Reconstructing pre-Pangean supercontinents

INVITED REVIEW

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ABSTRACT

Twenty-five years ago, initial plans for reconstructing the Rodinia supercontinent were being drafted, based on the growing recognition of correlatable mid-Neoproterozoic (0.8–0.7 Ga) rifted passive margins, many of which were established on the eroded remnants of late Mesoproterozoic (1.3–1.0 Ga) orogenic belts. The 1990s witnessed a surge of interest in Rodinia, with many regional studies of tectonostratigraphy and U-Pb geochronology generally conforming to the "inside-out" reconstruction model: juxtaposition of west Laurentia with east Australia/Antarctica, north Laurentia with Siberia, and east Laurentia with Baltica and cratons that would later form West Gondwana. This standard model of Rodinia appeared to be converging toward a solution with only minor variations by the turn of the millennium, but new paleomagnetic data and tectonostratigraphic information obtained in the succeeding decade chipped away at various aspects of the reconstruction; several cratons seemed to require exclusion from the supercontinent (thus questioning its very validity), or the landmass might have assembled much later (≤0.9 Ga) than originally envisaged (thus weakening the link to global Mesoproterozoic orogenesis). Although a consensus model of Rodinia's assembly and fragmentation has arisen from the International Geoscience Programme Project 440 working group, the reconstruction is supported by rather sparse definitive-quality data.

As the quest for Rodinia matures to a third decade of scrutiny, the search for its predecessor Nuna (a.k.a. Hudsonland or Columbia) is only now reaching a stage of global synthesis between tectonostratigraphic and paleomagnetic data. According to most definitions, Nuna assembled at 1.9–1.75 Ga, or perhaps as late as 1.6 Ga, and fragmented during the interval 1.5–1.2 Ga. Because mafic dike swarms are ideal targets for paleomagnetic study, and because they are now amenable to routine dating by U-Pb on baddeleyite, the global abundance of Paleo-Mesoproterozoic dike swarms might make Nuna more imminently solvable than Rodinia.

Prior to the assembly of Nuna, various "supercraton" connections such as Vaalbara, Superia, and Sclavia are only beginning to take form. Unmetamorphosed, early Paleoproterozoic (2.5–2.0 Ga) mafic dike swarms are commonplace features across the interiors of Archean cratons, and their joint paleomagnetic and geochronologic study can help reassemble the cratons into their supercraton parent landmasses. Progressively older geologic times require consideration of a greater number of potentially independent terranes, each needing individual kinematic constraints. Furthermore, the initial stabilizing events of most extant cratons during Neoarchean time (3.0–2.5 Ga) therefore render global reconstructions older than that interval improbable.

INTRODUCTION

This paper attempts to summarize the past 25 years of research on the configurations of ancient supercontinents. There is both empirical and theoretical evidence to suggest that the most recent supercontinent, Pangea, is merely the latest of a series of large continental aggregations, separated in time by ~500–600-million-year intervals (Fig. 1). The empirical data include the well-established global maxima and minima in isotopic age determinations and number of orogens (Condie, 1998, 2002; Campbell and Allen, 2008), the number and durations of ancient passive continental margins (Bradley, 2008), geochemical trends in sedimentary rocks (Shields, 2007), isotopic proxies for mantle extraction and continental growth (Collins et al., 2011), and other proxies for the amalgamation of landmasses (reviewed by Bradley, 2011). Theoretical expectations for a supercontinent "cycle" arise from numerical modeling of mantle convection that alternatively posit a thermal insulation effect under the supercontinent (Phillips and Coltice, 2010, and references therein), or a reorganization of subduction loci and convective cells due to oceanic closure (Zhong et al., 2007; O'Neill et al., 2009).

Some form of a supercontinent cycle is generally invoked to explain a number of global-scale phenomena in the long-term geologic record. Following an initial compilation of global peaks and troughs in isotopic ages (Gastil, 1960), early concepts of orogenic cyclicity (e.g., Sutton, 1963; Wilson, 1966) planted fertile seeds of thought regarding pre-Pangean supercontinents. The concept of "two Phanerozoic supercycles" (Fischer, 1984) subsequently organized many scholars' ideas on processes leading to long-term sea-level variations and ice ages (Worsley et al., 1984; Nance et al., 1986; Veevers, 1990) and possible links to geomagnetic superchrons through putative superplume events (Larson, 1991). The "supercycle" idea has been extended through geologic time, and according to some researchers, with a constant periodicity (Krapez, 1999; Bozhko, 2011) that would seem astonishing given the stochastic nature of many well-dated orogenic events in the Phanerozoic, and also given likely scenarios for secular changes in the thermal evolution of the planet (e.g., Korenaga, 2008). The originally proposed cycle focuses on the history of closing and opening of the Atlantic Ocean and its predecessor, Iapetus (Wilson, 1966; Harland and Gayer, 1972). Today's wide Atlantic Ocean would be akin to a perhaps equally wide Iapetus in the Cambrian–Ordovician time, and Pangea's predecessor would have existed prior to establishment of those earliest Paleozoic passive margins (Bond et al., 1984). Upon critical examination, however, the Pangean supercycle concept fails to account for many of the other geologic features of Phanerozoic Earth history. For example, sea level (Fig. 1C) has fallen through the Cenozoic Era, despite continued widening of the Atlantic. Sea level may better reflect the broad pattern of ice ages (Fig. 1D), but those appear equally divorced from the supercontinental record, because they are temporally related to latest Precambrian rifting (cf. Young, 1995), Pangea assembly, and the present wide-Atlantic stage. Geomagnetic superchrons (Fig. 1E) appear unconnected to either the existence of supercontinents or the

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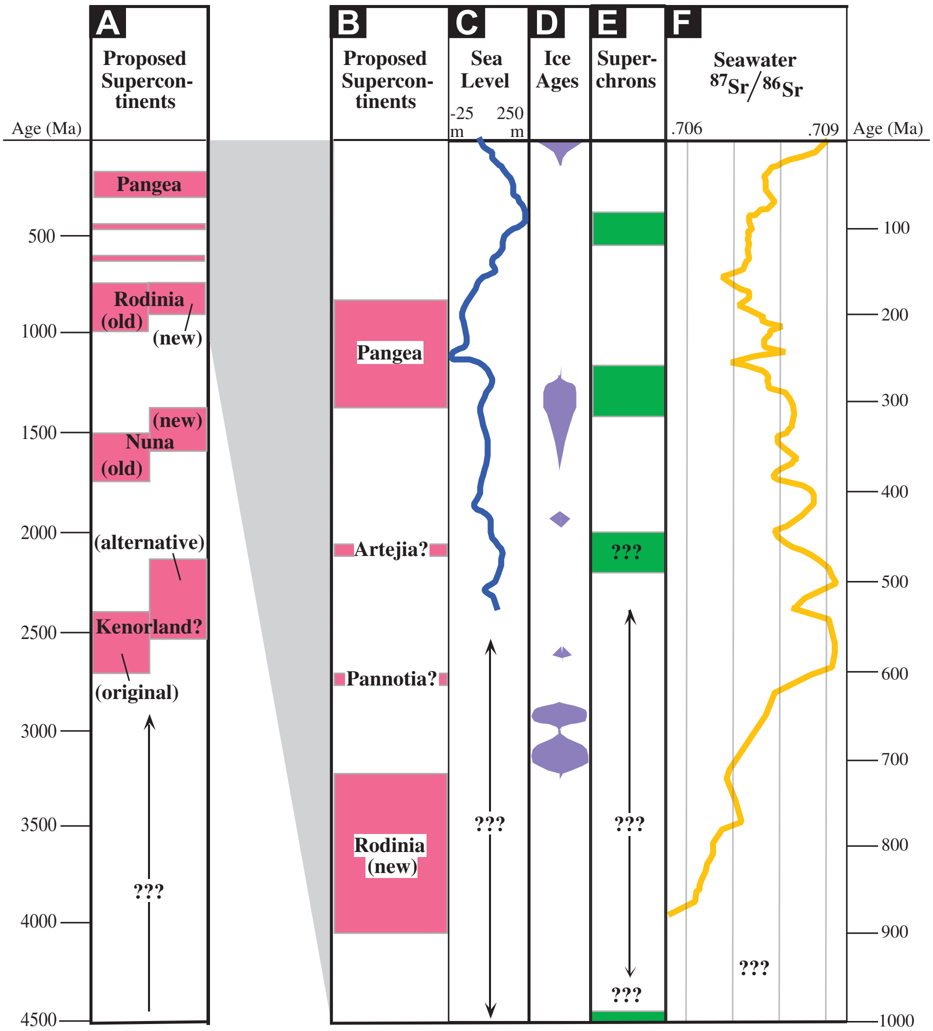


Figure 1. Supercontinental hypotheses versus time, and first-order geological events of Neoproterozoic–Phanerozoic time. (A) Entire Earth timeline, with Pangea and putative pre-Pangea supercontinents, in both original or old conceptual ages of assembly and dispersal, and updated ages as necessary. (B) Enlargement of the last billion years of Earth history; pre-Pangea supercontinents are as summarized by Dalziel (1997). (C) Estimates of sea level, relative to that at present, based on varying continental hypsometry, from Algeo and Seslavinsky (1995). (D) Ice ages scaled horizontally according to latitude distribution (panglacial fills the column); after Evans (2003b) and Hoffman (2009). (E) Geomagnetic superchrons, either well defined or proposed for the Ordovician (Pavlov and Gallet, 2005) and early Neoproterozoic (Gallet et al., 2012). (F) Isotopic composition of seawater strontium, from Halverson et al. (2007).

global climate state. Finally, there may be a link between supercontinents and the global seawater $^{87}Sr/^{86}Sr$ ratio (Fig. 1F), but the connection is counterintuitive, because the apices of supercontinental assembly coincide with the lowest ratios, and hence the least amount of continental weathering relative to juvenile oceanic sources of strontium—opposite to what one might expect during times of orogenic collisions.

Given these uncertainties and contradictions, paleogeographic definition of earlier supercontinents is essential for understanding any connections to a cyclic pattern, if one existed at all. The Pangea puzzle was essentially solved 100 years ago (Wegener, 1912), although discussions still remain on details of the reconstruction (e.g., Domeier et al., 2012). More fundamental problems exist with older posited supercontinents, such as (in order of increasing age) Pannotia, Rodinia, Nuna/Columbia, and Kenorland (reviewed by Nance et al., 2013). Among these hypothetical landmasses, only Pannotia is characterized by an unambiguous reconstruction (Dalziel, 1997), and all of them are questionable even in principle. Nonetheless, the proxy evidence for pre-Pangean supercontinents for at least the latter half of Earth history has motivated substantial efforts to create plausible reconstructions of their cratonic arrangements.

WHAT IS A SUPERCONTINENT?

Identification of ancient supercontinents requires a standard by which the large sizes of former landmasses merit the prefix "super." Pangea is the quintessential supercontinent, yet during its brief tenure it still excluded some eastern Asian cratons, which at the time were on a northward track across Tethys (Fig. 2A), lying on distinct tectonic plates even if ephemerally connected via land bridges. Bradley (2011) opted for a flexible definition of a supercontinent as merely "a grouping of formerly dispersed continents," but this flexibility comes at the cost of ambiguity. Meert's (2012) proposed minimum requirement of 75% of the preserved crustal area from a given age seems reasonable, as it conforms to most earlier usage (i.e., Pangea is, but Gondwana in itself is generally not, considered to be a supercontinent). It is also simple and quantifiable in an objective manner. Most reconstructions of Rodinia (Figs. 2B–2E) appear to satisfy the 75% minimum area criterion for at least brief intervals of kinematic evolution, although some tectonic blocks with limited or no paleomagnetic data and largely unconstrained evolution are usually included arbitrarily within the landmasses for the mere sake of completeness (e.g., Li et al., 2008).

Other measures of a supercontinent's importance could include its effects on the broader Earth system, whether in terms of the surface environment or the underlying mantle. In terms of effects on the surface environment, Pangea was clearly a major influencing factor during a relatively brief reign (Veevers, 1989). According to some, consolidation of the Pangea landmass was the major influence on global mantle convection, with a time constant of ~50 million years (Doblas et al., 1998; Li and Zhong, 2009). According to others, the time constant for global mantle circulation is longer, on the order of 300 million years (Gurnis, 1988), and thus Gondwana in its own right would have been able to alter convection patterns during its long-lived existence between Cambrian assembly and Mesozoic breakup (Evans, 2003a).

Until unequivocally constrained by kinematics integrating complete tectonic and paleo-

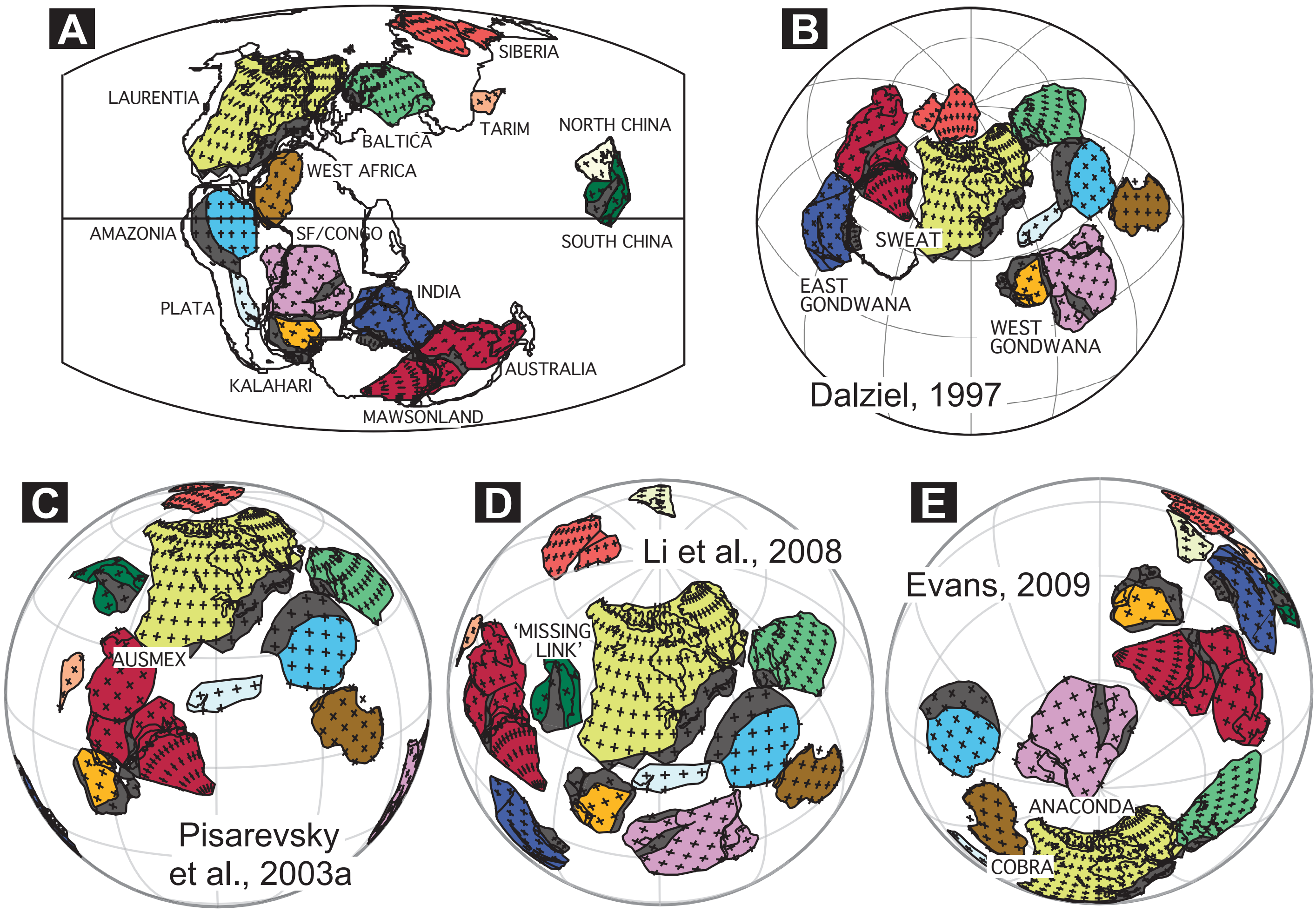


Figure 2. (A) Pangea base map, 200 Ma relative reconstruction in present South American coordinates. 1.3–0.9 Ga orogens in gray. SF—São Francisco. (B–E) Alternative reconstructions of Rodinia, shown in modern North American coordinates and plotted using the same color scale to facilitate comparisons. Figure modified from Evans (2009).

magnetic data sets, the most feasible way to organize supercontinental episodicity might be via tectonic proxies such as orogenic ages and large igneous provinces (Condie, 2002; Bradley, 2011). Such analyses clearly recognize Rodinia assembly (mainly 1.1–1.0 Ga) and breakup (mainly 0.8–0.7 Ga) prior to the Phanerozoic Pangea cycle (Fig. 1). The Rodinia era was preceded by amalgamation (mainly 1.9–1.8 Ga) and breakup (mainly 1.4–1.2 Ga) of a possible supercontinent that was originally named Hudsonland by Williams et al. (1991). The coauthor of that paper with the most vested interest in supercontinent reconstructions, Paul Hoffman, renamed Hudsonland to the more elegant Nuna in 1997. Hudsonland or Nuna has also been called Capricornia (Krapez, 1999), Columbia (Rogers and Santosh, 2002), and Midgardia (Johansson, 2009), but Nuna has priority over these (Hoffman, 1997).

The global crystallization age peaks and troughs can be misunderstood if not viewed in paleogeographic context. For example, much of Pangea assembly occurred in Ediacaran–Cambrian time (Pan-African and Brasiliano orogenesis; Trompette, 1994; Meert, 2003), more than two hundred million years prior to the Hercynian-Appalachian and Uralian orogens suturing Gondwana and Laurasia (Veevers et al., 1997). In the case of the Rodinia model by Li et al. (2008), final assembly is represented by a single, rather small orogen almost completely confined to South China (Sibao orogen); although its activity is now constrained largely to ca. 0.9 Ga (references in Li et al., 2008), the tardiness of that final Rodinia-forming suture does not detract from the global orogenic age peaks that organize our definition of Rodinia assembly, in the context of the Gondwana/Pangea example. Two recent paleogeographic models of Nuna also include a delayed (ca. 1.6 Ga), centrally located suture zone between western North America and eastern Australia (Pisarevsky et al., in press; Pehrsson et al., 2012), long after the global orogenic/isotopic age peak of ca. 1.9–1.8 Ga (Hoffman, 1989; Condie, 1998). If these models are broadly correct, then a general pattern of supercontinental assembly appears to be emerging: initial orogenic construction of continent-sized "pillars" followed by central "keystone" orogens forming the final supercontinental constructions.

Dalziel (1999) presented six guidelines for assessing the credibility of proposed supercontinent reconstructions, in the context of (1) passive margins created at the time of breakup, (2) geometric shapes of cratons among the amalgamated landmass, (3) sutures from collisions during assembly, (4) older tectonic fabrics if breakup cuts through cratons rather than follows previous sutures, (5) paleomagnetic data, and (6) "realistic" kinematic evolution toward eventual Pangea amalgamation. The first four items are informed directly by the geologic record, whereas the fifth and sixth are more geophysical in scope. Additional criteria, such as once-contiguous epicontinental basins and radiating dike swarms as precursors to breakup, are discussed and graphically illustrated as intersecting lines of complementary evidence by Li et al. (2008). Much of the variation in proposed Rodinia reconstructions stems from the subjective selection of some of the criteria over others. In particular, because the geologic and paleomagnetic data sets are largely independent, different weighting of those two classes of constraints has led to the greatest variability in the alternative models.

BUILDING RODINIA

The concept of a pre-Pangea, late Precambrian supercontinent arose in limited discussion for some decades (e.g., Wilson, 1966; Valentine and Moores, 1970; Worsley et al., 1984), including initial attempts to identify specific Neoproterozoic juxtapositions of Laurentia with Baltica (Patchett et al., 1978), Siberia (Sears and Price, 1978), and Australia (Jefferson, 1978), but only in the late 1980s did the broader Earth-science community investigate these possible configurations in earnest. Bond et al. (1984) provided better age constraints on the global development of Cambrian passive margins, presumably created during rifting of a Neoproterozoic supercontinent. Quickly thereafter, compelling similarities between two such margins, in northwest Canada and eastern Australia, followed Jefferson's (1978) suggestion that they could have been conjugates once directly joined together (Eisbacher, 1985; Bell and Jefferson, 1987). Then, within a span of just half a year, three profoundly influential manuscripts were submitted and published on the late Precambrian supercontinent (Moores, 1991; Dalziel, 1991; Hoffman, 1991), which only during the previous year had been named Rodinia (McMenamin and McMenamin, 1990). These papers laid the foundation stones for nearly all Rodinia models hypothesized since. They incorporated the Canada-Australia connection, including its extension farther south (in both areas' present coordinates) to the Southwest U.S.–East Antarctic ("SWEAT") connection. The Rodinia models of Dalziel (1991) and Hoffman (1991) also posited a late Precambrian connection between eastern Laurentia and cratons that would later become incorporated into "West" Gondwana (i.e., Amazonia, Rio Plata or Congo, and Kalahari; Fig. 2). Baltica was positioned adjacent to the Labrador or Greenland margin of Laurentia, and Siberia next to the arctic Canadian margin. Because of the requisite sweeping closure of Gondwana cratons from their earlier Rodinia configuration, the model was referred to as an "inside-out" form of evolution (Hoffman, 1991). Key features guiding these Rodinia reconstructions included matches of 1.3–1.0 Ga "Grenvillian" orogens, thought to manifest Rodinia assembly, and 0.75–0.55 Ga rifted margins, mainly around Laurentia and considered to represent supercontinental fragmentation. Much early work centered around possible kinematic evolution of Laurentia executing an "end run" (alluding to an American football play) around South America to arrive next to West Africa in Pangea (Dalziel, 1992; Dalziel et al., 1994).

After a brief debate of nomenclature (Young, 1995; Dalziel and McMenamin, 1995; Powell, 1995), by the mid-1990s it became recognized that there may actually have been two land assemblages attaining supercontinental proportions in the Neoproterozoic Era: an older one, now universally referred to as Rodinia, that formed via assembly ca. 1.0 Ga and began to fragment at ca. 0.8 Ga; and a possible younger one, now universally referred to as Pannotia, that could have existed briefly, at most, after Gondwana assembly and prior to separation of Laurentia from Amazon. Dalziel (1997) presented a timely review of Rodinia and Pannotia in context with Paleozoic motions leading to Pangea. The only major remaining cratons to be considered were the three Chinese blocks (Tarim, North China, and South China), which were brought into Rodinian context by Zheng-Xiang Li and colleagues (Li et al., 1995, 1996). In particular, South China was proposed as the "missing link" between Australia and Laurentia, inserting a "Grenvillian" orogen (Sibao belt or belts) in between the two larger blocks. These final additions paved the way toward establishment of the Tectonics Special Research Centre (TSRC; existing from 1997 to 2005), led by Christopher McA. Powell, and based primarily at the University of Western Australia in Perth. The TSRC eventually attracted a large international team of researchers focused on solving Precambrian supercontinents, and many of their collaborations continue today.

Whereas it was recognized that paleomagnetic data could provide an independent test of the reconstructions, it was also appreciated from the outset that existing data were sparse by Phanerozoic standards, and in many cases lacking indications of reliability (Van der Voo and Meert, 1991). The early Rodinia models did, however, gain paleomagnetic confirmation for both Neoproterozoic evolution (Powell et al., 1993) and, given the ages then available, for Paleoproterozoic Australia and Laurentia (Idnurm and Giddings, 1995), which by the SWEAT hypothesis were predicted to have been connected for a billion years prior to Rodinia breakup (though not so according to the "missing link" model involving South China). Two more paleomagnetic syntheses provided additional support for quantitatively viable Rodinia reconstructions (Weil et al., 1998; D'Agrella-Filho et al., 1998).

Toward the end of its first decade of investigation, then, the standard "inside-out" model of Rodinia was well established: its proposed configuration was clearly defined, passing an impressive number of initial tectonostratigraphic tests, and it could be fit reasonably well with the global paleomagnetic database. The TSRC's Chris Powell, together with Raphael Unrug, launched the International Geoscience Programme (IGCP) Project 440, "Rodinia Assembly and Breakup." The TSRC bore a logo of reconstructed Rodinia that seemed to require mere filling in of details. Transition to the new millennium, however, would mark Rodinia's second decade as one of fundamental challenges to the model; some would favor retention of its essential features, whereas others considered complete dismantling and redrafting of the supercontinent.

RODINIA'S CONCEPT'S NEAR COLLAPSE AND RESTORATION

Initial criticism focused on the proposed SWEAT connection. Karlstrom et al. (1999) suggested a benign modification with Australia adjacent to western United States (rather than Canada), a juxtaposition abbreviated "AUSWUS." Burrett and Berry (2000) independently proposed a nearly identical model, and deferred to the earlier paper's evocative acronym. More importantly, Fitzsimons (2000) and later Boger et al. (2001) demonstrated that East Gondwana did not exist as a coherent entity prior to latest Proterozoic time; thus Rodinia models would need to treat its three (or more) component cratons independently. To this day, thick Antarctic ice cover hinders efforts to define even the geometries of Rodinian cratons in that region.

Paleomagnetism struck next, particularly the work of Michael Wingate and colleagues from Australia. Wingate and Giddings (2000) first showed that the SWEAT reconstruction was not viable according to new, high-quality paleomagnetic data from Western Australia, at 755 Ma. Shortly thereafter, both SWEAT and AUSWUS were demonstrated to be incompatible with additional, equally robust paleomagnetic results (also from Western Australia) at 1070 Ma (Wingate et al., 2002). The latter study introduced "AUSMEX," a further revision of Australia-Laurentia connections that brought together Australia and the southwesternmost extremity of Laurentia. AUSMEX was incorporated into the Rodinia paleomagnetic synthesis work of Pisarevsky et al. (2003a), but then demonstrated to be invalid for ca. 1200 Ma later that same year (Pisarevsky et al., 2003b). An invalid Rodinia juxtaposition at 1200 Ma might at first be considered harmless to the concept of a Neoproterozoic supercontinent, but remember that the SWEAT, AUSWUS, and AUSMEX connections were proposed to link Paleoproterozoic features from both sides of the Pacific (following Dalziel's [1999] criterion 4, above). In other words, any paleomagnetic discordance of coeval Australian and Laurentian poles between Paleoproterozoic craton assembly (ca. 1.8–1.6 Ga) and late Precambrian breakup (0.8–0.7 Ga) could, in principle, refute the direct connections entirely.

The presence of a post–1200 Ma orogen between Western Australia and Laurentia could account for the discordance of the ca. 1200 Ma poles between the two regions, and potentially permit any of the above proposed juxtapositions in Rodinia. The Albany-Fraser belt, between Western and South Australia, includes an episode of intense deformation and granitic magmatism at 1190 Ma (Black et al., 1992) and prograde metamorphic mineral growth as late as ca. 1150 Ma (Clark et al., 2000), though it is not known whether such activity is able to account for the 60°–90° gap between the ca. 1200 Ma paleomagnetic poles in the proposed juxtapositions (Pisarevsky et al., 2003b). The Sibao orogen in South China, if truly a late and centrally located suture within the "missing link" of Rodinia, can also salvage the SWEAT reconstruction from the 1070 Ma and 755 Ma paleomagnetic discordances, as long as both assembly and breakup in South China occurred entirely between those two constrained times. Such an argument was used by Li et al. (2008) to permit SWEAT and the "missing link" for South China, more of which will be discussed below.

Other regions of Rodinia were also challenged and refined after the year 2000. Siberia may have been slightly separated from the supercontinent (Pisarevsky and Natapov, 2003), or perhaps a promontory of the landmass (Pisarevsky et al., 2008). India was excluded from the assembly based on near-polar paleolatitudes—in contrast to low paleolatitudes of Laurentia and neighboring cratons—at ca. 1070 and 820 Ma (Pisarevsky et al., 2003a), although the poles could later be accommodated into an acceptable Rodinia model (Li et al., 2008). A series of papers by Eric Tohver and colleagues (Tohver et al., 2002, 2004, 2006) developed the model of the Amazon craton initially colliding with the southern Grenville Province as exposed in the Llano uplift in Texas, then translating sinistrally 3000 km to arrive ultimately adjacent to eastern Canada and Baltica. The model now includes a dynamically improbable rotation of Amazon by nearly 180° as it translated along the Laurentian margin, as if rolling like a wheel (Elming et al., 2009; Fig. 3A). However, if one abandons the 980 Ma Aguapei sills paleomagnetic pole as a possible Mesozoic overprint (see discussion of the widespread Permian to Cretaceous South American remagnetization events in Font et al. [2012]), and chooses the alternative polarity for the 1200 Ma Nova Floresta Formation pole (Tohver et al., 2002), an attractive alternative kinematic model is generated for collision of Amazonia with eastern Laurentia (Fig. 3B), readily derived from an earlier proposed Paleo-Mesoproterozoic association between Amazonia and Baltica (see below). Kröner and Cordani (2003) suggested that several African and South American cratons were never part of Rodinia, although those blocks remain incorporated in several subsequent reconstructions (Li et al., 2008; Evans, 2009). Meert and Torsvik (2003) questioned the existence of a coherent early Neoproterozoic supercontinent altogether, suggesting numerous independently drifting cratons; and in the opposite direction, Piper (2000, 2007, 2010, 2011) continued to promote a very long-lived Proterozoic supercontinent, named Palaeopangaea, the latter papers outright ignoring quantitative paleomagnetic refutations of the model's foundations (Li et al., 2009). In general terms, though, the question of how many early Neoproterozoic cratons were independently drifting, excluded from Rodinia, remains unsolved.

The signatures of Pb isotopes in crystalline rocks add a new dimension to the investigation of Precambrian craton associations. Such data were used to support an allochthonous affinity of the Argentine Precordillera basement relative to other basement regions of South America,

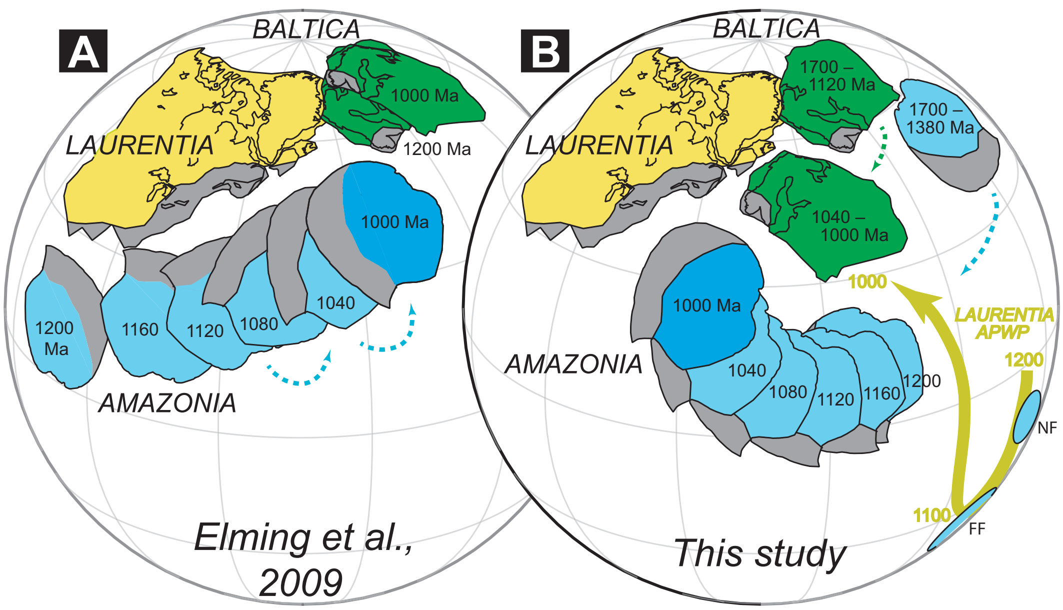


Figure 3. Alternative scenarios for the collisions among Laurentia, Baltica, and Amazonia in the supercontinent Rodinia. (A) Model by Elming et al. (2009), after Tohver et al. (2002, 2004, 2006), in which Amazonia collides with Laurentia at the southernmost Grenville exposures, then translates ~3000 km sinistrally along the Grenville margin, rotating nearly 180° in the process. Baltica must be shifted toward Greenland to accommodate the most northerly position of Amazonia at the end of its translation and rotation. (B) Alternative model introduced herein, utilizing the opposite polarities of Amazonia's Mesoproterozoic poles, in which both Baltica and Amazonia rotate clockwise relative to Laurentia, across a Tethys-like wedge-shaped oceanic tract, prior to Grenvillian/Sveconorwegian/Sunsas collision. APWP—apparent polar wander path (ages in Ma); NF—Nova Floresta; FF—Fortuna Formation.

with favored comparisons to Grenvillian inliers in the Appalachian belt of North America (Kay et al., 1996; Tosdal, 1996). Subsequently, a more comprehensive data set confirmed a Laurentian origin of the Precordillera but suggested affinity of more northerly Andean basement inliers with the Kalahari craton (Loewy et al., 2003). In Laurentia, there appears to be a clear divide between isotopically nonradiogenic Grenvillian basement of the northern Appalachians, versus relatively radiogenic Pb of the central and southern Appalachians, perhaps marking a Rodinian suture (Sinha et al., 1996; Tohver et al., 2004). Two cautionary notes must be made, however. First, the Pb isotope data set is far from global in scope, thus any previously proposed connections remain non-unique. Second, strong Pb isotopic gradients appear to be achievable via accretionary tectonics, as documented in the Proterozoic basement province of southwest Laurentia (Wooden and Miller, 1990).

Despite the untimely deaths of three IGCP Project 440 leaders (Rafael Unrug, Chris Powell, and Henri Kampunzu), that working group continued to synthesize tectonostratigraphic and paleomagnetic data, producing a GIS-based reconstruction map of Rodinia, an animation of its assembly and dispersal, and a series of papers in a special volume of the journal *Precambrian Research* (most notably Li et al., 2008). The model is a landmark in supercontinent research, given its comprehensive integration of tectonics, stratigraphy, and paleomagnetism; yet by incorporating the South China "missing link" position in the center of the supercontinent, it hangs precariously from tectonic interpretation and age of the Sibao orogen, topics of contention among Chinese geologists (e.g., Li et al., 2006; Sun et al., 2008; Zhou et al., 2009). Because the IGCP 440 Rodinia model's late timing of assembly (ca. 900 Ma or even younger, according to the Sibao orogen) strayed so far away from an original definition of the supercontinent based on Mesoproterozoic orogenic belts (Grenvilleland of Williams et al., 1991), Evans (2009) developed an alternative model of Rodinia that sought to incorporate all of the cratons' robust paleomagnetic poles in a long-lived assemblage spanning 1100 to 750 Ma. The reconstruction was a radical departure from all previous Rodinia models, although some cratonic juxtapositions were similar to those proposed earlier. The advantage of a long-lived supercontinent hypothesis is that it is more vulnerable to paleomagnetic refutation, because it requires all poles from a longer time span to agree with the model. Several subsequent paleomagnetic results have shown the "radical Rodinia" of Evans (2009) to fail such tests (Evans et al., 2010; Hanson et al., 2011b), which implies that the supercontinent either did not contain all of the paleomagnetically constrained cratons, or was not a coherent landmass through the entire interval 1100–750 Ma. The IGCP 440 model satisfies the second criterion, though it remains a non-unique solution.

Recent progress on Rodinia includes refinements of regional tectonic synthesis and paleomagnetic analysis, such as accommodation of a large intra-Australian shear system in latest Neoproterozoic time (Li and Evans, 2011). This development recalls that of Fitzsimons (2000), in that blocks previously supposed to be rigid are now broken into fragments that need to be considered separately, both in their tectonics and their paleomagnetic poles. The effect of such deformation on paleomagnetic poles has been extended into global paleogeographic models that incorporate both kinematics and lithostratigraphy of sedimentary basins (Li et al., 2013). A promising avenue of future research lies in accumulating evidence for an oscillatory pair of true polar wander (TPW) events coinciding with the "Bitter Springs" carbon-isotope and relative sea-level anomalies recorded on several cratons at ca. 800 Ma (Maloof et al., 2006; Swanson-Hysell et al., 2012; note that Li and Zhong [2009] posited only the second of these putative events, with a different proposed arrangement of planetary inertial moments). If either or both of those events really occurred as surmised, with Rodinia as well as all other tectonic plates sharing the same oscillatory motion, then there is potential for unique determination of both paleolatitude and relative paleolongitude from paleomagnetic studies of mid-Neoproterozoic volcanic-sedimentary successions around the world.

The standard model of Rodinia, including the SWEAT connection, has also experienced some resurgence. Goodge et al. (2008) demonstrated similarities in 1.4 Ga granitic magmatism between western North America and East Antarctica. Such connections are viable according to the original SWEAT hypothesis, which proposed a billion-year connection between the two cratons prior to their late Neoproterozoic separation, but they may also be viable according to an alternative hypothesis of "proto-SWEAT," an arrangement which might have entirely predated Rodinia in the Paleo-Mesoproterozoic cycle of Nuna (Betts et al., 2008; Payne et al., 2009) and implicitly accommodates the possibility of that juxtaposition's pre-Rodinia breakup and subsequent evolution to a non-SWEAT configuration during Rodinia time. Following earlier suggestions that the Kalahari craton lay adjacent to southern Laurentia, after a collisional orogeny between the southern Grenville and Namaqua/Natal provinces at ca. 1100 Ma (Dalziel, 1997; Loewy et al., 2003; Li et al., 2008; Jacobs et al., 2008), Loewy et al. (2011) suggested that Coats Land is a small, orphaned fragment of Laurentia. It should be noted that (1) in order for this latest model to be paleomagnetically viable, Coats Land must have experienced ~90° of local rotation commensurate with the proposed Kalahari collision between 1100 and 1000 Ma; (2) for the 1100 Ma connection with southern Laurentia to be viable, paleomagnetic uncertainties must be pushed slightly beyond their 95% limits; and (3) the polarity of Coats Land data, in the proposed reconstruction, appear at odds with those of the pre–1100 Ma data from the Laurentian mid-continent rift succession (cf. Hanson et al., 2004).

In summary, Rodinia enters its third decade of investigation at the crest of a new growth spurt in our understanding. Proposed reconstructions are geometrically accurate, and, by example of the groundwork laid by Li et al. (2008), should henceforth include well-illustrated animations of assembly and breakup. A substantial global community of researchers is tackling the problem by a variety of methods, integrating stratigraphy, geochronology, tectonics, and paleomagnetism. Thus, although no clear community consensus has emerged on Rodinia's exact configuration, investigations are under way in an attempt to uncover crucial data that will directly test the various alternative hypotheses and their implications for the broader Earth system.

FITFUL CONSTRUCTION OF NUNA MODELS

In contrast to the history of Rodinia investigations, which exploded onto the mainstream of geoscience in the span of months, the development of models of Rodinia's Paleo-Mesoproterozoic predecessor supercontinent has been slow in the making. Its original definition was based on the presumed timing of assembly at 1.9–1.8 Ga, corresponding to the dramatic assembly of Laurentia during the so-called Hudsonian orogeny, and recognition of similar orogenic ages elsewhere around the world (Hoffman, 1989). Consequently, the supercontinent presumably formed at that time was named Hudsonland (Williams et al., 1991). One likely element of Hudsonland was the "NENA" juxtaposition between northern Europe and North America (Gower et al., 1990). Two variations on that juxtaposition are widely illustrated, one paleomagnetically feasible, the other not. The viable connection has Baltica in a somewhat "upside-down" position relative to Laurentia, such that the Timanide margin from northern Norway to the polar Urals restores parallel to the East Greenland margin of Laurentia (Fig. 4A). This is essentially the geologically based NENA model of Gower et al. (1990),

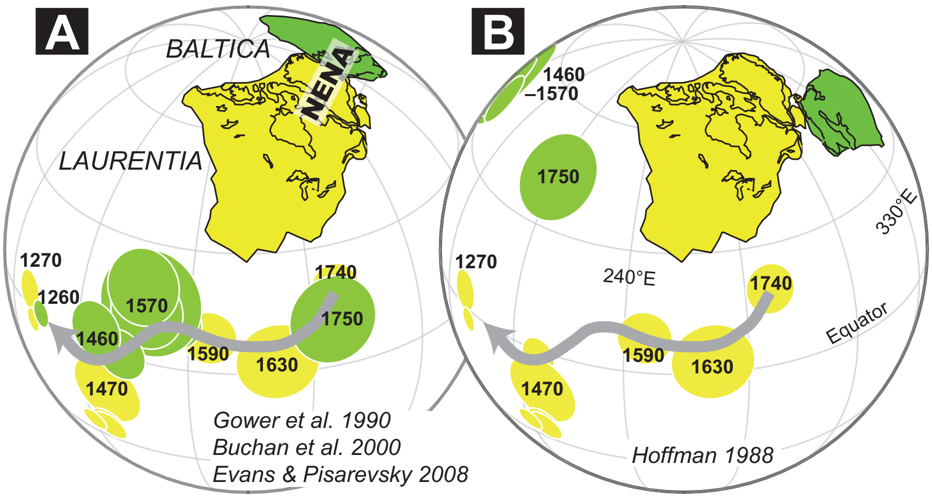


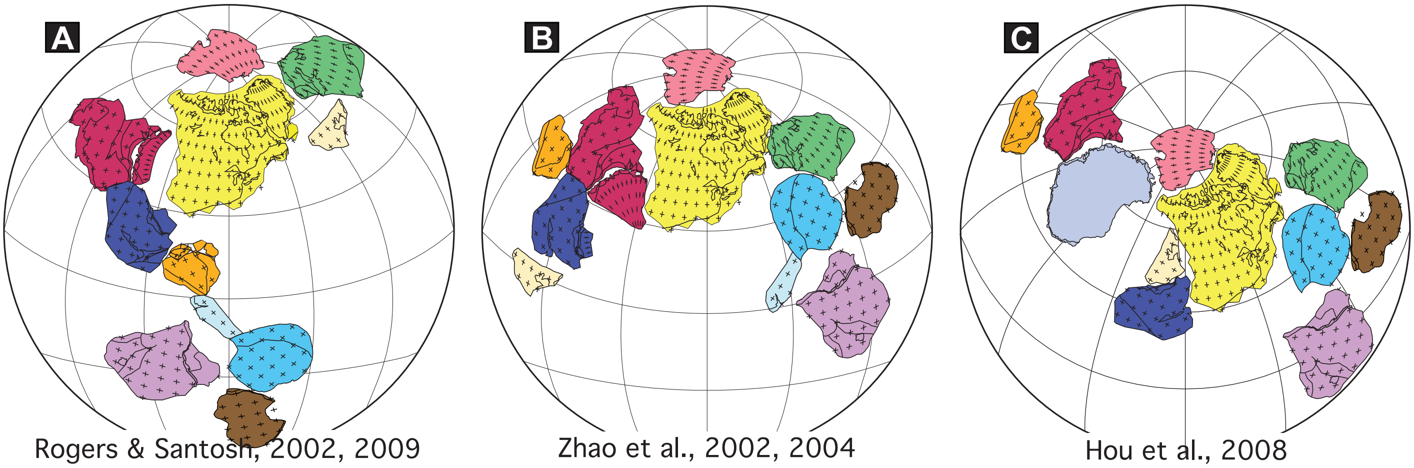
Figure 4. Variations on juxtapositions between Laurentia and Baltica/Fennoscandia in the Paleo-Mesoproterozoic. (A) NENA model of Gower et al. (1990), confirmed paleomagnetically by Buchan et al. (2000), and quantified by Evans and Pisarevsky (2008) with Baltica to North America Euler parameters (47.5, 001.5, +49). (B) "Right-way-up" model of Hoffman (1988), recapitulated by Zhao et al. (2002, 2004), Hou et al. (2008), and Johansson (2009) despite its paleomagnetic unviability. Euler parameters of Baltica to North America are (65.2, 218.1, –43.7). Ovals are the 95% confidence regions of paleomagnetic poles, color-coded to their host cratons (ages in Ma; selected from the poles cited by Salminen et al., in press); Gray arrowed curves are the implied apparent polar wander paths.

confirmed paleomagnetically to first order, over the interval 1.8–1.2 Ga, by Buchan et al. (2000), and given quantitative Euler parameters with only slight variations by Salminen and Pesonen (2007), Evans and Pisarevsky (2008), Salminen et al. (2009), and Pisarevsky and Bylund (2010). The unviable, superficially NENA-like connection includes a "right-way-up" paleogeography of Baltica relative to Laurentia (Fig. 4B), as popularized by Hoffman (1988) and many subsequent authors (Zhao et al., 2002, 2004; Hou et al., 2008; Johansson, 2009). Although this variation may appear only subtly distinct from the paleomagnetically viable model, the right-way-up configuration is clearly refuted by the 1.8–1.2 Ga data. It should be noted, however, that a right-way-up configuration of Baltica relative to Laurentia *is* compatible with Neoproterozoic geology and paleomagnetism, forming an important connection within Rodinia (Cawood and Pisarevsky, 2006). The rotational transition from upside-down Baltica (NENA *sensu stricto*)), to right-way-up Baltica within Rodinia, is well established in the literature, first noted by Patchett et al. (1978) and Piper (1980). The rotation occurred between 1.12 Ga and 1.05 Ga (Salminen et al., 2009; Evans, 2009), commensurate with distinctive patterns of orogenesis and sedimentation around the common pivot point shared between Scoresby Sund, East Greenland, and Finnmark, Norway (Cawood et al., 2010).

During the 1990s, as research on Rodinia stole the limelight of Precambrian tectonic reconstructions, Hudsonland appeared as a distant concept far too unpolished to take center stage. Rogers (1996) introduced a schematic model of supercontinent evolution over three billion years of Earth history. His reconstructions, though cartoonish and inconsiderate of paleomagnetic data (particularly regarding the Bullard fit or Pangea-like configuration of Laurentia and Baltica, a right-way-up variation that is unviable for 1.8–1.2 Ga, as just described above), laid out a clear hypothesis of only Rodinia and Pangea as true supercontinents; all pre-Rodinia landmasses were not considered to be of supercontinental areal stature (his figure 9). Global-scale orogeny in the late Paleoproterozoic, however, was long recognized (Hoffman, 1989), and evidenced, for example, by the International Committee on Stratigraphy who defined 2.05–1.80 Ga as the Orosirian Period (Plumb, 1991; see also Plumb and James, 1986). Hoffman (1997) revived the concept of a truly global-scale, 1.8 Ga supercontinent, renaming Hudsonland to Nuna, after an Inuktitut word for "the lands bordering the northern oceans and seas" (ibid.). The name is well chosen, because Hoffman's tectonic synthesis of the Canadian Shield (Hoffman, 1988) truly demonstrated the rapidity of continent-scale assembly at 1.9–1.8 Ga, coincident with the global-scale orogenesis of possible supercontinental extent at that time (Hoffman, 1989, 1997). By the end of the 1990s, however, the late Paleoproterozoic supercontinent was still largely conceptual in form.

Rogers and Santosh (2002) brought the 1.8 Ga supercontinent hypothesis into the mainstream, introducing the alternative name "Columbia, because the key evidence for that model's existence is the relationship between eastern India and the Columbia region of North America" (Rogers and Santosh, 2002, p. 5). Zhao et al. (2002, 2004) quickly followed suit with their own alternative reconstruction, providing additional details on the orogenies contributing to the proposed landmass's assembly. Unfortunately, these reconstructions revert to cartoon representations of cratonic outlines that are geometrically inaccurate; but the concepts are clear enough to allow approximate quantification using Euler poles (Figs. 5A, 5B). One notable aspect of the models by Zhao et al. (2002, 2004) is their similarity to existing Rodinia model configurations (compare to Fig. 2B). The authors did not discuss the implications of such similarity, which would necessarily invoke either tectonic stasis or, at most, narrow ocean opening and closing as the older landmass evolved to the younger. Such a concept is reminiscent of the "ensialic" interpretations of Proterozoic orogens (e.g., Kröner, 1977), at odds with the currently more mobilistic paradigm for global tectonics through most if not all of that eon (Cawood et al., 2006; see below for discussion of the 2.4–2.2 Ga interval in particular). Hou et al. (2008) produced another alternative Columbia model incorporating many elements from the earlier models (Fig. 5C).

Meert (2012) has argued that because these models were the first to propose a specific reconstruction of the 1.8 Ga supercontinent, the name Columbia gains priority over the more conceptual, age-defined entities named earlier. One may adopt that approach, but then one must endeavor to use it consistently: if paleogeographic nomenclature is going to rest entirely on a proposed reconstruction, then refutation of that reconstruction should force abandonment of those particular names. In this case, Meert (2002, p. 213 himself provided such a refutation, stating, "the paleomagnetic data provide little support for the existence of a Columbia-type supercontinent at 1.77 Ga." He was referring to the configuration shown in Figure 5A, herein. Subsequent high-quality paleomagnetic data from India similarly contradict the key Columbia direct connection to cratons within western Laurentia at 1.88 Ga (Meert et al., 2011) and 1.47 Ga (Pisarevsky et al., 2013). Nonetheless, and despite these refutations of Columbia *sensu stricto*, there is clear desire



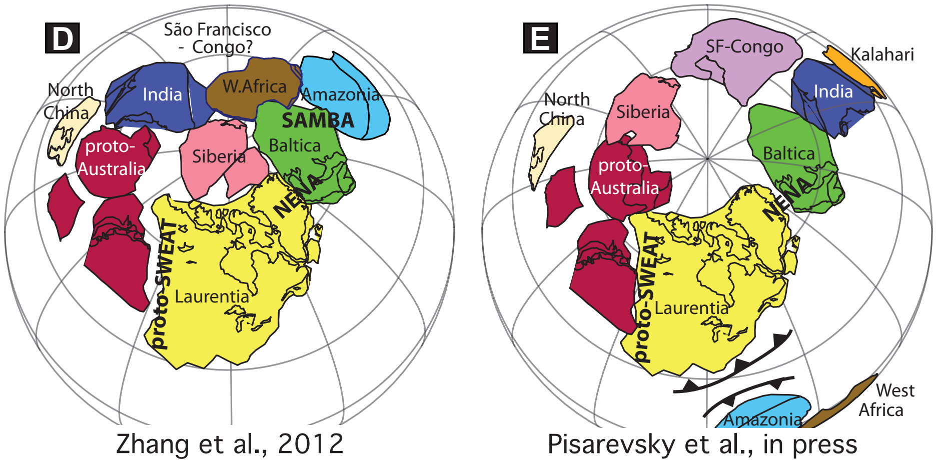


Figure 5. Variable configurations of the Paleo-Mesoproterozoic supercontinent referred to as Columbia (A–C) or Nuna (D–E). All projections are in present North American coordinates, with a common color scale (linked to Fig. 2) to facilitate comparison and contrast. (A) Rogers and Santosh (2002). (B) Zhao et al. (2002, 2004). (C) Hou et al. (2008). (D) Zhang et al. (2012). (E) Pisarevsky et al. (in press).

among paleogeographers to consider the possible existence of a supercontinent assembled in the late Paleoproterozoic, regardless of its exact configuration and thus adhering to a definition by age—hence priority for either of the age-defined terms Hudsonland or Nuna. Indeed, the review article by Pesonen et al. (2003) referred to this entity as Hudsonland; but one shortcoming of the models presented in that paper was that the authors did not incorporate the uncertainties of paleomagnetic data, and thus invoked impractical back-and-forth shearing between Laurentia and Baltica through the 1.8–1.5 Ga interval, rather than the simpler alternative of a coherent NENA juxtaposition that is acceptable for that time interval within those uncertainties (Salminen et al., in press).

The past few years have witnessed dramatic developments in rigorously quantitative kinematic models of Nuna's assembly and dispersal. Betts et al. (2008), Payne et al. (2009), and Hamilton and Buchan (2010) demonstrated both geologic and paleomagnetic plausibility of a proto-SWEAT juxtaposition between western Laurentia and variably rotated portions of the Australian cratonic regions between 1.75 and 1.59 Ga. The proto-SWEAT concept is important in guiding Paleoproterozoic reconstructions forward in time, toward an eventual realization of the standard Rodinia model with relatively modest amounts of cratonic rearrangement. Goodge et al. (2008) identified compelling matches between 1.4 Ga granitic rocks of the North American autochthon and granitic clasts found within the central Transantarctic Mountains, which could be interpreted in either a SWEAT or proto-SWEAT framework.

Pisarevsky and Natapov (2003) noted that the Siberian craton is nearly surrounded by Mesoproterozoic passive margins and may have thus been either excluded from Rodinia, or located on its periphery. Evans and Mitchell (2011) extended this suggestion with the implication that Siberia may have lain near the center of Nuna and subsequently "broke out" of that older supercontinent during Paleoproterozoic rifting, in the same manner as Laurentia out of Rodinia, or Africa out of Pangea. Their tight reconstruction of Laurentia, Baltica, and Siberia resembles that proposed earlier by Wu et al. (2005). Alternatively, Pisarevsky et al. (2008) had preferred a reconstruction of Siberia on the order of 1500 km away from the northern margin of Laurentia, based on paleomagnetic data at 1.1–1.0 Ga, continuation of that distal reconstruction back to the Nuna interval. Didenko et al. (2009) provided high-quality paleomagnetic data from 1.88 Ga that allegedly supported the gap between Siberia and Laurentia, but that comparison was being made to the Superior craton, which had not yet joined the growing Laurentia assembly (see Corrigan et al., 2009). A more apt comparison of the same data to the developing Slave craton apparent polar wander (APW) path (Mitchell et al., 2010a) generated an equally plausible tight fit between Siberia and the Laurentian nucleus for Nuna time, with those cratons' separation proposed to be at the time of 1.38–1.27 Ga mafic magmatism (Evans and Mitchell, 2011). Currently there are insufficient data to distinguish between the proximal versus distal positions of Siberia relative to Laurentia, within Nuna; but the placement of additional blocks around those two cratons may eventually provide clues for more precise positioning (Figs. 5D, 5E).

Reconstructions on the far side of Baltica are also gaining constraints at rapid pace. An enduring and coherent Atlantica continental nucleus is postulated to contain the Amazon, West Africa, and São Francisco/Congo cratons (plus smaller adjacent blocks) in their Gondwana configuration as far back as 2.0 Ga, based on largely juvenile tectonic assembly at ca. 2.1 Ga, and scattered exposures of slightly younger fluvial-deltaic sedimentary rocks that are interpreted as remnants of a regional blanket (Ledru et al., 1994; Rogers, 1996; Neves, 2011). Reliable paleomagnetic data are sparse, particularly from West Africa and São Francisco/Congo, but there is tentative support for at least the West Africa and Amazon cratons being conjoined in Atlantica, with or without modest amounts of internal shearing (Onstott and Hargraves, 1981; Onstott et al., 1984; Nomade et al., 2003).

A further step in this conjunction of cratons is the "SAMBA" hypothesis, suggesting the long-lived assembly of the Amazon craton in South America, and Baltica, together with West Africa, as a coherent entity from 1.8 Ga terrane amalgamation until late Proterozoic breakup of Rodinia (Johansson, 2009). The reconstruction is based on Paleo-Mesoproterozoic orogens and magmatic belts, including distinctive Mesoproterozoic rapakivi granite suites, particularly in Amazon and Baltica. When adding Laurentia to the assemblage, Johansson's model includes a ca. 1.1 Ga rotation of Baltica of broadly the same magnitude, sense, and timing as required by paleomagnetism (see above), but the Paleoproterozoic starting configuration of his SAMBA is in the paleomagnetically unviable model. New paleomagnetic and geochronological data from the Amazon craton (Bispo-Santos et al., 2008, 2012; D'Agrella-Filho et al., 2012; Reis et al., 2013) permit a SAMBA-like configuration (Zhang et al., 2012; Fig. 5D), though admittedly not exactly the same as that originally proposed (Pisarevsky et al., in press). Some flexibility is afforded by the possible rotation of Sarmatia/Volgo-Uralia (southern Baltica) relative to Fennoscandia (northern Baltica), perhaps as late as 1.7 Ga, along the buried and poorly known Central Russian orogen (Bogdanova et al., 2008). As an alternative to SAMBA, Pisarevsky et al. (2013) suggested that India lay on the exterior side of Baltica during the Mesoproterozoic Era (Fig. 5E), and in a further elaboration, ejected Amazonia and West Africa together into the global ocean as an independently drifting craton (Pisarevsky et al., in press).

São Francisco/Congo is a large craton that is yielding important new constraints on its possible position within Nuna. Thus far, the data are principally U-Pb ages on prominent magmatic events, at 1.73 Ga (Danderfer et al., 2009), 1.50 Ga (Silveira et al., 2013; Ernst et al., 2013), 1.38 Ga (Mayer et al., 2004; Drüppel et al., 2007; Maier et al., 2007; Tack et al., 2010), and 1.11 Ga (Ernst et al., 2013). The 1.50 Ga age, in particular, is unusual in the global (mafic) magmatic record with the exception of northern Siberia, and suggests a direct connection of that block with São Francisco/Congo (Ernst et al., 2013; Fig. 5E).

India's hypothesized position within Nuna varies considerably in the recent literature. Recall that a direct Columbia connection of India with western Laurentia is demonstrably invalidated by recent paleomagnetic data (Meert et al., 2011; Pisarevsky et al., 2013). The Indian subcontinent includes several cratonic regions that might or might not have been contiguous throughout Proterozoic time. Most high- or moderate-quality paleomagnetic data come from the areas south of the central Indian tectonic zone, which records deformation and/or magmatism as old as 2.5 Ga (Stein et al., 2004), alternatively at 1.6 Ga (Sanyal and Sengupta, 2012), or as young as ca. 1.0 Ga (Karmakar et al., 2011). North of the central Indian tectonic zone, the Bundelkhand craton and adjacent Aravalli-Delhi belt are only beginning to yield paleomagnetic data (Pradhan et al., 2012). With such unquantifiable uncertainties in mind, India (or one or more of its constituent cratons) has been tentatively placed either near Australian sectors of Nuna (Zhang et al., 2012; Fig. 5D), or adjacent to the Sarmatia margin of Baltica (Pisarevsky et al., 2013; Fig. 5E).

Somewhat like the situation with India, placements of North China in Nuna vary from one model to another. Those two cratons have been linked together by Zhao et al. (2002, 2004) and Hou et al. (2008), either indirectly or directly joined to western Laurentia. A location of North China near Baltica and Amazon was preferred by Bispo-Santos et al. (2008) in a regional reconstruction at 1.77 Ga; this was incorporated by Rogers and Santosh (2009) in their updated Columbia model. Syntheses that incorporate both 1.77 Ga and ca. 1.5 Ga paleomagnetic poles, however, find a singular position for North China off the northwest margin of Laurentia, in the vicinity of northern Australia (Wu et al., 2005; Zhang et al., 2012; Fig. 5D). That location is unique (within uncertainties and geomagnetic polarity option) because two poles from North China are overlain atop the combined Laurentian and Baltic APW path—thus constrained in both latitude and relative longitude to Nuna's central cratons.

The most recent development of Nuna reconstructions takes advantage of innovative software, called GPlates (Williams et al., 2012), which incorporates animations at the core of its architecture (using stage-pole interpolations as did its predecessor codes, PaleoGIS and PLATES). Global paleogeographic models through Paleo-Mesoproterozoic time are thus allowed to incorporate more mobility of cratons, in a kinematically consistent manner from one age to the next. Two such mobilistic models from middle Earth history have been completed, at least in preliminary form. One (Pehrsson et al., 2012) draws largely on the Zhang et al. (2012) reconstruction incorporating SAMBA-like juxtapositions (Fig. 5D), and the other (Pisarevsky et al., in press) draws largely from the alternative placement of India next to Baltica, as proposed earlier by Pisarevsky et al. (2013; Fig. 5E). Both of these latest kinematic models, interestingly, have included Nuna-amalgamating collisions as young as ca. 1.6 Ga to form the proto-SWEAT connection between western Laurentia and Australia/Mawsonland. If Mesoproterozoic igneous activity as early as 1.5–1.4 Ga (Ernst et al., 2013) heralded the onset of Nuna fragmentation, then that supercontinent would thus be nearly as short-lived as both Pangea (0.3–0.2 Ga) and Rodinia (0.9–0.7 Ga) with possibly similar patterns of geodynamic evolution (Li and Zhong, 2009).

In summary, investigations of Nuna had a long nascent period prior to a recent spark of activity in the last few years (Evans and Mitchell, 2011; Zhang et al., 2012; Pisarevsky et al., 2013, in press; Pehrsson et al., 2012). Two general classes of reconstruction models are being explored currently, with some common elements (the largely agreed-upon positions of Laurentia, Baltica in its "upside-down" option, Siberia either near or far, proto-Australia, and North China) and some more contentious positions (such as Amazon, West Africa, and India). The rapid accumulation of new paleomagnetic pole data, particularly high-quality results from U-Pb–dated mafic dike swarms (e.g., Bleeker and Ernst, 2006), will likely soon generate definitive tests of these models. Because the Paleo-Mesoproterozoic interval appears better globally endowed with such dike swarms than early Neoproterozoic time, advancement of knowledge about Nuna may soon surpass that of Rodinia.

KENORLAND OR NEOARCHEAN SUPERCRATONS?

It is not yet known whether Nuna was preceded by an earlier continental assemblage large enough to be classified as a supercontinent using the definitions provided above. Bleeker (2003) recognized that, among 35 Neoarchean cratons distinguishable in the Pangean collage (Fig. 6A), some of them must have been connected

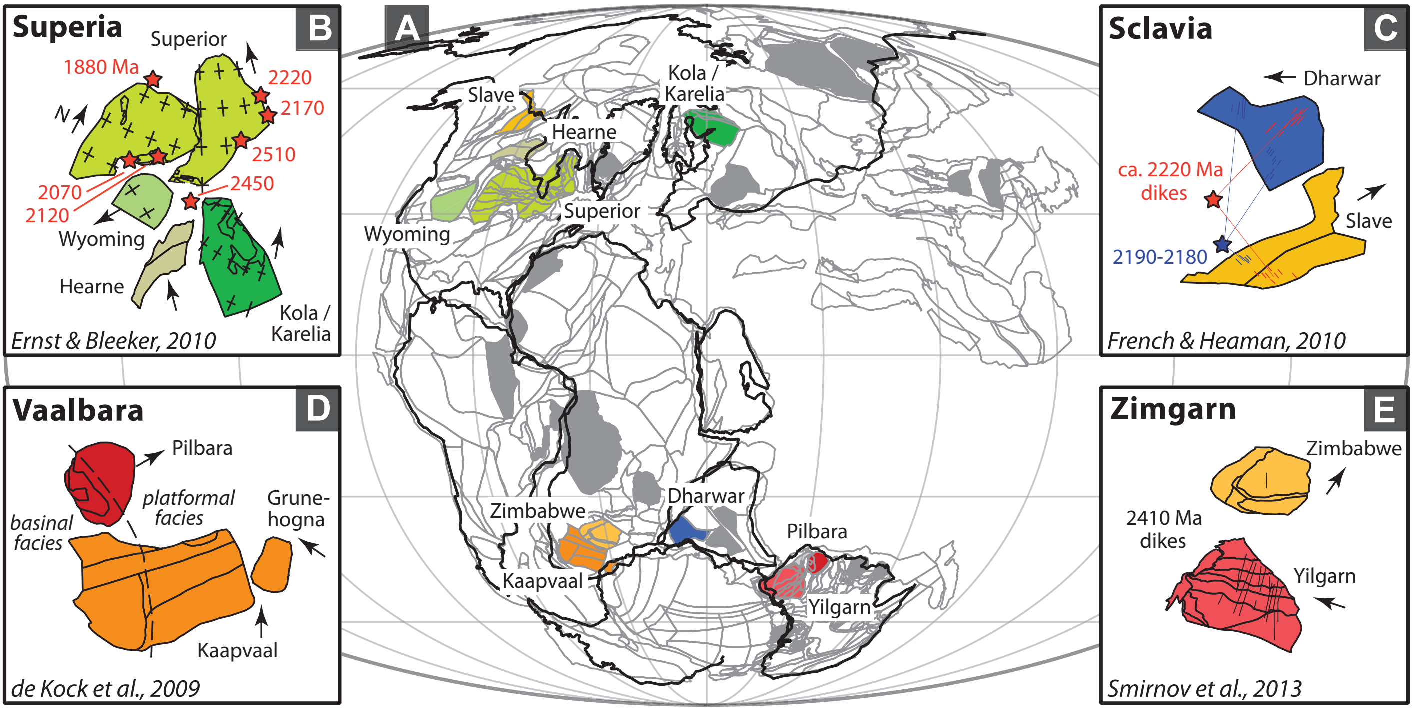


Figure 6. Possible Neoarchean–Paleoproterozoic supercraton reconstructions. (A) Pangea reconstruction at 200 Ma, in present South American coordinates, showing Archean cratons (gray, or colored and labeled) embedded within younger terranes (polygon outlines in gray, defined by Pehrsson et al., 2012; modern continental outlines in black).. (B) Proposed Superia supercraton (Ernst and Bleeker, 2010), based primarily on geometries of radiating dike swarms, with foci marked by stars. (C) Proposed Sclavia supercraton (French and Heaman, 2010) with its radiating dike foci. (D) Proposed Vaalbara supercraton (de Kock et al., 2009) based on stratigraphic comparison and paleomagnetic constraints. (E) More speculative Zimgarn juxtaposition (Smirnov et al., 2013) based on a limited number of dike ages, geometries, and paleomagnetic data. In (B)-(E), arrows show the present north orientation of each craton.

to each other (or to original continuations that have been destroyed by orogenic reworking or subduction) because their internal architectural fabrics are truncated by Paleoproterozoic rift margins. Therefore, the Neoarchean to earliest Paleoproterozoic puzzle should contain fewer than those 35 cratonic pieces; a solution with a single largest piece would be known as Kenorland (Williams et al., 1991), but an alternative model with separate, continent-sized pieces was called the "supercraton" solution. Bleeker (2003) identified distinctive "clans" of cratons defined by ages of stabilization and named after key cratonic nuclei: Vaalbara (2.9 Ga, named after the allegedly connected Kaapvaal and Pilbara cratons), Superia (2.7 Ga, after the Superior craton) and Sclavia (2.6 Ga, after the Slave craton). Pehrsson et al. (2013) identified a fourth family of cratons linked by extensive 2.5–2.3 Ga orogenesis, and named a hypothetical supercraton Nunavutia after the type example of the Rae craton in northern Canada.

Proposed assemblages of some supercratons utilize the radiating geometries of dike swarms fanning from presumed plume centers (Bleeker and Ernst, 2006; Ernst and Bleeker, 2010). The most complete application of this method, thus far, is to the Superia assemblage (Fig. 6B). Interestingly, based on this "barcode" approach of matching precisely dated mafic igneous events from one extant craton to another, even members of other clans such as Zimbabwe have been suggested to have joined the Superia landmass (Söderlund et al., 2010). Similar analyses of dike ages and geometries can be applied to other putative cratonic connections, e.g., Dharwar and Slave (French and Heaman, 2010; Fig. 6C), Dharwar and Yilgarn (Mohanty, 2011), or Dharwar and the North Atlantic craton (Nilsson et al., 2013).

A variant of the supercraton suite of models is that proposed by Rogers (1996), including entities named Ur, Atlantica, and Arctica. Each of these continent-sized pieces contains a distinctive Archean–Paleoproterozoic geologic record, but Ur and Atlantica also contain post-Paleoproterozoic orogens. A mobilistic interpretation of those orogens, supported by both tectonic and paleomagnetic data (Trompette, 1994; Boger et al., 2001; Meert, 2003; Jacobs and Thomas, 2004; D'Agrella-Filho et al., 2011; Li et al., 2013), would refute the Ur and Atlantica hypotheses, yet some tectonic syntheses still refer to and perpetuate the fixist interpretation (e.g., Kusky et al., 2007; Yakubchuk, 2010).

The Kenorland model had been originally defined by Williams et al. (1991) as a putative global continuation of the Kenoran orogenic pulse in the Superior craton, at ca. 2.7 Ga. Initial development of the Huronian rifted margin at 2.45 Ga (Ketchum et al., 2013) would then appear to mark the onset of breakup of that broader landmass. Aspler and Chiaranzelli (1998) prescribed a more strict definition of Kenorland, holding the various North American cratons fixed in their present configuration and thus relegating the intervening Paleoproterozoic orogenic belts (e.g., Thelon, Snowbird, Trans-Hudson) to intracontinental in character, or involving narrow oceanic tracts at most. Creating further ambiguity in definitions, Barley et al. (2005) used the name Kenorland to refer to a supercontinent assembling as late as ca. 2.5 Ga and fragmenting at ca. 2.1 Ga. An intriguing feature of the Barley et al. (2005) Kenorland model is its inclusion of distinct "clans" of cratons reconstructed variably to internal or external subduction margins of the landmass, thus accounting for their differences in tectonic histories. Lubnina and Slabunov (2011) loosely connected such distinct cratonic elements in an older version of the Kenorland model: Pilbara, Karelia, and Superior at 2.78–2.70 Ga. Piper (2003) proposed a long-lived (2.9–2.2 Ga) supercontinent that he calls Protopangea and that he claimed was consistent with the global paleomagnetic database; however, upon close examination of the rotated poles according to the reconstruction, their ages do not align satisfactorily.

In principle, any Kenorland (or supercraton) reconstruction model can be tested quantitatively by paleomagnetic data: all of the constituent cratons should document the same amount of motion, relative to the geomagnetic reference frame, during the time interval of putative assembly. In practice, such a method is challenging for the Neoarchean–Paleoproterozoic interval because it requires reliable paleomagnetic data from several cratons at precisely the same ages. Evans and Pisarevsky (2008) reviewed the global database for pre–800 Ma rocks, and found only ~50 results satisfying strict quality criteria. Using a current version of the database (T. Veikkolainen, L.J. Pesonen, D.A.D. Evans, and P. Sangchan, unpublished), a similar filter yields ~75 results of the same highest level of quality; about half of the new data are novel paleomagnetic studies, and the other half gain quality via new geochronological constraints. Many of the highest-quality results are from mafic dike swarms and sill provinces, which have for decades produced excellent paleomagnetic data (e.g., Strangway, 1964; McElhinny and Opdyke, 1964; Fahrig et al., 1965), but only recently have become amenable to routine dating by U-Pb on baddeleyite (e.g., Heaman and LeCheminant, 1993; Söderlund and Johansson, 2002). Integration of the two techniques is one of the most effective ways to gain precise constraints on Precambrian cratonic motions (e.g., Buchan et al., 1994).

The Superior craton has the best-constrained APW path for the early Paleoproterozoic interval, gained almost exclusively from precisely dated mafic dikes and sills (Buchan et al., 2007). The poles are so well defined that a relative rotation between eastern and western halves of the craton, across the Kapuskasing structural zone at ca. 1.9 Ga, can be quantified to 14° with rigorous Euler analysis (Evans and Halls, 2010). Similar constraints are being obtained from the Slave craton (e.g., Buchan et al., 2012), and the combined Superior-Slave data set confirms regional mobilistic interpretations of Canadian Shield tectonics (e.g., Hoffman, 1988) that the two cratons were likely not near neighbors in the 2.22–2.03 Ga interval, prior to Laurentian assembly. The possibility remains that they could have been distant members of a Kenorland supercontinent, or a large continent spanning at least 75° (~8000 km) across the Earth's surface (Mitchell et al., in press).

The third Paleoproterozoic craton with a substantial amount of reliable paleomagnetic data is Kaapvaal, which merged with Zimbabwe to form Kalahari. The timing of Kalahari assembly, via the intervening Limpopo belt, is open to discussion, generally considered to be either 2.7 Ga or 2.0 Ga (Kramers et al., 2006). Recent precise dating of the 1.88–1.87 Ga Mashonaland mafic sills in Zimbabwe, coeval within a few million years of sills emplaced within the Waterberg redbeds of South Africa, would appear to support their direct connection, sharing a single large igneous province; however, paleomagnetic data from the two regions differ by nearly 40°, thus Hanson et al. (2011) proposed a surprisingly late assembly of the Limpopo belt to account for the discrepancy. Nonetheless, the 1.88–1.87 Ga interval is also characterized by large paleomagnetic scatter within both the Slave and Superior data sets (Mitchell et al., 2010a), and a common cause such as TPW could alternatively be invoked in the case of an earlier-assembled Limpopo orogen. For the period prior to 2.0 Ga, Kaapvaal has a moderately complete paleomagnetic data set, which permits a direct juxtaposition with the remarkably similar Pilbara craton in Western Australia for the 2.78–2.72 Ga interval, extending to Paleoproterozoic time by stratigraphic comparisons (de Kock et al., 2009; Fig. 6D). Zimbabwe has a much more sparse paleomagnetic record, but the data allow a speculative original connection with Yilgarn craton, also in Western Australia, forming the putative Zimgarn landmass (Smirnov et al., 2013; Fig. 6E). Zimgarn may also have been a component of the Superia supercraton (Söderlund et al., 2010).

The preceding discussion should illustrate just how primitive are the blueprints currently being drawn for Neoarchean–Paleoproterozoic paleogeography. The tools required to advance the science, however, are ready for use: tectonic synthesis integrated with high-precision geochronology and reliable paleomagnetic studies. Despite the difficulties presented by smaller areas of intact lithosphere from this interval, the Archean-Proterozoic transition appears to be of crucial importance to geodynamic evolution of the Earth. Most discussions on the origin of plate tectonics favor a threshold at least as old as 3.0 Ga, if not earlier (cf. Condie and Kröner, 2008). Even if plate tectonics had begun long before Paleoproterozoic time, there is the possibility of a global tectonic standstill between 2.35 and 2.25 Ga, as introduced by Condie et al. (2009) based on a paucity of orogenic belts and isotopic ages in that interval of time. However, the age gap can be filled by a recently recognized, additional clan of cratons and metacratons that experienced prominent ca. 2.3 Ga tectonism (Pehrsson et al., 2013). It thus appears that plate tectonics has continued in uninterrupted fashion throughout the past 2.5 billion years or longer, and it remains our challenge to document those plate motions to the fullest extent that the geologic record permits.

CLOSING REMARKS

The existence and timing of supercontinents through Earth history bear profound influence on many other aspects of the long-term Earth system, from the core to the atmosphere (Reddy and Evans, 2009). Full treatment of such effects is beyond the scope of this already lengthy review, but Nance et al. (2013) have ably described many of them within an independent retrospective chronicle of the topics discussed herein. In my concluding remarks I will only briefly touch on a few geodynamic issues that bear directly on the methods used to formulate the reconstructions.

Because paleomagnetism measures cratonic motions relative to the geomagnetic reference frame, it is essential that such a frame be stable over geologic time. Several tests of the geocentric axial dipole (GAD) hypothesis have shown that, at least throughout the last two billion years, the GAD model is a satisfactory description of the geomagnetic field when averaged over several thousand years or more. A profound discrepancy between Proterozoic glacial deposits and their near-equatorial paleomagnetic latitudes (Evans, 2003b) is explained by panglacial ice ages (Hoffman, 2009) rather than failure of the GAD hypothesis; an independent test using Proterozoic evaporites shows concordance of their paleolatitudes in arid subtropical belts (Evans, 2006). Reversals of the geomagnetic field are shown to be symmetrically antiparallel by the most thorough tests of Proterozoic strata (Swanson-Hysell et al., 2009), and secular variation of the geodynamo through the Proterozoic is broadly consistent with that of the last five million years (Biggin et al., 2008; Smirnov et al., 2011). Earlier studies of inclination frequencies across the paleomagnetic database suggested moderate departures from GAD in Proterozoic time (e.g., Kent and Smethurst, 1998), but more recent analyses with data-quality filtering show non-GAD components (axial quadrupole, axial octupole, etc.) of magnitude similar to the present day (Veikkolainen et al., in press). Lastly, variations of paleomagnetic directions across large Proterozoic dike swarms are more consistent with a stationary GAD-like field than any of the earlier-proposed alternatives (Panzik and Evans, submitted). In sum, all of the most recent tests of the GAD hypothesis have confirmed its validity to first order, for Proterozoic time. A possible exception is the mid-Ediacaran interval, when paleomagnetic data are more complex than at any other time in Earth history, at present knowledge; various explanations have been offered to explain the unusual patterns of data, from a nonuniformitarian geodynamo (Abrajevitch and Van der Voo, 2010) to multiple and oscillatory episodes of TPW (Evans, 1998; Raub et al., 2007).

Cratonic motions relative to the geomagnetic reference frame are due to a combination of processes acting in parallel: plate tectonics and TPW. Plate tectonic motions occur between the lithosphere and mesosphere, whereas TPW occurs between the mesosphere and the outer core. Since the breakup of Pangea, TPW has been small relative to most plate motions, yet measurable and significantly nonzero (e.g., Besse and Courtillot, 2002). Recent global kinematic surveys that avoid using a fixed hotspot reference frame—instead identifying coherent trends of continental rotations—find two modest, back-and-forth TPW oscillations in Mesozoic time (Steinberger and Torsvik, 2008; Torsvik et al., 2012). Paleozoic TPW may have been more prevalent (e.g., Van der Voo, 1994; Marcano et al., 1999; Mitchell et al., 2010b, 2012), but with no intact oceanic lithosphere preserved and very few large igneous provinces (LIPs) that could provide hotspot tracks from that era, such TPW estimation is more ambiguous. Precambrian TPW is even harder to quantify, especially due to the absence of global biostratigraphy and thus a reliance on chronometric dating to correlate geology across cratons. Ediacaran cratonic motions appear to be extremely rapid, which as noted above could be due to nonuniformitarian geophysics, either unusual geomagnetic behavior or unusually rapid TPW (or both). TPW may have been dominant in the rapid motions of Laurentia and other cratons between 1.1 and 1.0 Ga (Powell et al., 2001; Evans, 2003a; Swanson-Hysell et al., 2009). Finally, and also as discussed above, multiple TPW oscillations could have occurred in the 1.9–1.85 Ga interval (Mitchell et al., 2010a). Given these numerous observation-based hypotheses, bolstered by theoretical advances in explaining oscillatory TPW from a geodynamic perspective (Creveling et al., 2012), we should perhaps begin to consider nonzero TPW as the rule rather than the exception for pre-Pangean cratonic motions. Claims of ancient plate kinematics based merely on varying paleomagnetic directions (e.g., Strik et al., 2003) are rendered ambiguous by the likelihood of TPW on the early Earth.

Although TPW may be considered "noise" in the effort to reconstruct past histories of supercontinental assembly and dispersal, its "signal" can also be useful. If there are epochs when TPW dominates cratonic motions relative to subsidiary rates of plate tectonics, then the common (equatorial) axis of the TPW rotation can be used as an additional reference frame providing relative paleolongitude constraints (Evans, 2003a; Raub et al., 2007). Under the assumption that oscillatory TPW occurs around large, lower-mantle shear velocity provinces (LLSVPs) anchoring Earth's inertial tensor to a defined paleolongitude, then the TPW oscillations around the LLSVP-anchored equatorial axis can even provide absolute paleolongitude in deep time (Torsvik et al., 2008, 2012). Such anchoring has been shown to be stable for the past 200 million years; whether the stability can be extended throughout Earth history (Dziewonski et al., 2010; Burke, 2011), or whether LLSVPs disintegrate by convection entrainment and shift their locations by 90° of longitude across each supercontinental cycle (Mitchell et al., 2012), remains to be tested.

The shifting-LLSVP model is conceptually tied to a style of supercontinental transition called "orthoversion" (Mitchell et al., 2012), because in a deep-mantle reference frame, the location of each supercontinent and pair of LLSVPs relocates ~90° away from their predecessors. The name alludes to earlier models of supercontinental transition (Murphy and Nance, 2003, 2005): new supercontinents assembling either in nearly the same configuration, and presumably at the same location in a mantle reference frame, as the previous breakup ("introversion"); or in an inverted ("inside-out") topology, presumably toward the opposite side of the world ("extroversion"). Isotopic proxies such as Sm-Nd and Lu-Hf (Collins et al., 2011) from the presumed margins of ancient supercontinents can yield an independent assessment of global reconstructions based on tectonostratigraphy and paleomagnetism.

In addition to new developments in geochronology, paleomagnetism, and isotopic proxies for orogenic style, another exciting advance in deep-time global reconstructions is through the cross-platform, free software package GPlates (Williams et al., 2012). More than just a tool for visualizing cratonic motions, the software incorporates active kinematic evolution at the core of its reconstruction architecture. More than ever before, a broad spectrum of geologists and geophysicists have the ability to create animations that can test the viability of reconstruction models across geologic time. The ability to import geological and geophysical data sets in the form of GIS-based data files can further aid users who wish to test their reconstruction models by comparison with the rock record in accurately rendered paleogeographic maps.

Given these recent developments and looking forward, there is great optimism for major advances in understanding pre-Pangean supercontinents. I expect that by the year 2038, as the Geological Society of America reaches its sesquicentennial celebration, any review of this nature will be able to describe the first-order solution to Earth's global paleogeography from the present back to at least 2 Ga, with contemporary discussions on merely second-order paleogeographic issues from that interval. Such a unified paleogeographic architecture will provide a solid backdrop to the rich drama of Proterozoic–Phanerozoic geodynamic, paleoenvironmental, and evolutionary changes.

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