



## Reply

## How not to build a supercontinent: A reply to J.D.A. Piper

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## ABSTRACT

The hypothesized existence of a Neoproterozoic supercontinent called Rodinia is based on a series of geological and paleomagnetic observations, with details about the configuration and evolution of this supercontinent still a matter for debate. Regrettably, we found that the comment by Piper (this volume) lacks scientific objectiveness. The 'Palaeopangaea' that he promotes is, in our view, based on incorrect application of paleomagnetic data, and is not supported by geological evidence.

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As pointed out in the introduction of Li et al. (2008), "although few still doubt the existence of a late Precambrian supercontinent, there is still no consensus regarding the number of participating cratons, their relative configuration within the supercontinent and the chronology and mode of assembly and break-up of the supercontinent". Healthy debates on alternative reconstructions based on sound scientific observations and approaches, and rational deductions, are thus most welcome in order to move the subject forward. Unfortunately, we found the comment by Piper (this volume) neither rational nor based on sound scientific observations and approaches. His comment, instead, starts with numerous unsubstantiated accusations, followed by another promotion of the 'Palaeopangaea' hypothesis which he first developed in 1970s through unconventional paleomagnetic approaches that lack the necessary scientific rigor, and based on geological arguments that are biased and outdated. Below we address major points raised in the comment following the order of their appearance.

### 1. Model-driven or evidence-driven

In a number of instances of the comment (first and third paragraphs), Piper accuses Li et al. (2008) of uncritical acceptance of the SWEAT hypothesis, of hiding controversies in Neoproterozoic paleogeography, and of ignoring new paleomagnetic and geological data. We reject these accusations outright, as they are untrue and are offensive to the larger Precambrian geoscience community, the 300-plus members of International Geoscience Programme (IGCP) Project 440 in particular.

Li et al. (2008) stated explicitly in the introduction, in the concluding remarks, and in the acknowledgments, that the issue of Rodinia reconstruction is highly controversial, and that the model presented in the paper is permissible but non-unique geologically and paleomagnetically at our current level of knowledge. A number of competing models were discussed, including the

Laurentia–Siberia connection proposed by Sears and Price (1978, 2000) (see Fig. 2e of Li et al., 2008), and Appendix I illustrated two of the alternative Rodinia reconstructions. In the same volume, some of the co-authors presented alternative reconstructions. Piper's Palaeopangaea reconstruction was cited in the introduction to the special issue but not discussed extensively by Li et al. (2008) because its numerous paleomagnetic and geological flaws (see below) have in part already been refuted (e.g., Van der Voo and Meert, 1991; Torsvik and Meert, 1995; Meert and Torsvik, 2004). Piper's continued insistence (2007 and this volume) on his nearly 40-year-old model (Piper et al., 1973) with only minor adjustments that do not address these quantitative refutations, requires us to restate them yet again.

Joining this reply is David Evans, who is publishing a radically different Rodinia reconstruction (Evans, 2009) bearing no resemblance to the SWEAT configuration of Moores (1991), Dalziel (1991) and Hoffman (1991). This further illustrates that we, as a group of scientists, are open to consider all possible paleogeographic scenarios, provided that they are based on credible paleomagnetic and/or geological arguments.

Piper also criticised the Li et al. (2008) model for it requires "extraordinary and unlikely differential movements to achieve the Gondwana palaeogeography by early Phanerozoic times". Apart from the documented potential ca. 800–750 Ma true polar wander events (Li et al., 2004; Maloof et al., 2006), the relative plate movements as in Fig. 9 and Appendix II of Li et al. (2008), ranging from the assembly of Rodinia until the ca. 530 Ma formation of Gondwanaland, are no more "extraordinary" or "unlikely" than accepted plate movements during the Phanerozoic.

### 2. 'Palaeopangaea' for ever?

Piper's Palaeopangaea supercontinent model (Piper, 1974, 1976; Piper et al., 1973) began with a comparison of global paleomagnetic data from 2200 to 1000 Ma, producing a reconstruction featuring a united Gondwanaland and Laurasian assembly with only minor adjustments relative to that within Pangea. At the time, this was a noble effort to bring together pioneering attempts of obtaining Precambrian paleomagnetic data into a kinematically simple structure.

Nonetheless, even then, there were problems. McGlynn et al. (1975) showed that the model failed to align paleomagnetic poles from Africa and North America during the interval 2200–1800 Ma. The African (Kaapvaal–Kalahari) path through that interval of time has largely withstood subsequent reproducibility (de Kock et al., 2006), whereas the paths from North American blocks have been changed considerably (e.g., Buchan et al., 1994; Irving et al., 2004). Since then, the core elements of Piper's reconstructions have remained the same (Piper, 1982, 1987, 2000, 2003, 2007). One adjustment occurred in the year 1982, when Piper adopted the Sears and Price (1978) reconstruction of Siberia adjacent to southwest Laurentia; we discuss this case below, in specific reference to the arguments of Piper's comment (this volume). In other cases, Piper (e.g., 2007) has shown an increasing tendency to adopt minor rotations of marginal blocks at distinct ages within Palaeopangaea's proposed duration, presumably to produce better fits of the paleomagnetic poles, but without comparing such motions to geological records.

In many Precambrian paleomagnetic studies, several remanence components are identified and converted to multiple poles from the same rock units. Especially among older studies, prior to the widespread use of techniques to determine which component is primary in a given study (see Van der Voo and Meert, 1991), the ages of many poles were assigned with some constraints but also much educated guesswork. As new data accumulated and ages of the components became constrained, Piper dealt with this issue by making his aggregate apparent polar wander path increasingly complex. Already evident in Fig. 4 of Piper et al. (1973), the process reached its nadir in Fig. 7.9 of Piper (1987; also see Fig. 5 in Piper and Grant, 1989). By such an approach, any new but discrepant paleomagnetic result can be accommodated by a long-lived supercontinent reconstruction hypothesis, simply by adding another loop in its apparent polar wander path. Note that any randomly chosen aggregation of continents would produce comparably complex paths (especially if one limits the paths to one hemisphere due to polarity ambiguities and with the  $\pm 150$  Ma age precision applied by Piper as one of his few reliability criteria), so these paleomagnetic solutions are non-unique at best and degenerate at worst. As more Precambrian data arose, the multi-looped paths of Piper's earlier papers became replaced by "clouds" of data from age bins of typically 200 million years durations (Piper, 2000, 2003, 2007, this volume). This change in strategy coincided with the advent of precise dating techniques for ideal paleomagnetic targets such as mafic dikes (e.g., Krogh et al., 1987). Ironically, as age constraints on the various remanence components improved, Palaeopangaea appeared to survive pole discordances merely on the basis of broad-brush similarities rather than the precise tests to which it should have been subjected. The value of such a non-predictive and non-testable supercontinent model rests only with its ability to explain geological data, or else as a null hypothesis to be discarded if its geological implications are unreasonable. Thus we turn to the geological predictions of Palaeopangaea.

Although it is still too early to depict precisely the timing and configuration of all supercontinents in Earth's history, evidence for episodic (or even cyclic?) global continental assembly and break-up led many to conclude that Pangea-like, relatively short-lived supercontinents have come and gone since at least the Paleoproterozoic Era if not earlier (e.g., Williams et al., 1991; Hoffman, 1997; Aspler and Chiarenzelli, 1998; Rogers and Santosh, 2002; Bleeker, 2003; Evans, 2003; Zhao et al., 2004; Brown, 2008). By contrast, Piper has retained the fixist interpretation of most Proterozoic orogens, writing that (this volume) "*the nuclei [sic] of south-central India, southern Africa and western Australia comprise the most ancient crustal protolith with comparable geological histories implying their close proximities since ~3000 Ma*". This exposes Piper's conviction that once two continents were together, they likely remain so forever despite geological and paleomagnetic evidence might suggest

otherwise. The geological flaw of this conviction is best illustrated by the presence of numerous 1100–900 Ma collisional orogenic belts in the interior of his Palaeopangaea (see Fig. 1; also Figs. 1 and 9 of Piper, 2007). This implies that well-documented collisional orogens like the Albany–Fraser Orogen in Australia (e.g., Condie and Myers, 1999; Clark et al., 2000), the Eastern Ghats Orogen in India and adjacent orogenic belt in East Antarctica (Mezger and Cosca, 1999; Fitzsimons, 2000; Boger et al., 2001; Kelly et al., 2002), the Namaqua–Natal Belt in southern Africa (Dalziel et al., 2000) Jacobs et al., 2008), and the Irumide Belt along the southern margin of the Congo craton (De Waele et al., 2003, 2008, 2009) are, instead, all of intracratonic origin; and it neglects evidence for subduction and continental collisions along those belts. The long-lived 'Palaeopangaea' configuration also leaves the Grenville Belt in Laurentia, the Sveconorwegian Orogen in Baltica, and the Sunsás and equivalent orogens in Amazonia (e.g., Rivers, 1997; Davidson, 2008; Dalziel et al., 2000; Tohver et al., 2005, 2006; Bogdanova et al., 2008; Fuck et al., 2008; Gower et al., 2008; Mosher et al., 2008; Santos et al., 2008) facing an open ocean, which deserves at least a mention as a potential refutation (e.g., Evans, 2009) rather than outright omission.

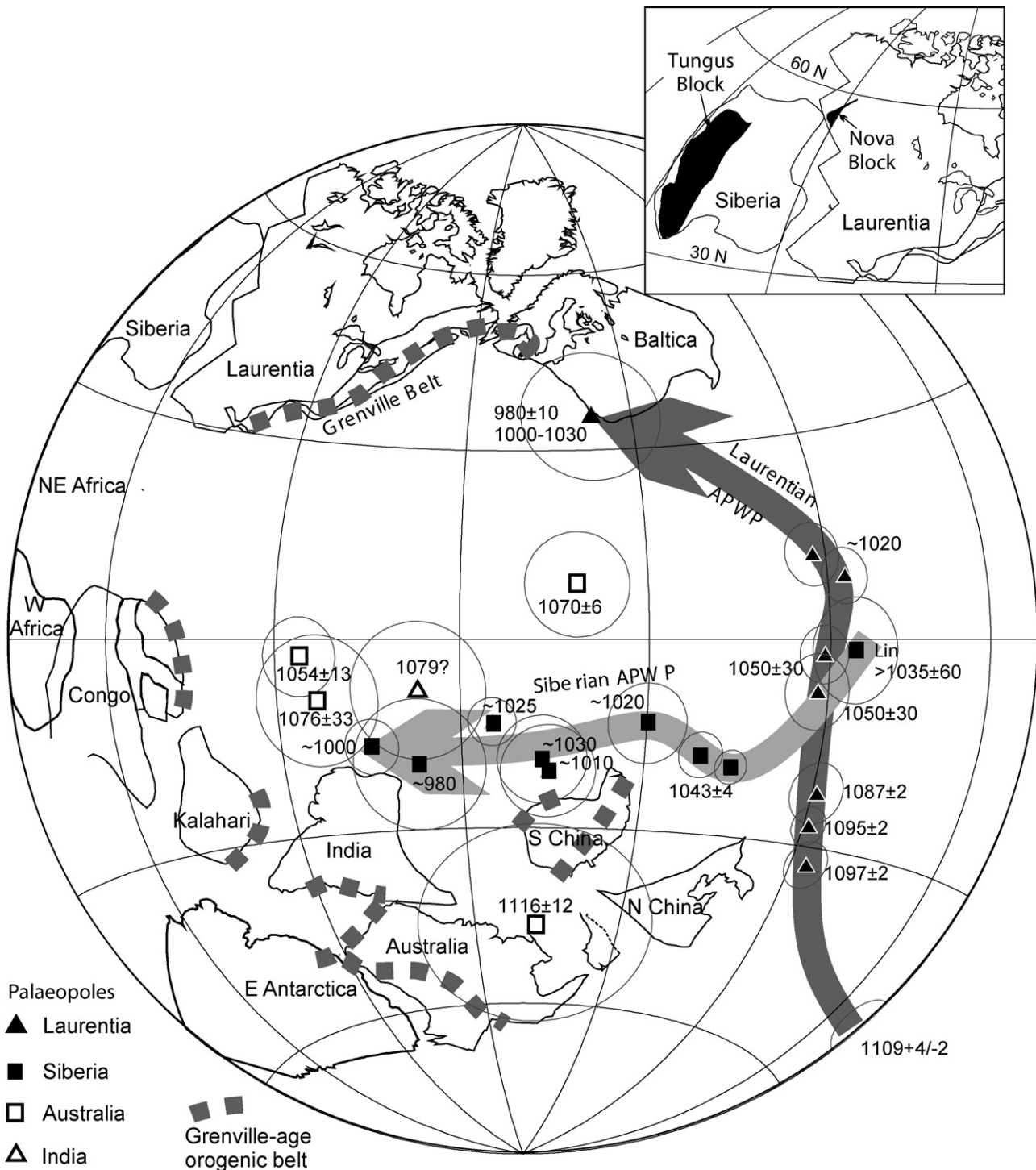
### 3. Handling of paleomagnetic data and Euler rotations: scientific rigor and care are needed

When reconstructing global paleogeographic maps, apart from geological considerations (see Sections 2 and 4), it is paramount that some objective rules are observed, such as (1) using proper geographic projections of the 3D continental outlines, (2) accurate Euler rotation for both continents and related paleopoles, (3) critical assessment of the available paleomagnetic data, and (4) constructing meaningful common apparent polar wander paths (APWPs).

We regret to observe that none of these common practices appear to have been rigorously followed by Piper (2007; this volume). As shown in Figs. 1 and 2 of the comment, he merely uses elongated shading to show his 'Palaeopangaea', with no continental outline at all—a practice that adds vagueness to the border of duplicity. Readers are forced to refer to Piper (2007) to look for the exact composition and configuration of 'Palaeopangaea'. Again, in most of his figures (Figs. 2–4, 6, 7–9, Piper, 2007) 'Palaeopangaea' was shown either as an elongated shadow, or with mostly unidentifiable cratonic outlines. In the only figure (Fig. 1 in Piper, 2007) where he has shown more identifiable continental outlines, no geographic coordinates or projection type was given.

In order to verify the 'Palaeopangaea' reconstruction, we plot in Fig. 1 the continental outlines following Euler rotations for the "secondary reconstruction" given in Table 2 of Piper (2007). This produces numerous unacceptable problems such as that the West Africa craton overlaps with the Congo craton (Fig. 1). Using the Euler rotations for the "primitive" or pre-1100 Ma 'Palaeopangaea' reconstruction, we found northern Australia directly atop Kalahari, portions of North China directly atop eastern India, and East Antarctica overlapping with all three of the following: Amazonia, West Africa and Congo.

Paleomagnetism provides the only quantitative means of reconstructing the paleolatitudes and relative positions of continents in geological history before the Jurassic. Like all scientific data, a paleomagnetic data set needs to possess a number of essential quality attributes before it can be used with some confidence. For instance, a paleopole based on an incorrect paleohorizontal correction (i.e., the attitude at which the rock unit acquired the magnetic remanence) has no geological meaning, and a paleopole with an uncertain magnetization age cannot be assumed of primary origin and be automatically applied to the continent concerned for the age of the rock formation. There are a number of paleomagnetic quality-control schemes used by researchers, such as the quality

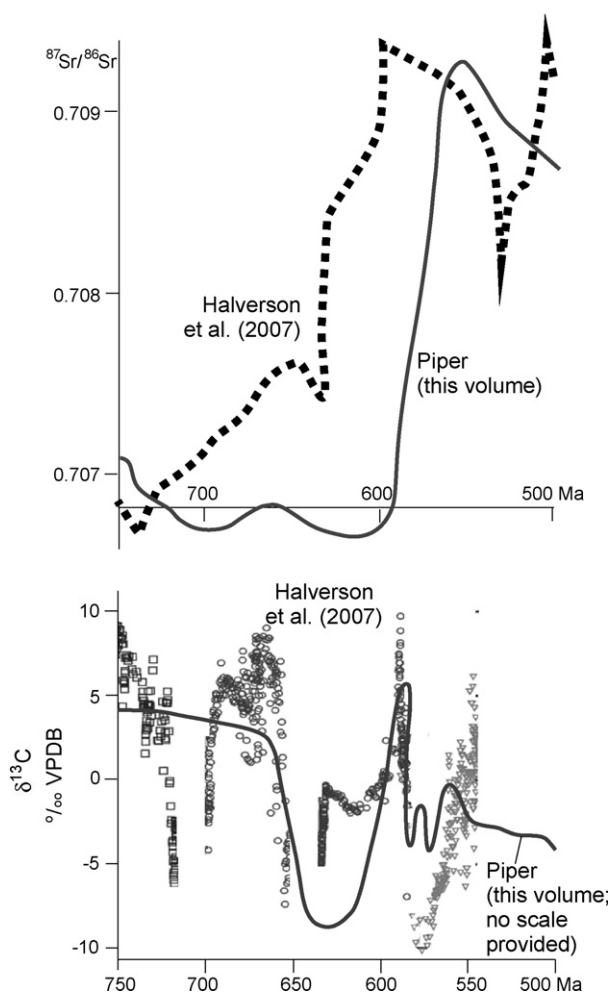


**Fig. 1.** 'Palaeopangaea' according to rotation parameters in Table 2 of Piper (2007) and modified Euler pole for Siberia from Piper (this volume). Where two sets of Euler rotations are given in Piper (2007), those from the "secondary reconstruction" are used, which are relevant to the period 1100–600 Ma. Note the overlap between West Africa and Congo cratons. 1100–1000 Ma palaeomagnetic poles as in Table 2 of Li et al. (2008) are plotted following the 'Palaeopangaea' rotations, showing that the apparent polar wander path (APWP) of Siberia diverges from that of Laurentia, and that poles from Australia and India also fall away from the concurrent Laurentia APWP. Laurentia is in its present geographic position.

filters of Briden and Duff (1981) and Li et al. (1990), and the more commonly used point systems of McElhinny and Embleton (1976) and Van der Voo (1990).

We have two major problems with the approaches that Piper (2007; this volume) takes in dealing with paleomagnetic data. First, his uncritical acceptance of almost all paleomagnetic results in the literature and the application of a statistical approach in treating those data. For instance, Piper's data selection only requires a pale-

omagnetic pole to have an estimated age of within  $\pm 150$  Ma (page 206 of Piper, 2007), a time span equivalent to the entire Paleozoic Era. This leads to the large number of paleopoles in his data analysis, with little if any selection for reliability. For instance, for the 1110–700 Ma interval of Laurentia, Meert and Torsvik (2003) selected 28 poles, Pisarevsky et al. (2003) 14 poles, Buchan et al. (2000) eight key and non-key poles, Li et al. (2008) 15 poles, and Evans (in press) 16 poles. Piper (2007; this volume) uses >100 poles!



**Fig. 2.** Plot of the  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{13}\text{C}$  curves as in Piper's Fig. 6 on top of more recently published curves (e.g., Halverson et al., 2007), showing that (1) Piper's 1 "evidences" are out of date and (2) there is no sign of a singular isotopic shift at ca. 600 Ma corresponding to the break-up of 'Palaeopangaea' as Piper claims.

He also applies equal weight to all such poles, generating cluster plots like those in Fig. 3 of Piper (this volume) with a broad "swathe" of poles as wide as >6000 km—an error margin comparable to the dimension of the supercontinent that he is proposing. Second, even when using selected (and better quality) poles only, as in the case of Fig. 1 in Piper (this volume), his common APW "swathe" is about  $30^\circ$  (~3100 km) wide. If one includes the poles lying outside the "swathe", the width is up to  $45^\circ$  (close to 5000 km; see Fig. 1 of Piper, this volume). In addition, the ~750 Ma poles from different continents are as much as ~6000 km apart, as best illustrated by the distance between the  $750 \pm 3$  Ma Mahe dykes pole from Seychelles (pole SE1 in Fig. 1 of Piper, this volume) and the  $748 \pm 12$  Ma Liantuo Formation pole from South China (pole SC2 in Fig. 1 of Piper, this volume). With such a high "flexibility", one would be able to accommodate just about any paleogeographic reconstruction.

Piper is strongly supportive of the Siberia–Laurentia connection as proposed by Sears and Price (2000). However, the rotation parameters he used in his Fig. 4 are not "slightly", but rather significantly modified from that of Sears and Price (2000). Li et al. (2008) addressed the Sears and Price (2000) model in their Section 2.1.4. and Fig. 2e (also see Pisarevsky and Natapov, 2003; Pisarevsky et al., 2003, 2008). Here we address the modified version of the Sears and Price (2000) as in Piper (this volume). As both Siberia and Laurentia in Piper's Fig. 4 (this volume) are hardly recognisable, we made a rotation of Siberia to Laurentia using the rotation parameters of

$77^\circ\text{N}$ ,  $271^\circ\text{E}$ ,  $107.3^\circ$  anticlockwise as in the caption of Piper's Fig. 4 (this volume) (Fig. 1 insert). The original reconstruction of Sears and Price (1978, 2000, 2003) was based mainly on apparent continuation of Precambrian basement and cover rocks from Siberia to Laurentia. In Piper's modification of their reconstruction such connecting basement blocks were laterally shifted by ~1200 km (we show in the insert of Fig. 1 the lateral offset between the Tungus block of Siberia and the Nova block of Laurentia as an example). By comparing this with Fig. 1 of Sears and Price (2000), it is not difficult to see that Piper's "modification" (this volume) of the Sears and Price model has even violated the geological connections used in its original proposal.

In his Fig. 3 caption of the comment, Piper states that he has plotted a set of rotated Siberian poles in this figure, but it is impossible to spot these poles in a half-hemisphere-wide cloud of unmarked dots, which Piper calls "Keweenawan track and Grenville Loop". So in Fig. 1 we plot the 1100–1000 Ma paleomagnetic poles for both Laurentia and Siberia. All but the poorly dated "Lin" pole (Fig. 1) from the Linok Formation of Siberia are from Table 1 of Li et al. (2008). It is obvious that although the Linok pole plots on the right part of the APWP of Laurentia in Piper's modified configuration, the overall trend of the Siberian APWP still runs nearly perpendicular to that of Laurentia. Therefore, despite Piper's (this volume) claim of being supported by paleomagnetic data, his modified configuration fares no better than that of the original model.

It is also clear from Fig. 1 that the relative positions of Australia and India in Piper's configuration are not supported by paleomagnetic data either, because the poles from those continents all fall away from the concurrent APWP of Laurentia in the 'Palaeopangaea' configuration.

The cornerstone of the Palaeopangaea hypothesis, however, is the rotation of Africa to North America by the Euler parameters ( $73^\circ\text{N}$ ,  $138^\circ\text{E}$ ,  $-146^\circ$ ), which have remained invariant since the first presentation (Piper et al., 1973) and through all subsequent iterations of 'Palaeopangaea' and 'Protopangaea' (Piper, 1974, 1976, 1982, 1987, 2000, 2003, 2007). The pre-800 Ma global paleomagnetic database has recently been reviewed by Evans and Pisarevsky (2008), and the strictest quality filters have identified about 50 of the most-reliable poles from more than 1500 of that age range in the database. Three coeval pairs of poles from the two blocks, at 2220, 1880, and 1110 Ma, can test Piper's reconstructions quantitatively (Table 1). None of the three pairs of poles overlap at the 95% confidence level when reconstructed according to Piper, although the Umkondo–Logan pair is somewhat similar and perhaps could be consistent with only minor modifications to the model. The failure of all three of these highest-quality tests indicates that we can reject, with a high level of confidence, the hypothesized Africa–North America juxtaposition in 'Palaeopangaea' and 'Protopangaea'—indeed the cornerstone of Piper's reconstructions.

#### 4. A need for staying up to date with geological literature

##### 4.1. Continental rifting and basin subsidence curves

In Piper's (this volume) so-called test #2, he cites Bond et al.'s (1984) milestone paper on widespread basin subsidence curves to support the hypothesis that there was only one episode of continent rifting and break-up between 600 and 550 Ma, with no continental rifting and break-up events between 820 and 720 Ma, as discussed in Li et al. (2008).

We address this criticism in two aspects. First, the Li et al. (2008) paper recognized the significance of the work by Bond et al. (1984), and explained their observations as partly reflecting the second major episode of Rodinia break-up between ca. 600 Ma and 550 Ma (see pages 200–201 and Fig. 9i–k of Li et al., 2008). According to

**Table 1**  
High-quality paleomagnetic tests of Palaeopangaea and Protopangaea.

Age (Ma)	Africa rock unit	Africa pole ( $^{\circ}$ N, $^{\circ}$ E), $A_{95}$	Rotated ( $^{\circ}$ N, $^{\circ}$ E)	N. America rock unit	N. Am. pole ( $^{\circ}$ N, $^{\circ}$ E), $A_{95}$	Angular dist. ( $^{\circ}$ )
1110	Umkondo mean	(64,039), 4	(53,201)	Logan sills	(49,220), 4	13 $\pm$ 8
1880(a)	post-Waterberg	(17,017), 8	(07,226)	Molson dikes	(27,219), 4	21 $\pm$ 12
1880(b)	post-Waterberg	(09,015), 17	(00,228)	Molson dikes	(27,219), 4	28 $\pm$ 21
2220	Ongeluk lavas	(-01,101), 5	(29,313)	Nipissing N1	(-17,272), 10	61 $\pm$ 15

Notes: For the 1880 Ma comparison, there are two alternative African poles considered: (a) the published result (in revised form, Gose et al., 2006) combining post-Waterberg sills with Soutpansberg lavas, or (b) the post-Waterberg sill subset only. Discussion of these options, and all references, are given in Evans and Pisarevsky (2008). Angular distance is given between the rotated African pole and its North American counterpart for each age. Error estimates on these values are the sums of  $A_{95}$  of the compared poles; this overestimates the true 95% error, strengthening our arguments.

Li et al. (2008), continental break-ups during that interval include South American and African cratons from the Appalachian margin of Laurentia, Baltica from the southeastern Greenland margin of Laurentia, Siberia ( $\pm$ North China) from the northern margin of Laurentia, and possibly Tarim from the northwestern margin of Australia (Li et al., 1996; Cawood and Pisarevsky, 2006).

Second, Bond et al. (1984) did recognize the possibility of a protracted supercontinent breakup with episodic continental rifting and break-up, as they stated in the first paragraph of their paper:

“By Early Cambrian time the total length of passive margins probably was on the order of tens of thousands of kilometers [references] implying the occurrence of a widespread episode (or episodes) of rifting and continental breakup. At present, the age of initiation or onset of drift can be placed only between about 850 and 560 Ma [references], and breakup could have occurred continuously within that interval or in one or more temporally discrete episodes”.

This statement has been substantiated by work in the following two decades, with well documented 820–700 Ma rifting events in Australia and along the Cordilleran margin of Laurentia (e.g., Ross, 1991; Heaman et al., 1992; Young, 1992; Powell et al., 1994; Rainbird et al., 1996; Ross and Villeneuve, 1997; Karlstrom et al., 2000; Preiss, 2000; Lund et al., 2003; Fanning and Link, 2004), at the Appalachian margin of Laurentia (Su et al., 1994; Aleinikoff et al., 1995; Fetter and Goldberg, 1995), South China (Li et al., 1999, 2002; Wang and Li, 2003), Tarim (Zhang et al., 2006; Lu et al., 2008; Xu et al., 2009), Arabian-Nubian Shield (Leather et al., 2002), Congo (Johnson et al., 2007), and Kalahari (Frimmel et al., 1996, 2001; de Kock, 2001). The precise timing of rift–drift transition at different parts of the world is not easy to depict, but for both the Cordilleran margin of Laurentia (e.g., Ross, 1991) and southeastern Australia (Powell et al., 1994) the timing of rift–drift transition (i.e., time of continental break-up) were estimated to be at least tens of million years prior to the 600 Ma age depicted by Piper (this volume). Piper (this volume) is either unaware of these developments, or is ignoring them.

#### 4.2. Isotopic curves

Piper (this volume) cites various isotopic curves to support his hypothesis of a single supercontinent break-up event at ca. 600 Ma (see Fig. 6 of Piper, this volume). We plot in Fig. 2 both the  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{13}\text{C}$  curves as in Piper's Fig. 6 on top of recently published curves (e.g., Halverson et al., 2007). They are grossly different, and the new data do not seem to support the singular continental break-up event at  $\sim$ 600 Ma as claimed by Piper (this volume). Recent  $\delta^{34}\text{S}$  data (e.g., Gorjan et al., 2000; Hurtgen et al., 2005) are also at variance with the curve shown by Piper (this volume).

#### 4.3. Paleomagnetic data

Among the highest-quality poles compared in Table 1, several are the results of grand-mean calculations from original data that were available from the 1960s (Umkondo), early 1980s (Logan sills),

or mid-1990s (Nipissing N1 sills). The Ongeluk–Nipissing N1 pole mismatch was available as of the year 1997, and Piper (2003) tabulated both poles but ignored their implications. Although Piper (2003) preferred the “N2” pole as primary at 2220 Ma, this had already been discounted in favor of N1 with extensive discussion by Buchan et al. (1994, 2000). Even if the “N2” pole were primary at that age, its angular distance from the rotated Ongeluk pole ( $58^{\circ}$ ) should have been recognized by Piper as a quantitative refutation of ‘Protopangaea’. The 1880–Ma comparison was available in print as of the year 2004 (Hanson et al., 2004). This age range falls outside of typical Rodinia vs. Palaeopangaea discussions, but the constancy of Piper's Africa–North America reconstruction parameters – hypothesized for the interval 2900–600 Ma in a series of papers spanning more than 30 years – suggests to us that he should have recognized its implications for testing (and refuting) the proposed connection.

To conclude, we reject not only Piper's unsubstantiated claims against our scientific approaches and conclusions, but also his ‘Palaeopangaea’ hypothesis because it was based on faulty application of paleomagnetic results, selective usage of geological information, and unacceptable level of technical inaccuracy.

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