involve only minor adjustments between the constituent blocks.

4.2. Bias in perception

What if modern-style plate tectonics operated during the Proterozoic? The presence of strange attractors and, to a lesser extent, spiritual interlopers, suggests a rather rigid form of Wilson-cycle (or introversion) whereby oceans open and close along almost exactly the same boundaries. In fact, if one looks at Siberia-Baltica-North America connections (Fig. 2a–c), the connections in all three supercontinents would suggest some sort of 'memory' that results

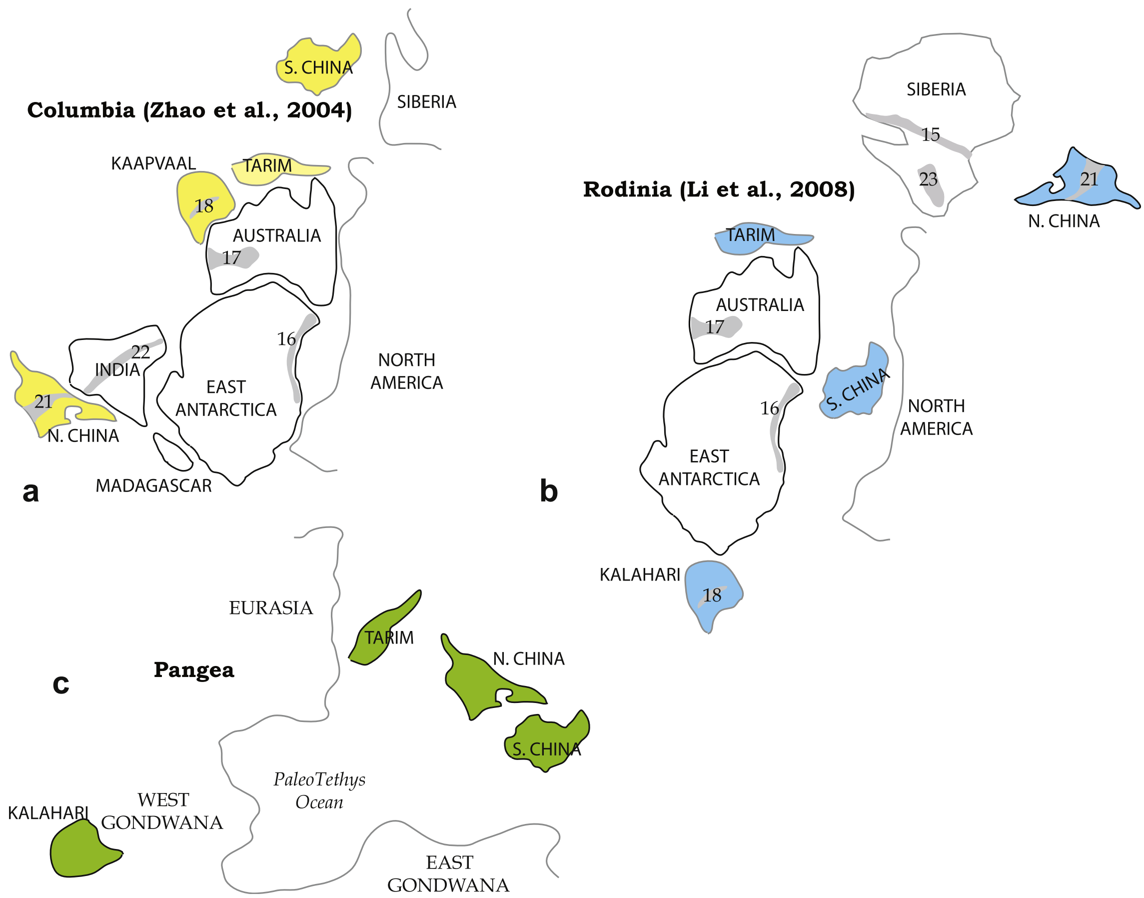

Figure 8. The lonely wanderers. (a) The positions of the North China, South China, Tarim and Kaapvaal blocks in Columbia according to Zhao et al. (2004); (b) the same four blocks in the Rodinia reconstruction of Li et al. (2008). Note that Tarim maintains its position along the northern margin of Australia and thus does not 'wander'; however, in (c) Tarim is now located along the Eurasian margin of Pangea, North China and South China occupy space in the PaleoTethys Ocean and Kalahari (including the Kaapvaal nucleus) is now incorporated into West Gondwana (see also Fig. 4c). Gray orogenic belts as in Fig. 2.

in a juxtaposition of a similar geometry no matter how much movement occurs during the intervening 'drift' period. Although knowledge of individual drift histories of continents during the Proterozoic is poor, the Phanerozoic record shows a complex series of ocean opening and closure ahead of Pangea formation. The evidence is convincing that during the Paleozoic, Baltica, Siberia and Laurentia maintained separate plate identities until their incorporation into the Laurasia and ultimately Pangea (Torsvik et al., 2012; Stampfli et al., 2013).

In addition to introversion, it has been suggested that supercontinents might undergo extroversion wherein the exterior margins of one supercontinent collide during the formation of the next younger supercontinent (Murphy and Nance, 1991, 2003). The *casus belli* for extroversion is the breakup of the archetypal Rodinia supercontinent and the subsequent formation of Gondwana (Hoffman, 1991). If the Rodinia reconstruction of Li et al. (2008) is correct, then the extroversion model makes sense for describing the formation of Gondwana, but no explanation is provided for why the individual elements that make up "East Gondwana" and "West Gondwana" maintain the same integral relationships for nearly two billion years until they were cleaved in the Mesozoic.

Those who model supercontinent reconstructions may 'fall-back' on the well-established Pangea model simply because the Pangea connections are less ambiguous. This bias in perception may arise from the non-uniqueness of the methods/data used to reconstruct supercontinents.

5. Conclusions

The observation is made that there are very strong similarities between the supercontinents Columbia, Rodinia and Pangea. In particular, Baltica, Laurentia and Siberia form one group of 'strange attractors' as do the elements of East Gondwana (India, Australia, Antarctica, Madagascar). The pieces of "West Gondwana" are positioned as a slightly looser amalgam of cratonic blocks in all three supercontinents and are referred to as 'spiritual interlopers'. Relatively few landmasses are positioned in distinct locations within each of the three supercontinents and these are referred to as 'lonely wanderers'.

There may be several explanations for why these supercontinents show such remarkable similarities. One possibility is that modern-style plate tectonics did not begin until the late Neoproterozoic and horizontal motions were restricted and a vertical style of 'lid tectonics' dominated with episodes of true polar wander. If relative horizontal motion was limited for most of the Proterozoic, it would explain the remarkable similarities seen in the Columbia and Rodinia supercontinents. The motions of the continents documented by changes in their apparent polar wander paths might be the result of large-scale true polar wander with minimal relative motion between the blocks.

A second possibility is that our views of older supercontinents are shaped by well-known geological connections documented for the most recent supercontinent, Pangea. If plate tectonics was operating over the past 2.5 billion years of Earth history, and dominated by extroversion and introversion of ocean basins, then the striking resemblance between the three supercontinents would be less probable. In that light, it is intriguing that three of the four 'lonely wanderers' (Tarim, North China, South China) did not unite until just before the breakup of Pangea (Stampfli et al., 2013). Since these three were not part of the Pangean supercontinent, there is no *a priori* bias that would influence their placement in the more ancient reconstructions.

The fourth 'lonely wanderer', the Kalahari (and core Kaapvaal) craton has a somewhat unique Archean-age geology compared to its nearest neighbors in Gondwana, but very similar to that of western Australia (Wingate, 1998; Zegers et al., 1998; de Kock et al., 2009). Due to the lack of a strictly West Gondwana bias, the Kalahari craton was not rigidly fixed in the supercontinents.

Acknowledgments

I wish to thank M. Santosh for encouraging me to submit this idea to the journal; to discussions with Alex Webb that prompted me to finally put 'fingers to keyboard'; and finally to many colleagues that I have worked with over the years that helped shape the views in this review. Critical reviews by G.C. Zhao and Nick Roberts improved the manuscript and pointed out several omissions in the original submission. This work has been supported in part by grants from the National Science Foundation EAR09-10888 and EAR11-19038.

References

Aitken, A.R.A., Raimondo, T., Capitano, F.A., 2013. The intraplate character of supercontinent tectonics. Gondwana Research 24, 807–814.
Allmendinger, R.W., Jordan, T.E., Kay, S.M., Isacks, B.L., 1997. The evolution of the Alti-plano-Puna plateau of the Central Andes. Annual Reviews of Earth and Planetary Science 25, 139–174.
Andersen, T., 2014. The detrital zircon record: supercontinents, parallel evolution-or coincidence. Precambrian Research. http://dx.doi.org/10.1016/j.precamres.2013.10.13 (in press).
Baer, A.J., 1983. Proterozoic orogenies and crustal evolution. Geological Society of America Memoir 161, 47–58.
Berthelsen, A., Marker, M., 1986. Tectonics of the Kola collision suture and adjacent Archean and Early Proterozoic terrains in the northeastern region of the Baltic Shield. Tectonophysics 126, 31–55.
Betts, P.G., Giles, D., Aitken, A., 2011. Palaeoproterozoic accretion processes of Australia and comparisons with Laurentia. International Geology Review 53, 1357–1376.
Bispos-Santos, F., D'Agrella-Filho, M., Janikian, L., Reis, N.J., Trindade, R.I.F., Reis, M.A.A.A., 2013. Towards Columbia: paleomagnetism of 1980–1960 Ma Surumu volcanic rocks, Northern Amazonia. Precambrian Research. http://dx.doi.org/10.1016/j.precamres.2013.08.005 (in press).
Buchan, K.L., Ernst, R.E., Hamilton, M.A., Mertanen, S., Pesonen, L.J., Elming, S.A., 2001. Rodinia: the evidence from integrated paleomagnetism and U-Pb geochronology. Precambrian Research 110, 9–32.
Burke, K.C.A., Dewey, J.F., 1973. Plume-generated triple junctions: key indicators in applying plate tectonics to old rocks. Journal of Geology 86, 406–433.
Burrett, C., Berry, R., 2000. Proterozoic Australia-Western United States (AUSWUS) fit between Laurentia and Australia. Geology 28, 103–106.
Calvert, A.J., Sawyer, E.W., Davis, W.J., Ludden, J.N., 1995. Archaean subduction inferred from seismic images of a mantle suture in the Superior Province. Nature 375, 670–673.
Campbell, I.H., Allen, C.M., 2008. Formation of supercontinents linked to increases in atmospheric oxygen. Nature Geosciences 1, 554–558.
Cawood, P.A., 2005. Terra Australis Orogen: Rodinia breakup and development of the Pacific and Iapetus margins of Gondwana during the Neoproterozoic and Paleozoic. Earth Science Reviews 69, 249–279.
Cawood, P.A., Kroner, A., Pisarevsky, S.A., 2006. Precambrian plate tectonics: criteria and evidence. GSA Today 16, 4–11.
Cawood, P.A., Nemchin, A.A., Strachan, R., Prave, T., Krabbendam, M., 2007. Sedimentary basin and detrital zircon record along East Laurentia and Baltica during assembly and break up of Rodinia. Journal of the Geological Society of London 164, 257–275.
Cawood, P.A., Kröner, A., Collins, W.J., Kusky, T.M., Mooney, W.D., Windley, B.F., 2009. Accretionary orogens through Earth history. In: Cawood, P.A., Kröner, A. (Eds.), Earth Accretionary Systems in Space and Time, Geological Society of London, Special Publication, vol. 318, pp. 1–36.
Cawood, P.A., Hawkesworth, C.J., Dhuime, B., 2013. The continental record and the generation of continental crust. Geological Society of America Bulletin 125, 14–32.
Chen, L., Huang, B., Yi, Z., Zhao, J., Yan, Y., 2013. Paleomagnetism of ca. 1.35 Ga sills in northern North China Craton and implications for paleogeographic reconstruction of the Mesoproterozoic supercontinent. Precambrian Research 228, 36–47.
Condie, K.C., 2002. Breakup of a Paleoproterozoic supercontinent. Gondwana Research 5, 41–43.
Condie, K.C., Aster, R.C., 2010. Episodic zircon age spectra of orogenic granitoids: the supercontinent connection and continental growth. Precambrian Research 180, 227–236.
Corrigan, D., Pehrsson, S., Wodicka, N., de Kemp, E., 2009. The Paleoproterozoic Trans-Hudson Orogeny: A Prototype of Modern Accretionary Processes. In: Geological Society of London Special Publication, vol. 327, pp. 457–479.
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.
DeCelles, P.G., 2004. Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western U.S.A. American Journal of Science 304, 105–168.
de Kock, M.O., Evans, D.A.D., Beukes, N.J., 2009. Validating the existence of Vaalbara in the Neoarchean. Precambrian Research 174, 145–154.
Ernst, R.E., Wingate, M.T.D., Buchan, K.L., Li, Z.X., 2008. Global record of 1600–700 Ma Large Igneous Provinces (LIPs): Implications for the reconstruction of the proposed Nuna (Columbia) and Rodiniaa supercontinents. Precambrian Research 160, 159–178.
Ernst, R.E., Srivastava, R.K., 2008. India's place in the Proterozoic world: Constraints from the Large Igneous Province (LIP) record. In: Srivastava, et al. (Eds.), Indian Dyke: Geochemistry, Geophysics and Geochronology. Narose Publishing House, India, pp. 41–56.
Ernst, R.E., Srivastava, R.K., Bleeker, W., Hamilton, M., 2010. Precambrian Large Igneous Provinces (LIPs) and their dyke swarms: new insights from high-precision geochronology integrated with paleomagnetism and geochemistry. Precambrian Research 183, vii–vxi.
Ernst, R.E., Bleeker, W., Soderlund, U., Kerr, A.C., 2013. Large Igneous Provinces and supercontinents: toward completing the plate tectonic revolution. Lithos 174, 1–14.
Evans, D.A.D., 2003. True polar wander and supercontinents. Tectonophysics 362, 303–320.
Evans, D.A.D., 2009. The palaeomagnetically viable, long-lived and all-inclusive Rodinia supercontinent reconstruction. In: Murphy, J.B., et al. (Eds.), Ancient Orogens and Modern Analogues: Geological Society of London Special Publication, vol. 327, pp. 371–405.
Evans, D.A.D., Mitchell, R.N., 2011. Assembly and breakup of the core of Paleoproterozoic-Mesoproterozoic supercontinent Nuna. Geology 39, 443–446.
Fedo, C.M., Sircombe, K.N., Rainbird, R.H., 2003. Detrital zircon analysis of the sedimentary record. In: Hanchar, J.M., Hoskin, P.W.O. (Eds.), Zircon. Reviews in Mineralogy and Geochemistry, vol. 53, pp. 277–303.
Frisch, W., Mescheda, M., Blakey, R., 2011. Early Precambrian plate tectonics. In: Frisch, et al. (Eds.), Plate Tectonics: Continental Drift and Mountain Building. Springer Publications, Heidelberg, Germany, pp. 139–147.
Gastil, R.G., 1960. The distribution of mineral dates in time and space. American Journal of Science 258, 1.
Giles, D., Betts, P., Lister, G., 2002. Far-field continental backarc setting for the 1.80–1.67 Ga basins of northeastern Australia. Geology 30, 823–826.
Gray, D.R., Foster, D.A., Meert, J.G., Goscombe, B.D., Armstrong, R., Truow, R.A.J., Passchier, C.W., 2008. A Damaran Perspective on the Assembly of Southwestern Gondwana. In: Geological Society of London Special Publication, vol. 294, pp. 257–278.
Hamilton, W.B., 2003. An alternative Earth. GSA Today 13, 4–12.
Hamilton, W.B., 2011. Plate tectonics began in Neoproterozoic time, and plumes from deep mantle have never operated. Lithos 123, 1–20.
Hand, M., Sandiford, M., 1999. Intraplate deformation in central Australia, the link between subsidence and fault reactivation. Tectonophysics 305, 121–140.
Hartz, E.H., Torsvik, T.H., 2002. Baltica upside down: a new plate tectonic model for Rodinia and the Iapetus Ocean. Geology 30, 255–258.
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 167, 229–248.
Hoffman, P.F., 1989. Speculations on Laurentia's first gigayear (2.0–1.0 Ga). Geology 17, 135–138.
Hoffman, P.F., 1991. Did the breakout of Laurentia turn Gondwanaland inside out? Science 252, 1409–1412.
Hou, G., Santosh, M., Qian, X., Lister, G.S., Li, J., 2008. Configuration of the Late Paleoproterozoic supercontinent Columbia: insights from radiating mafic dyke swarms. Gondwana Research 14, 395–409.
Ireland, T.R., Flöttmann, T., Fanning, C.M., Gibson, G.M., Preiss, W.V., 1998. Development of the early Paleozoic Pacific margin of Gondwana from detrital-zircon ages across the Delamerian orogen. Geology 26, 243–246.
Irving, E., Emslie, R.F., Ueno, H., 1974. Upper Proterozoic palaeomagnetic poles from Laurentia and the history of the Grenville Structural Province. Journal of Geophysical Research 79, 5491–5502.
Johansson, Å., 2009. Baltica, Amazonia and the SAMBA connection – 1000 million years of neighbourhood during the Proterozoic? Precambrian Research 175, 221–234.
Kaur, P., Chaudhri, N., 2014. Mettalogeny associated with the Paleo-Mesoproterozoic Columbia supercontinent cycle: a synthesis of major metallic deposits. Ore Geology Reviews 56, 415–422. http://dx.doi.org/10.1016/j.oregeorev.2013.03.005.

Kroner, A., 1983. Proterozoic mobile belts compatible with the plate tectonic concept. Geological Society of America Memoirs 161, 59–74.
Kröner, A., Cui, W., Wang, S., Wang, C., Nemchin, A., 1998. Single zircon ages from high-grade rocks of the Jianping Complex, Liaoning Province, NE China. Journal of Asian Earth Sciences 16, 519–532.
Kusky, T.M., Li, J., 2003. Paleoproterozoic tectonic evolution of the North China Craton. Journal of Asian Earth Sciences 22, 383–397.
Kusky, T., Li, J., Santosh, M., 2007. The paleoproterozoic north Hebei orogen: North China Craton's collisional suture with the Columbia supercontinent. Gondwana Research 12, 4–28.
Kusky, T.M., Windley, B.M., Safonova, I., Wakita, K., Wakabayashi, J., Polat, A., Santosh, M., 2013. Recognition of ocean plate stratigraphy in accretionary orogens through Earth history: a record of 3.8 billion years of sea floor spreading, subduction and accretion. Gondwana Research 24, 501–547. http://dx.doi.org/10.1016/j.gr.2013.01.004.
Kuznetsov, N.M., Meert, J.G., Romanyuk, T., 2014. Ages of detrital zircons (U/Pb, LA-ICP-MS) from the latest Neoproterozoic-Middle Cambrian (?) Asha Group, the south-western Urals: a test of an Australia-Baltica connection within Rodinia. Precambrian Research. http://dx.doi.org/10.1016/j.precamres.2013.09.011 (in press).
Lahtinen, R., Huhma, H., Kousa, J., 2002. Contrasting source components of the Paleoproterozoic Svecofennian metasediments: detrital zircon U–Pb, Sm–Nd and geochemical data. Precambrian Research 116, 81–109.
Li, Z.X., Evans, D.A.D., Zhang, S., 2004. A 90 degree spin on Rodinia: possible causal links between the Neoproterozoic supercontinent, superplume, true polar wander and low-latitude glaciation. Earth and Planetary Science Letters 220, 405–421.
Li, Z.X., Zhang, L., Powell, C.M., 1996. Positions of the East Asian cratons in the Neoproterozoic supercontinent Rodinia. Australian Journal of Earth Sciences 43, 593–604.
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.
Li, Z.X., Zhong, S., 2009. Supercontinent-superplume coupling, true polar wander and plume mobility; plate dominance in whole mantle tectonics. Physics of the Earth and Planetary interiors 176, 143–156.
McMenamin, M.A.S., McMenamin, D.L.S., 1990. The Emergence of Animals: The Cambrian Breakthrough. Columbia University Press, New York, p. 217.
Meert, J.G., Pandit, M.K., Kamenov, G.D., 2013. Further geochronological and paleomagnetic constraints on Malani (and pre-Malani) magmatism in NW India. Tectonophysics 608, 1254–1267. http://dx.doi.org/10.1016/j.tecto.2013.06.019.
Meert, J.G., 2002. Paleomagnetic evidence for a Paleo-Mesoproterozoic supercontinent Columbia. Gondwana Research 5, 207–215.
Meert, J.G., 2012. What's in a name? The Columbia (Palaeopangea/Nuna) supercontinent. Gondwana Research 21, 987–993.
Meert, J.G., 2003. A synopsis of events related to the assembly of eastern Gondwana. Tectonophysics 362, 1–40.
Meert, J.G., Torsvik, T.H., 2003. The making and unmaking of a supercontinent: Rodinia Revisited. Tectonophysics 375, 261–288.
Meert, J.G., Torsvik, T.H., 2004. Reply to JDA Piper: the making and unmaking of a Supercontinent. Tectonophysics 383, 99–103.
Meert, J.G., Lieberman, B.S., 2004. A Palaeomagnetic and Palaeobiogeographic perspective on Latest Neoproterozoic and Early Cambrian tectonic events. Journal of the Geological Society of London 161, 477–489.
Meert, J.G., Lieberman, B.S., 2008. The Neoproterozoic assembly of Gondwana and its relationship to the Ediacaran-Cambrian Radiation. Gondwana Research 14, 5–21.
Meert, J.G., Pandit, M.K., Pradhan, V.R., Kamenov, G., 2011. Preliminary report on the paleomagnetism of 1.88 Ga dykes from the Bastar and Dharwarcratons, peninsular India. Gondwana Research 20, 335–343.
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.
Moore, W.B., Webb, A.A.G., 2013. Heat pipe Earth. Nature 501, 501–505.
Moores, E.M., 1991. Southwest US–East Antarctica (SWEAT) connection: a hypothesis. Geology 19, 425–428.
Moores, E.M., 2002. Pre-1 Ga (pre-Rodinian) ophiolites: their tectonic and environmental implications. Geological Society of America Bulletin 114, 80–95.
Murphy, J.B., Nance, R.D., 1991. A supercontinent model for the contrast- ing character of Late Proterozoic orogenic belts. Geology 19, 469–472.
Murphy, J.B., Nance, R.D., 2003. Do supercontinents intravert or extravert?: Sm-Nd isotopic evidence. Geology 31, 873–876.
Pacheco Neves, S., Mariano, G., 2004. Heat producing element-enriched continental mantle lithosphere and Proterozoic intracontinental orogens; insights from Brasiliano/Pan-African belts. Gondwana Research 7, 427–436.
Peng, P., Zhai, M., Zhang, H., Guo, J., 2005. Geochronological constraints on the paleoproterozoic evolution of the North China craton: SHRIMP zircon ages of different types of Mafic dikes. International Geology Review 47, 492–508.
Pesonen, L.J., Elming, S.A., Mertanen, S., Pisarevski, S., D'Agrella-Filho, M.S., Meert, J., Schmidt, P.W., Abrahmsen, N., Bylund, G., 2003. Assemblies of continents during the Proterozoic: Rodinia and beyond. Tectonophysics 375, 289–324.
Piper, J.D.A., 1976. Palaeomagnetic evidence for a Proterozoic supercontinent. Philosophical Transactions of the Royal Society of London, Series A 280, 469–490.
Piper, J.D.A., 2000. The Neoproterozoic supercontinent: Rodinia or Paleopangaea? Earth and Planetary Science Letters 176, 131–146.
Piper, J.D.A., 2004. Discussion on: "The making and unmaking of a supercontinent: Rodinia revisited by J.G. Meert and T.H. Torsvik. Tectonophysics 383, 91–97.
Piper, J.D.A., 2007. The Neoproterozoic supercontinent Paleopangaea. Gondwana Research 12, 202–227.
Piper, J.D.A., 2010. Protopangaea: palaeomagnetic definition of Earth's oldest (mid-Archaean-Palaeoproterozoic) supercontinent. Journal of Geodynamics 50, 154–165.
Piper, J.D.A., 2013a. A planetary perspective on Earth evolution: Lid Tectonics before Plate Tectonics. Tectonophysics 589, 44–56.
Piper, J.D.A., 2013b. Continental velocity through Precambrian times: the link to magmatism, crustal accretion and episodes of global cooling. Geoscience Frontiers 4, 7–36.
Powell McA., C., Li, Z.X., McElhinny, M.W., Meert, J.G., Park, J.K., 1993. Paleomagnetic constraints on the Neoproterozoic breakup of Rodinia and the mid-Cambrian formation of Gondwanaland. Geology 21, 889–892.
Powell McA., C., Pisarevsky, S.A., 2002. Late Neoproterozoic assembly of East Gondwanaland. Geology 30, 3–6.
Qian, X., Chen, Y., 1987. Late Precambrian mafic dyke swarms of the North China craton. Mafic Dyke Swarms. Geology Association of Canada, Special Papers 34, 385–391.
Rainbird, R.H., Stern, R.A., Khudoley, A.K., Kropachev, A.P., Heaman, L.M., Sukhorukov, V.I., 1998. U-Pb geochronology of Riphean sandstone and gabbro from southeast Siberia and its bearing on the Laurentia-Siberia connection. Earth and Planetary Science Letters 164, 409–420.
Reddy, S.M., Evans, D.A.D., 2009. Palaeoproterozoic supercontinents and global evolution: correlations from core to atmosphere. In: Geological Society London Special Publications, vol. 323, pp. 1–26.
Rino, S., Komiya, T., Windley, B.F., Katayama, I., Motoki, A., Hirata, T., 2004. Major episodic increases of continental crustal growth determined from zircon ages of river sand: implications for mantle overturns in the Early Precambrian. Physics of the Earth and Planetary Interiors 146, 369–394.
Roberts, N.M.W., 2013. The boring billion? Lid tectonics, continental growth and environmental change associated with the Columbia supercontinent. Geoscience Frontiers 6, 681–691. http://dx.doi.org/10.1016/j.gsf.2013.05.004.
Rogers, J.J.W., Santosh, M., 2002. Configuration of Columbia, a Mesoproterozoic supercontinent. Gondwana Research 5, 5–22.
Rogers, J.J.W., Santosh, M., 2009. Tectonics and surface effects of the supercontinent Columbia. Gondwana Research 15, 373–380.
Runcorn, S.K., 1962. Convection currents in the Earth's mantle. Nature 195, 1248–1249.
Salminen, J., Mertanen, S., Evans, D.A.D., Wang, Z., 2013. Paleomagnetic and geochemical studies on the Sakunta dyke swarms, Finland, with implications for a northern Europe-North American (NENA) connection within the Nuna supercontinent. Precambrian Research. http://dx.doi.org/10.1019/j.precamres.2013.08.006 (in press).
Sawkins, F.J., 1976. Widespread continental rifting: some considerations of timing and mechanism. Geology 4, 427–430.
Sears, J.W., Price, R.A., 2002. The hypothetical Mesoproterozoic supercontinent Columbia: implications of the Siberian-West Laurentian connection. Gondwana Research 5, 35–40.
Sizova, E., Gerya, T., Brown, M., 2013. Contrasting styles of Phanerozoic and Precambrian continental collision. Gondwana Research. http://dx.doi.org/10.1016/j.gr.2012,12.001 (in press).
Stampfli, G.M., Hochard, C., Verard, C., Wilhelm, C., vonRaumer, J., 2013. The formation of Pangea. Tectonophysics 593, 1–19.
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 33, 557–560.
Stern, R.J., 2008. Modern-style plate tectonics began in Neoproterozoic time: an alternative interpretation of Earth's tectonic history. In: Condie, K., Pease, V. (Eds.), When Did Plate Tectonics Begin on Planet Earth?, Geological Society of America Special Paper, vol. 440, pp. 265–280.
Sutton, J., 1963. Long term cycles in the evolution of continents. Nature 198, 731–735.
Tauxe, L., Kent, D.V., 2004. A simplified statistical model for the geomagnetic field and the detection of shallow bias in paleomagnetic inclinations: was the ancient magnetic field dipolar?. In: Channell, J.E.T., et al. (Eds.), Timescales of the Paleomagnetic Field, vol. 145American Geophysical Union, Washington, D.C., pp. 101–116.
Tapponnier, P., Molnar, P.J., 1976. Slip-line field theory and large-scale continental tectonics. Nature 264, 319–324.
Torsvik, T.H., Smethurst, M.A., Meert, J.G., Van der Voo, R., McKerrow, W.S., Brasier, M.D., Sturt, B.A., Walderhaug, H., 1996. Continental breakup and collision in the Neoproterozoic and Phanerozoic-A tale of Baltica and Laurentia. Earth Science Reviews 40, 229–258.
Torsvik, T.H., Van der Voo, R., Preeden, U., MacNiocaill, C., Steinberger, B., Doubrovine, P.V., van Hinsbergen, D.J.J., Domeir, M., Gaina, C., Tohver, E., Meert, J.G., McCausland, P.J.A., Cocks, R.M., 2012. Phanerozoic polar wander, palaeogeography and dynamics. Earth Science Reviews 114, 325–368.
Turner, C.C., Meert, J.G., Pandit, M.K., Kamenov, G.D., 2014. A detrital zircon U-Pb and Hf isotopic transect across the Son Valley sector of the Vindhyan basin, India: Implications for basin evolution and paleogeography. Gondwana Research. http://dx.doi.org/10.1016/j.gr.2013.07.009 (in press).
Valentine, J.W., Moores, E.M., 1970. Plate tectonic regulation of faunal diversity and sea level: A model. Nature 228, 657–659.

Valentine, J.W., Moores, E.M., 1972. Global tectonics and the fossil record. Journal of Geology 80, 167–184.
Van der Voo, R., Meert, J.G., 1991. Late Proterozoic paleomagnetism and tectonic models: a critical appraisal. Precambrian Research 53, 149–163.
Wells, M.L., Hoisch, T.D., Cruz-Uribe, A.M., Vervoort, J.D., 2012. Geodynamics of syn-convergent extension nd tectonic mode switching: constraints from the Sevier-Laramide orogeny. Tectonics 31. http://dx.doi.org/10.1029/2011TC002913.
Wilde, S.A., Zhao, G., Sun, M., 2002. Development of the North China Craton during the late Archean and its final amalgamation at 1.8 Ga: Some speculations on its position within a global Paleoproterozoic supercontinent. Gondwana Research 5, 85–94.
Wingate, M.T.D., 1998. A palaeomagnetic test of the Kaapvaal–Pilbara (Vaalbara) connection at 2.78 Ga. South African Journal of Geology 101, 257–274.
Wingate, M.T.D., Pisarevsky, S.A., Evans, D.A.D., 2002. Rodinia connections between Australia and Laurentia: no SWEAT, no AUSWUS? Terra Nova 14, 121–128.
Weil, A.B., Van der Voo, R., MacNiocall, C., Meert, J.G., 1998. The Proterozoic supercontinent Rodinia: paleomagnetically derived reconstructions for 1100 to 800 Ma. Earth and Planetary Science Letters 154, 13–24.
Wu, L., Dong, J., Haibin, L., Fei, D., Li, Y., 2010. Provenance of detrital zircons from the late Neoproterozoic to Ordovician sandstones of South China: implications for continental affinity. Geological Magazine 147, 974–980.
Yang, Y., Liu, M., 2002. Cenozoic deformation of the Tarim plate and the implications for mountain building in the Tibetan Plateau and the Tian Shan. Tectonics 21. http://dx.doi.org/10.1029/2001TC001300.
Yin, A., Harrison, T.M., 2000. Geologic evolution of the Himalayan-Tibetan orogen. Annual Reviews of Earth and Planetary Sciences 28, 211–280.
Zegers, T.E., De Wit, M.J., Dann, J., White, S.H., 1998. Vaalbara, Earth's oldest assembled continent? A combined structural, geochronological, and palaeomagnetic test. Terra Nova 10, 250–259.
Zhao, G., Wilde, S.A., Cawood, P.A., Sun, M., 2001. Archean blocks and their boundaries in the North China Craton: lithological, geochemical, structural and PT path constraints and tectonic evolution. Precambrian Research 107, 45–73.
Zhao, G., Cawood, P.A., Wilde, S.A., Sun, M., 2002a. Review of 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., 2002b. Did South America and West Africa marry and divorce or was it a long-lasting relationship? Gondwana Research 5, 591–596.
Zhao, G.C., Sun, M., Wilde, S.A., Li, S.Z., 2003. Assembly, accretion and breakup of the Paleo-Mesoproterozoic Columbia Supercontinent: records in the North China Craton. Gondwana Research 6, 417–434.
Zhao, G., Sun, M., Wilde, S.A., Li, S.Z., 2004. A Paleo-Mesoproterozoic supercontinent: assembly, growth and breakup. Earth Science Reviews 59, 125–162.

Joseph Meert: Joseph Meert is a Professor of Geology in the Department of Geological Sciences at the University of Florida (Gainesville, Florida, USA). He is an associate Editor of Gondwana Research. He received his B.S. and M.S. from the University of Florida (1986, 1988); and his PhD from the University of Michigan (1993); worked as a Post-Doctoral Fellow (1994) at the University of Michigan and taught at Indiana State University (Terre Haute, Indiana) until 2001. Meert was a Fulbright Senior Scholar at the Norwegian Geological Survey (2000–2001; Trondheim, Norway) and a visiting Professor at the University of Paul Sabatier, France (2001). He has worked in Gondwana and peri-Gondwana regions (Kenya, Tanzania, Burundi, Namibia, Madagascar, India, Mongolia, Kazakhstan and Kyrgyzstan) since 1989 studying the assembly and breakup of Neoproterozoic supercontinents. Together with his students, the work is aimed at deciphering the interplay between tectonics, evolution and global climate. He has also worked on such diverse issues such as geodynamics, the character of the Earth's magnetic field and the formation of Terra Rossa soils.