The Columbia Supercontinent revisited

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Abstract

Just over 15 years ago, a proposal forwarded by Rogers and Santosh (2002) posited the existence of a pre-Rodinia supercontinent which they called Columbia. The conjecture invigorated research into the Paleo-Mesoproterozoic interval that was; in our opinion, inappropriately dubbed 'the boring billion'. Given the wealth of new information about the supercontinent, this review paper takes a careful look at the paleomagnetic evidence that is used to reconstruct Columbia. Our contribution represents a status report and indicates that; despite the exponential increase in available data, knowledge of the assembly, duration and breakup history of the supercontinent are contentious. The commonality of ~1.7-2.1 Ga orogenic systems around the globe are indicative of major changes in paleogeography and growth of larger landmasses. There is continued discussion about the interconnectedness of those orogenic systems in a global picture. Arguments for Columbia posit a ~1500-1400 Ma age for maximum packing. Paleomagnetic data from many of the constituent cratons during the 1500-1400 Ma interval can be interpreted to support a large landmass, but the consistency of the proposal cannot be reliably demonstrated for earlier or later times. One of the more intriguing advances are the apparent long-lived connections between Laurentia, Siberia and Baltica that may have formed the core of both Columbia and Rodinia.

1. Introduction

It can be argued that the plate tectonic revolution started with the rather simple observation of the jigsaw puzzle between the coastlines of modern-day western Africa and eastern South America (Suess, 1881, 1904). Wegener (1912) noted this unique relationship

and expanded the idea to include most of the Earth's continents into a single landmass (Fig. 1a) initially called "*Urkontinent*", or 'original continent'. Wegener (1922) later referred to the continent as "*die Pangäa*" (the Pangea or *Pangæa*; Rance, 2007). Although Wegener proposed these ideas in the early 20th century, the notion of wandering continents failed to take hold in academic circles until the middle of the century. This was due, in part, to the lack of a proposed mechanism for moving the continents through what was thought to be much older oceanic crust (see LeGrand, 1988). Extensive mapping of the seafloor during World War II led to the recognition of a wide range of volcanically active mountains in the central Atlantic initiating discussion of sea-floor spreading as a process giving rise to new oceanic crust.

By the late 1960's paleomagnetic, seismologic, paleontologic, heat flow and geological data led to the new paradigm of plate tectonics (LeGrand, 1988; Van der Voo, 1993; Rogers and Santosh, 2004). The Pangea supercontinent became the *casus belli* for continental drift and led Wilson (1966) to ask; "Did the Atlantic close and then re-open?". That question was, quite naturally, followed by the query "How many times?" suggesting that there might be a cyclical pattern to the formation and destruction of supercontinents.

Although first articulated by Wilson (1966), other arguments were marshalled that seemed to indicate cyclic behavior in the assembly and dispersal of continents. Most notable were models based on 'common' isotopic ages observed in the geochronological database (Gastil, 1960; Runcorn, 1962; Sutton, 1963). A review of the geochronological data from U-Pb dating of detrital zircons (Campbell and Allen, 2008) was consistent with earlier proposals that major orogenesis took place on earth at irregularly/regularly spaced intervals (Fig. 1b; Runcorn, 1962; Sutton, 1963). Recognition that "Wilson-cycles" (Wilson, 1966) might reflect the

assembly and dispersal of large landmasses led others to suggest the existence of earlier supercontinents in the 1970's (Valentine and Moores, 1970, 1972; Burke and Dewey, 1973; Irving et al., 1974; Piper, 1976; Sawkins, 1976). Piper (1976) was the first to propose a specific reconstruction of the Proterozoic supercontinent that he called "Paleopangea" (see also Piper 2000, 2007). Other suggested names (sans reconstruction) were "*Pangea-I*" or "*proto-Panged*" (Sawkins, 1976; Valentine and Moores, 1972; Bond et al., 1984).

McMenamin and McMenamin (1990) envisioned a Neoproterozoic supercontinent with shallow-bordering oceans that became the cradle of complex life. They called this supercontinent "Rodinia" (fig. 1c) and modeled the landmass based on previous proposals (Sears and Price, 1978; Donovan, 1978; McMenamin, 1982; Piper, 1987). Although the name Rodinia is now entrenched in the scientific literature as the name for the Neoproterozoic supercontinent, the exact arrangement of the landmasses within Rodinia is controversial (Moores, 1991; Dalziel, 1991, 1992; Hoffman, 1991; Torsvik et al., 1996; Weil et al., 1998; Meert and Torsvik, 2003; Li et al., 2008). The disagreement over the makeup of Rodinia is confounded by the fact that there is another supercontinent (Columbia) proposed for the Paleo-Mesoproterozoic interval that, in some models, strongly resembles Rodinia (see Meert, 2014).

The history of the Mesoproterozoic supercontinent is complicated and has led to an argument regarding its sobriquet (see Meert, 2012). In this paper, we use the nickname Columbia (Rogers and Santosh, 2002) as we believe it has precedence in the scientific literature while acknowledging that a smaller group of researchers prefer the term "Nuna".

In 2002, Rogers and Santosh published their seminal paper; “Configuration of Columbia, a Mesoproterozoic supercontinent”. The publication was based on several key observations; (1) the lack of orogenic activity from ~2.5 to 2.1 Ga followed by; (2) widespread tectonism during the 2.1-1.8 Ga interval (see also Zhao et al., 2002, 2003); (3) the presence of Mesoproterozoic rift basins particularly those in India and western North America (Rogers and Santosh, 2002, 2004). Figure 2a shows the original reconstruction based on the geological arguments forwarded by Rogers and Santosh (2002). Very shortly after the Rogers and Santosh (2002) paper, Zhao and colleagues (2002) proposed a more detailed map of Columbia which they called “Hudson” in an earlier draft and abstract (see fig. 2b; Zhao et al., 2000). Although, the Rogers and Santosh (2002) paper preceded the publication of Zhao et al. (2002) by only a few months, Rogers (2008) noted in his book “Earth Science and Human History”, pg 116):

“Guochun Zhao of Hong Kong University and three colleagues published a paper in 2002 proposing a supercontinent with an age of 1.8 Ga and a slightly different configuration from the one suggested for Columbia by Rogers and Santosh (2002). Because of the slight difference in age and configuration, Zhao and his colleagues could have used a new name for their proposed supercontinent, but they graciously decided that a new name would cause confusion in the geological literature and decided to use their work to suggest a different configuration and age for Columbia”

Neither Rogers and Santosh (2002) nor Zhao et al. (2000, 2002) provided paleomagnetic support for their models. Meert (2002) attempted to test the Rogers and Santosh (2002) proposal, but the data were too few and scattered to provide any rigorous test of the model.

In the remainder of this paper, we discuss the current status of the Columbia supercontinent on its 15th 'birthday'.

2. Geological arguments for Columbia

Zhao et al. (2002, 2003, 2004, 2011) provide excellent summaries of the geological data supporting Columbia. The common thread in all these publications is the ubiquitous record of 2.1-1.8 orogenesis (fig. 2b). Here we briefly discuss that evidence, the original Columbia hypothesis and refer the reader to the original publications for detailed analyses of the orogenic systems thought to weave them together.

2.1 Laurentia-Siberia-Baltica

The ancient core of present-day North America (Superior, Slave, Rae, Hearne, Nain and Wyoming provinces; Fig. 3a) were assembled piecemeal over a protracted interval of the Paleoproterozoic (Hoffman, 1988, 1997; Mitchell et al., 2014). Mitchell et al. (2014) use available paleomagnetic data from Laurentia to conclude that most of the core regions had assembled by ~1.8 Ga although the Wyoming craton did not become incorporated until ~1.7 Ga (Killian et al., 2016).

Bogdanova et al. (2013) outlined evidence for Sarmatia and Volgo-Uralia unification around 2.0 Ga followed by the assembly of the Baltic Shield at ~1.85 Ga when Volgo-Uralia/Sarmatia collided with Fennoscandia (Kola and Karelia; Fig. 3b) during the Svecofennian and related orogenic pulses (Bogdanova et al., 2008). Terentiev et al. (2016) documented extensive Paleoproterozoic magmatism in the East Sarmatian Orogen, located at the junction of the Sarmatian and Volga-Ural segments of the East European Craton. They correlated the

magmatism with tectonics associated with the amalgamation of the global supercontinent Columbia. More recently (Bogdanova et al., 2016; Lubnina et al., 2016;) outline geological and paleomagnetic evidence favoring a slightly younger age. In these models, Volgo-Uralia and Sarmatia coalesced between 2.1-2.05 Ga with thrusting of Volgo-Uralia over Sarmatia. This was followed by the 2.0-1.75 Ga Svecofennian orogeny that increased the size of both Volgo-Sarmatia and Fennoscandia via microcontinent and arc collisions. Final suturing of Volgo-Sarmatia and Fennoscandia took place around ~1.7 Ga (Bogdanova et al., 2016). The ~1.7 Ga collision finds support from recent paleomagnetic data (Lubnina et al., 2016). Thus, tectonic models should treat Volgo-Sarmatia and Fennoscandia as separate blocks until the interval between 1.75-1.70 Ga.

The Archean and Paleoproterozoic regions of Siberia (so-called superterrane) of Tungus, Anabar, Aldan, Stonovoy and the Olenek uplift were assembled during the 2.1-1.8 Ga interval (Glebovitsky et al., 2008; Gladkochub et al., 2006; Pisarevsky et al., 2008; Ernst et al., 2016; Fig. 3c). Mobile belts between the various Archean-age terrains include the East Tungusk (>1.87 Ga), the Idzhel-Nuyan (>2.0 Ga), West Olenek (1.9-1.8 Ga), Near-Sanavoi (>1.7 Ga), South Siberian (1.87-1.84 Ga) and Angara (?) collisional belts (Glebovitsky et al., 2008).

Rogers and Santosh (2002) followed Rogers (1996) connecting Laurentia and Siberia in the “*Arctica*” landmass and argued that Mesoproterozoic collisions brought together *Arctica* with Baltica. Rogers (1996) referred to the large assembly as “*Nena*” after Gower et al. (fig. 4a; 1990). Hoffman (1997) altered this slightly and added northern and western Australia to the Nena landmass and called it “*Nuna*” (fig. 4b). Rogers and Santosh (2002) included Nuna/Nena as the core of Columbia.

2.2 East Gondwana

There is a controversy regarding the long-term integrity of East Gondwana (India, Sri Lanka, Madagascar, the East Antarctic craton and Australia (see Meert, 2003; Meert and Lieberman, 2008).

Rogers (1996) proposed an alternative scenario with a central 'core' which he called "expanded-Ur". Expanded "Ur" was comprised of the Kaapvaal and Zimbabwe cratons (southern Africa); the Dharwar, Bastar, Singhbhum, Bundelkhand and Aravalli nuclei of India; an extension of the Dharwar craton in Madagascar; the Yilgarn, Pilbara, Gawler and Kimberley blocks of Australia; and the Dronning Maud, Napier Complex and Vestfold Hills regions of East Antarctica (see fig 2a). Expanded-Ur was used in the model of Rogers and Santosh (2002) as one of three principal landmasses that collided to form the Columbia supercontinent (fig 2a).

Proto Australia (lands to the west of the Tasman line; fig. 5a) is composed of Western Australia (Yilgarn and Pilbara cratons), North Australia and South Australia. The western Australian nucleus formed around 2000 Ma during the Capricorn Orogen. The Western Australian blocks were sutured to the Diamantina craton (north Australia, South Australia and parts of East Antarctica) along the Paterson orogen during the ~1800 Ma Yapungku Orogeny. Northern Australia (NA) and Western Australia (WA) remained united; however, southern Australia and parts of East Antarctica rifted around 1500 Ma to form the Mawson continent. Mawson was re-united with NA-WA during the assembly of Rodinia to form the "Great Southern Continent" (Cawood and Korsch, 2008). Wingate and Evans (2003) examined the available paleomagnetic data from Australia and concluded that North Australia and West Australia were in contact with each other by ~1.7 Ga and both were connected to South

Australia by 1.5 Ga. In contrast, Schmidt et al. (2006) concluded that the Precambrian nuclei of Australia were not in their present-day configurations until ~1070 Ma based on paleomagnetic data from the Alcurra dyke swarm. Li and Evans (2011) presented a potential solution to the disparate, but coeval, paleomagnetic data from South/Western Australia and Northern Australia. They suggested a 40-degree clockwise rotation of the former with respect to the latter during the Neoproterozoic. If correct, then the arguments for the younger, ~1.07 Ga unification are less compelling.

Elements of Peninsular India include the Northern India Block (NIB) composed of the Aravalli region and the Bundelkhand craton and the southern India Block (SIB) made up of the Dharwar (Western and Eastern), Bastar and Singhbhum cratons (Fig. 5b; Meert et al., 2010; Meert and Pandit, 2015). There is still considerable controversy regarding the unification of the NIB with the SIB along the Central Indian Tectonic Zone (CITZ) with ages ranging from 2.5 Ga to ~1.0 Ga.

The Dharwar and Bastar cratons are geographically separated by the Prahrita-Godavari Rift (PG), the Singhbhum and Bastar cratons by the Mahanadi Rift (MR) and the combined Bastar/Singhbhum and the combined Bundelkhand/Aravalli cratons are separated by the Central Indian Tectonic Zone (CITZ; see fig. 5b). In addition to the cratonic regions cited above, a large granulite region lies to the south of the Dharwar craton. The so-called 'southern granulite terrain' is a collection of highly metamorphosed crustal blocks of Archean to Neoproterozoic age in southern India south of the Dharwar craton.

The Mahanadi Rift region is the most cryptic among the craton-bordering regions (Lisker and Fachmann, 2001; Santosh et al., 2004; Dasgupta et al., 2017). The MR is filled with

Carboniferous-Triassic Gondwana rift sediments with very limited geochronology on basement rocks indicating activity during ~ 1.0 - 0.9 Ga Eastern Ghats orogenic cycle. Minor remnants of Archean basement are also found near the MR (Dasgupta et al., 2017). The Prahrita-Godavari Rift basin (PGB) contains both Proterozoic and Phanerozoic sedimentary sequences. The PGB is bordered to the north by the Bhopalpatnam granulite belt (BPG) and to the south by the Karimnagar granulite belts (KGB). The BPG granulites yield ages of 1.6 and 1.0 Ga and Santosh et al. (2004) proposed that the 1.6 Ga metamorphism in the BPG developed during Bastar-Dharwar collision and that the younger ages represented re-working during the Eastern Ghats orogenic cycle.

The Central Indian Tectonic Zone (CITZ) traverses Peninsular India from East to West and is thought to demarcate a major boundary between the Northern Indian Block (NIB; Aravalli Bundelkhand) and South Indian Block (SIB: Dharwar, Bastar and Singhbhum). The CITZ is partitioned into myriad smaller domains based on the tectonometamorphic events in those areas (see Meert et al., 2010). Key metamorphic ages from the CITZ fall at 2.5, 1.6 and 1.0 Ga. Stein et al. (2004, 2014) maintained that the younger ages (1.6 and 1.0 Ga) reflect re-working of material within an older 2.5 Ga suture zone between the NIB and the SIB. Other authors disagree with the Stein et al. (2004, 2014) model and favor a ~ 1.6 Ga collision between the SIB and the NIB (Bhandari et al., 2011) or, possibly between the Bastar-Bundelkhand cratons (Mondal et al., 2013). Still other authors favor much younger Stenian-Tonian (~ 1.1 - 0.88 Ga) collisions between the NIB, the SIB and the Marwar Block to form 'Greater India' (Bhowmik et al., 2012a, 2012b; Pradhan et al., 2012; Meert et al., 2013) with the ~ 1.6 Ga orogenesis resulting from island arc collisions with the SIB (Chatterjee, 2016).

Although the paleomagnetic database from India is now far more extensive than at the turn of the century, some of the answers regarding the assembly process remain unanswered. Paleomagnetic data from the northern block of the Southern Granulite Terrain (SGT) and the Dharwar craton were part of the same block by 2.36 Ga (Belica et al., 2013; Dash et al., 2012; Pivarunas, personal communication). The Bastar and Dharwar cratons show identical ages and paleomagnetic directions for a suite of 1.88 Ga dykes (Belica et al., 2013; Meert et al., 2011; French et al., 2008). This strong agreement between the ~1.9 Ga Bastar and Dharwar dykes indicates that models positing a later, ~1.6 Ga collision, between those two blocks is likely incorrect.

Inclusion of the Singhbhum craton into the SIB aggregate is less well constrained, but some have argued that the Singhbhum craton can be considered an integral part of the SIB by ~1.8-1.6 Ga (Meert et al., 2010; Basu and Bickford, 2015). It is far more difficult to ascertain the age of the NIB-SIB collision. Numerous ultramafic intrusions intrude the Bastar, Bundelkhand and Dharwar cratons with ages between 1050-1125 Ma (Gregory et al., 2006; Sahu et al., 2013; Miller and Hargraves, 1996; Pesonen et al., 2012; Venkateshwarlu and Chalapathi Rao, 2013). Paleomagnetic data from the Majhgawan kimberlite (1073 Ma; Gregory et al., 2006; Miller and Hargraves, 1996) and the Mahoba dykes (1113 Ma; Pradhan et al., 2012) of the Bundelkhand craton show good agreement with a with ~1100 Ma kimberlite rocks in the Dharwar craton (Venkateshwarlu and Chalapathi-Rao, 2013); however, other studies on kimberlites from the Wajrakarur field (~1100 Ma) show much steeper directions at odds with those from Bundelkhand (Venkateshwarlu and Chalapathi-Rao, 2013; Pesonen et al., 2012; Miller and Hargraves, 1996). For this review, we simply acknowledge the uncertainties regarding the

assembly of Peninsular India and urge restraint in the use of a unified Peninsular India in supercontinent models prior to Rodinia.

Assembly of the East Antarctic craton remains enigmatic due primarily to the lack of continuous exposure (Boger, 2011; Harley et al., 2013). There are several Archean/early Paleoproterozoic complexes exposed along the coast of East Antarctica (Grunehogna, Napier, Ruker, Vestfold Hills, Denman Glacier, Commonwealth Bay, Nimrod and Shackleton regions). Relationships between these nuclei both within East Antarctica and neighboring regions in Gondwana is problematic (Harley et al., 2013). Late Mesoproterozoic to Early Neoproterozoic tectonism (“Grenvillian”) was initially thought to mark the final assembly of East Antarctica, but the discovery of “Pan-African” age metamorphism along the margins of East Antarctica led some to propose that final assembly did not occur until the Late Ediacaran or Cambrian (Boger, 2011; Meert, 2003; Harley et al., 2013; Meert et al., in press). Boger (2011) outlined potential links of East Antarctica domains to their nearest neighbors in East Gondwana as having longer lived relationships. These links include the so-called “Mawson craton” (South Australia and the Commonwealth Bay, Nimrod and Shackleton complexes of East Antarctica); the Napier, Ruker, Denman Glacier and Vestfold Hills regions of East Antarctica with India; and the Grunehogna region of East Antarctica with southern Africa (fig. 5c). We propose the name “Mikkelsen block” for the Napier, Ruker, Denman Glacier and Vestold Hills (East Antarctica) connection with India after the discoverer of the Vestfold Hills region (captain Klarius Mikkelsen in 1935).

2.3 West Gondwana

Rogers (1996) and Rogers and Santosh (2002) included southern Africa (Zimbabwe and Kaapvaal) with East Gondwana. The super-craton “*Atlantica*” included the West African,

Congo/Kasai, Guyana, Brazilian, Sao Francisco and Rio de la Plata nuclei. These elements assembled during the 2.1-2.0 Ga interval according to the original Columbia model (Rogers and Santosh, 2002).

The Amazonian craton (fig. 6a) is composed of several smaller elements that grew over a protracted interval during the Paleo-Mesoproterozoic (Texeira et al., 2016; Tassinari et al., 2000) during the formation/breakup of Columbia and the assembly of Rodinia (Texeira et al., 2016; Rogers and Santosh, 2002). Tassinari et al. (2000) document evidence for the assembly of the Central Amazonian, Maroni-Itacaiunas, Ventauri Tapajos and Rio Negra-Juruena provinces between 2.3-1.6 Ga. The Rodonian-San Ignacio and Sunsas provinces are younger regions of the Amazonian craton that developed in the transitional interval between Columbia and Rodinia (Tassinari and Macambira, 1999; Tassinari et al., 2000; Texeira et al., 2016).

The Congo-Sao Francisco block (fig. 6b) is composed of the Sao Francisco, Gabon, Angola, Kasai and Tanzanian nuclei that were welded together during the Paleoproterozoic-Mesoproterozoic Transamazonian-Eburnean orogenic pulses (Texeira et al., 2000; Zhao et al., 2004; De Waele et al., 2008; Silveira et al., 2013). The Paleoproterozoic-aged Ubendian-Usagaran belts separate the Tanzanian craton from the highly re-worked Bangweulu Block. This is thought to reflect the Paleoproterozoic assembly of these two parts of the Congo craton at around 1.8 Ga.

Exposures of the Rio de la Plata craton are poorly exposed and its areal extent and tectonic history are enigmatic (Rapela et al., 2007). Hartmann et al. (2002) provided geochronological evidence for the Encatadas and Camboriu orogenies in the Early

Paleoproterozoic that they linked to the Transamazonian cycle (see also Rapela et al., 2007 and references therein).

Geological and paleomagnetic data preclude the existence of “Atlantica” prior to the Neoproterozoic (Saalman et al., 2007; Alkmim et al., 2001; D’Agrella-Filho et al., 2016; Gray et al., 2008) although there is evidence that elements of Atlantica may have longer lived connections (El Bahat et al., 2013; Texeira et al., 2013; Reis et al., 2013; Kouyate et al., 2013; D’Agrella-Filho et al., 2016; Texeira et al., 2016). The West African craton and portions of the Amazonian craton are featured in many Columbia models with Rio de la Plata commonly situated nearby (Kouyate et al., 2013; Saalman et al., 2007; Texeira et al., 2013; Reis et al., 2013; El Bahat et al., 2013; Texeira et al., 2016). The Congo and Sao Francisco cratons are positioned as an independent pair (i.e. not West Gondwana) until the Neoproterozoic assembly of West Gondwana (Gray et al., 2006; Cederberg et al., 2016).

2.4 North China, South China, Tarim Blocks

Rogers and Santosh (2002) did not include the North China Block, South China Block or Tarim in their Columbia supercontinent. They argued that although North China became a coherent craton around 1.8 Ga, rifting between 1.7 and 1.6 Ga removed the NCB from the assembling Columbia supercontinent. South China was not included on the basis that it was not fully formed until Rodinia assembly around 1.0 Ga and Tarim was not discussed.

In contrast, Zhao et al. (2004) placed the North China Block adjacent to the present-day western coast of Peninsular India. Zhao (2004) tentatively placed the South China Block (SCB) and Tarim sandwiched between Australia and Siberia although details for including Tarim and the SCB were scarce (see fig 2b).

Since then, numerous studies have identified major Paleoproterozoic tectonic events in the North China Craton with geological and geophysical evidence for subduction-accretion-collision (e.g., Santosh, 2010), involving major arc magmatism along the margins of crustal blocks (e.g., Yang and Santosh, 2015, and references therein) and ultrahigh-temperature metamorphism within collisional sutures (e.g., Santosh et al., 2012) associated with the assembly of the craton and its incorporation within Columbia.

3. Paleogeography of Columbia-Updated Status

The initial model forward by Rogers and Santosh (2002) was provided with no specific Euler rotation parameters although proposed linkages between various cratonic elements were discussed (see fig 2a). Meert (2002) provided Euler rotation parameters that approximated the configuration outlined by Rogers and Santosh (2002), but stressed that the available paleomagnetic data were too few to provide a rigorous test of the model. Over the past 15 years, the paleomagnetic database for the Paleo-Mesoproterozoic interval has vastly expanded such that initial paleomagnetic tests of the Columbia supercontinent are now available (Table 1).

Paleomagnetic data provide the only quantitative method for reconstructing supercontinents, but those data are not without flaws. For paleomagnetic data to be useful in paleogeographic models, several 'quality' criteria must be met (Van der Voo, 1990). Van der Voo (1990) introduced the "Q-factor" that is based on fulfillment of certain criteria in a paleomagnetic study. These include: (1) well-determined rock age and a presumption that magnetization is the same age; (2) sufficient statistics; (3) adequate demagnetization that demonstrably includes vector subtraction; (4) field tests that constrain the age of

magnetization; (5) structural control and tectonic coherence with craton or block involved. (6) The presence of reversals; (7) no resemblance to paleopoles of younger age. In principle, the higher the Q-factor, the greater is the likelihood that the remanence correctly reflects the ancient geomagnetic field at a certain time within a certain block. As noted by Van der Voo, the Q-factor should not be used solely as a reason to reject a pole, because a high Q value does not guarantee a primary magnetization nor does a low Q-value indicate that a pole is incorrect. Most modern paleomagnetic studies strive to meet two of the Q-checkboxes (sufficient statistical sampling and vector demagnetization). The remaining 5 criteria can be more difficult to fulfill although most paleomagnetists approach field and laboratory work with these in mind. It has been argued that the 7th point (i.e. resemblance to a younger paleopole) should be less important in evaluating Precambrian paleomagnetic data. The rationale is simple in that the likelihood that a continent occupied the same latitude and orientation increases with the amount of time available (Veikkolanien et al., 2014) although other studies note that resemblance to younger paleopoles should not be so readily dismissed when evaluating paleomagnetic data (Bazhenov et al., 2016).

We also note two other complications in evaluating paleomagnetic data in the Precambrian. The first is due to the symmetry of the dipolar field that results in any pole having an anti-pole. Thus, any paleomagnetic pole can be interpreted to position the continent in the southern or northern hemisphere (hemispheric ambiguity). The second issue also arises due to the symmetry of the field. Once a hemisphere has been chosen, the continent can be positioned at any longitude (longitudinal ambiguity). In a worst-case scenario (i.e. a single pole from each continent of interest), we may not be able to choose the proper hemisphere (for

latitude) or longitude. Given these sobering circumstances, we also note that paleomagnetism is rarely used in isolation and geological similarities are typically used in conjunction with the paleomagnetic data. In the ensuing discussion, we require that the paleomagnetic poles are well-dated and have a $Q \geq 3$. We then compare paleomagnetic poles from each craton to the Laurentian apparent polar wander path (APWP).

There are numerous approaches that can be used to reconstruct ancient supercontinents using paleomagnetic data. The simplest process involves using individual paleomagnetic poles for a given time slice. In this method, each continent is restored to its original latitude and orientation and then moved longitudinally into an assumed reconstruction (figs. 7a,b; 'closest approach'). The closest approach method requires a specific polarity choice for the paleomagnetic poles. The second method can be used if each block has paleomagnetic data that are reasonably spaced in time (ideally < 100 Ma between poles for the Meso-Paleoproterozoic). The poles can be assigned a polarity choice such that the lengths of the APWP's for each block are equivalent (figs. 7c,d). The APWP of one craton is then rotated so that it overlaps the other (fig. 7d). This method constrains the *relative* longitudinal distance between the two blocks. It is most relevant when the resultant overlay produces a fit that puts both blocks on the same plate with easily correlated geological connections.

Below, we examine the paleomagnetic data for the interval from ~ 1.7 - 1.8 Ga until ~ 1.2 Ga (Table 1). Our goal is not to provide rigid constraints on the Columbia reconstruction, but merely to give a status report. There are several publications that give an overly positive spin to the reconstruction of Columbia/Nuna (Evans and Mitchell, 2011; Zhang et al., 2012; Salminen et al., 2016) and others that present a more negative view on the status of the supercontinent

configuration (Pisarevsky et al., 2014; Meert, 2014). As an example, Pisarevsky et al. (2014) argue that paleomagnetic data support Columbia assembly between 1650-1580 Ma with connections between West Nuna (Laurentia, Baltica and India) and East Nuna (Australia, Mawson continent and North China) and perhaps Congo-Sao Francisco and Siberia joining at 1500 Ma. According to their model, Columbia was a short-lived supercontinent beginning with breakup between 1450-1380 Ma (50-120 million-year duration). Zhang et al. (2012) establish Columbia at ~1.75 Ga until about 1380 Ma. In the original Columbia proposal, Rogers and Santosh (2002, 2009) argue that Columbia formed in the 1.9-1.5 Ga interval (maximum packing around 1.5 Ga) with breakup commencing around 1.4 Ga. In a later paper that is consistent with the proposals by Zhao et al. (2002, 2003, 2004).

We caution that we are reporting the data available at present. It is likely that additional data will result in significant changes to Precambrian paleogeography. Thus, we encourage readers to view this as a status report.

3.1 Nena/Nuna Core

The Nena/Nuna core consists of cratonic Laurentia, Baltica, Siberia and perhaps parts of East Antarctica (figs. 3a,b). Evans and Mitchell (2011) analyzed data from Siberia, Laurentia and Baltica and argued for long-lived (1.9-1.3 Ga) coherence of the central core of the Columbia supercontinent (fig 8a). Their argument was based on the temporal agreement of paleomagnetic poles during that interval agree when rotated into their preferred configuration. It is important to note that there are large gaps (~100-300 Ma) in the database that may ultimately result in revision of that model. Additions to the 1.9 Ga central core include the Wyoming and Superior cratons in the 1.7-1.8 Ga interval (Killian et al., 2016). Ernst et al. (2016)

also argued that the Laurentia-Siberia connection might have persisted until ~720 Ma.

Salminen et al. (2009) suggested that the Baltica-Laurentia connection was valid until ~1.1 Ga.

Thus, current geological arguments would maintain the Nena/Nuna core (Siberia, Laurentia, Baltica) throughout the Mesoproterozoic interval. If the assumptions of Ernst et al. (2016) are correct, then both Columbia and Rodinia share the same Siberia-Laurentia connection and Baltica would change positions only slightly during the Columbia-Rodinia transition (see also Stearn and Piper, 1984; Roberts, 2013). This 'strange attraction' between Laurentia, Siberia and Baltica was noted by Meert (2014). Piper (2000) also maintained Paleoproterozoic-Mesoproterozoic relationships between Laurentia, Baltica and Siberia in his Paleopangea configuration which differs from Columbia in that Siberia is positioned against the present-day western margin of Laurentia in a similar fit to the one proposed by Sears and Price (1978).

Figure 8b shows available poles for Laurentia from 1740 Ma to 1237 Ma ($Q > 3$ with radiometric ages; Table 1). The apparent polar wander path (APWP) is shown as a time progression of poles and has several gaps between data points in excess of 100 million years. Euler Rotation parameters for the 'Nuna Core' elements (Siberia, Laurentia and Baltica) are given in table 1 and illustrated in figures 8c,d (fits according to Roest and Srivastava, 1989; Evans and Pisarevsky, 2008; Evans and Mitchell, 2011). We acknowledge that there are other possible rotation parameters, but note that all will display similar levels of incongruence between poles. Limited paleomagnetic data from Siberia are consistent with the configuration shown in our reconstruction at 1.5 Ga and is less precise at 1.38 Ga (fig. 8c). The comparison between Baltica and Laurentia (fig 8d) shows reasonable agreement during the ~1.59-1.27 Ga

interval, but with a wide scatter of poles before 1.59 Ga. Based on these limited data, confidence in a Nuna core assembly is presently restricted to the 1.5-1.38 Ga interval. Even during the intervals where the fit appears congruent, gaps between data points may exceed 200 million years.

3.2 Amazonia and Australia

Figure 9a-d shows available paleomagnetic data from Amazonia (figs 9a,b; Table 1) and Australia (figs 9c,d). For Amazonia, the poles were rotated into the Laurentian frame using the Euler pole in Salminen et al. (2016). Australian poles were rotated to Laurentia using Euler parameters described by Payne et al (2009) and Evans and Mitchell (2011). These data show significant differences from the Laurentian APWP with the exceptions of ~1440 Ma poles (Amazonia) along with ~1730 Ma and 1545 Ma poles (Australia) although the 1545 Ma pole from Australia may have been remagnetized (Schmidt and Clark, 2011).

Neither of the paleomagnetically controlled reconstructions are particularly convincing and different positions should be considered for both Australia and Amazonia within Columbia. We have evaluated several of these alternatives (see Salminen et al., 2016; Pisarevsky et al., 2014) and find that while some aspects of the APWP improve, a misfit balances these improvements elsewhere along the APWP. The range of options for positioning Australia and Amazonia is equally problematic when using geological data.

3.3 India

Paleomagnetic data from India are limited with only 3 well dated poles for the time interval of interest (see Table 1; Figs 10a,b,c). We have added paleomagnetic data from the

poorly dated (~1.8 Ga) Gwalior Traps and Sills (see Pradhan et al., 2010) for reference only. Due to these limited data, the position of India is problematic. In figures 10a,b, we position India according to Zhang et al. (2012) off the western margin of Laurentia. None of the paleomagnetic data from India fall along the Laurentian APWP in the Zhang et al. (2012) configuration making this a less likely position for India. In figures 10c and 10d, we use a rotation that gives the best fit between ~1465 Ma and 1200 Ma poles for the southern Indian Blocks (SIB; Figure 8g) to the Laurentian APWP. The 1465 Ma Lakhna pole falls within a grouping of similar-age poles from Laurentia whereas the 1192 Ma pole falls some 30 degrees displaced from similar-aged poles. To accommodate this particular reconstruction, India must be placed at a considerable distance from Laurentia making it unlikely that both continents are occupying the same plate. Figures 10e and 10f, the Lakhna pole is rotated to Laurentia coordinates and the resultant reconstruction places India off present-day northeastern Laurentia and potentially close to Baltica. A similar fit was proposed by Pisarevsky et al. (2014).

3.3 Congo-Sao Francisco, North China and Rio de la Plata

Paleomagnetic data are limited for these three nuclei (figs. 11a,b; Table 1) and the comparisons made in this paper follow previously published conjectures. When compared to the Laurentian APWP, all three blocks are significantly displaced in terms of relative longitude. The Congo-Sao Francisco and North China Block have Mesoproterozoic poles of ~1450 Ma age that are discussed below in our assessment of the Columbia supercontinent at ~1450-1500 Ma.

3.4 The Columbia Supercontinent

The available paleomagnetic data are insufficient to rigorously test Columbia configurations for any extended interval of the Paleo-Mesoproterozoic range from ~1.8-1.3 Ga. That is not surprising given the limited dataset available. Rogers and Santosh (2002) argued that maximum packing of the supercontinent likely occurred around 1.5 Ga. Fortunately, many of the cratonic nuclei have paleomagnetic data in the 1.5-1.4 Ga interval and we can evaluate those in the context of various models. Figure 12 provides one possible reconstruction of Columbia based on these paleomagnetic data. We draw from previous publications and make small adjustments to provide our view of the Columbia supercontinent at ca. 1450 Ma. According to Rogers and Santosh (2002), this is the period of maximum packing preceding breakup. Continents without paleomagnetic data are not shown in the reconstruction (Kaalvaal, Zimbabwe, West Africa, East Antarctica, South China, Tarim). Although these blocks are typically featured in Columbia proposals (see Zhao et al., 2002, 2003, 2004), we do not position them in our reconstruction.

4. Conclusions

The proposal forwarded by Rogers and Santosh (2002) posited the existence of a Mesoproterozoic supercontinent which they called “Columbia”. The moniker was chosen based on a proposed connection between eastern India and the Columbia basalts region of North America (NW Laurentia). The speculation invigorated research into the Paleo-Mesoproterozoic interval that was, in our opinion, inappropriately dubbed ‘the boring billion’. Given the wealth of new data about Columbia, this review paper reports on the paleomagnetic evidence that is used to reconstruct Columbia. Our contribution represents a status report and indicates that; despite the exponential increase in available

paleomagnetic and geochronological data, knowledge of the assembly, duration and breakup history of the supercontinent are contentious. The commonality of ~1.7-2.1 Ga orogenic systems around the globe are indicative of major changes in paleogeography and growth of larger landmasses. There is continued discussion about the interconnectedness of those orogenic systems in a global picture and the tectonic setting of these orogenic belts (i.e. intra- or inter-cratonic in nature). Arguments for Columbia posit a ~1500-1400 Ma age for maximum packing. Paleomagnetic data from many of the constituent cratons during that interval can be interpreted to support a large landmass, but the consistency of the proposal cannot be reliably demonstrated for earlier or later times. One of the more intriguing advances are the apparent long-lived connections between Laurentia, Siberia and Baltica that may have formed the “Nuna” core of both Columbia and Rodinia. In our review of the models for both Columbia and Rodinia, it is apparent that the supercontinents resemble one another. If that resemblance represents a bias or some fundamental signal about Proterozoic tectonics remains an open question. Lastly, we acknowledge that our review is based mostly on paleomagnetic arguments and that there are subtle (and not so subtle) differences in Columbia reconstructions generated using different data sets.

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Figure Legends

Fig 1: (a) Pangea; (b) detrital zircon record (reference); (c) Rodinia after McMenamin and McMenamin (1990)

Fig 2: (a) Columbia after Rogers and Santosh (2002); (b) Columbia after Zhao et al. (2002).

Fig. 3: (a) Sketch of the Laurentian mega-craton showing the location of Archean nuclei and orogenic belts (see Meert, 2012 and references therein); (b) Map of the Baltica mega-craton with the various nuclei and orogenic belts (after Bogdanava et al., 2008); (c) map of the Siberian craton after Gladkochub et al. (2006).

Fig 4: (a) Nena after Rogers (1996); (b) Nuna after Hoffman (1997).

Fig. 5: (a) Sketch map of the Australian craton outlining the south Australian, north Australian and West Australian cratons (Cawood and Korsch, 2008); (b) Map of India showing major cratonic nuclei, intervening mobile belts and Precambrian sedimentary basins (after Meert and Pandit, 2015); (c) Antarctica connections (after Boger, 2011) with adjacent regions of Gondwana including the Mawson craton and the Mikkelsen block.

Fig 6: (a) Map of the Amazonian craton with geochronological provinces associated with Amazonian assembly (Tassinari and Macambira, 1999); (b) The makeup of the Congo-Sao Francisco cratons with Paleo-Neoproterozoic mobile belts (De Waele et al., 2008).

Fig 7: (a) Paleomagnetic poles from two continental regions as measured in their own reference frame; (b) continents reconstructed according to the paleomagnetic poles in 5a using the north polarity option; (c) hypothetical apparent polar wander paths (APWP's) for two continents in their own reference frame; (d) combined APWP made by rotating block 2 to block 1. In this case, relative paleolongitudes are fixed.

Fig 8: (a) Nuna core following rotation parameters given in Table 1; (b) APWP for Laurentia using poles in Table 1; (c) Siberian poles (green) rotated to the Laurentian reference frame (red) using parameters listed in Table 1. (d) Baltica poles (blue) rotated to the Laurentian frame using poles in Table 1. Note filled green and blue poles have good spatial and temporal fits with the Laurentian reference path.

Fig 9: (a) Amazonian poles (light grey) rotated to the Laurentian framework using parameters listed in Table 1; (b) Paleogeographic fit of Amazonia to Laurentia using rotation parameters listed in Table 1; (c) Australian poles (orange) rotated to the Laurentian framework (Table 1); (d) Paleogeographic fit of Australia and Laurentia with Australia rotated to Laurentia. Filled light grey and orange poles have good spatial and temporal fits with the Laurentian reference path.

Fig 10: (a) South Indian block paleomagnetic poles (green) rotated to the Laurentian framework using rotation parameters option A in Table 1; (b) paleogeographic fit of India to Laurentia based on 8a; (c) South Indian block paleomagnetic poles rotated to the Laurentian framework using Option B, Table 1; (d) paleogeographic fit of south Indian blocks to Laurentia based on 8c; (e) South Indian block paleomagnetic poles rotated to the Laurentian framework using Option

C, Table 1; (f) paleogeographic fit of the south Indian block to Laurentia based on 8e. Filled green poles have good spatial and temporal fits with the Laurentian reference path.

Fig 11: Congo-Sao Francisco (purple), North China Block (pink) and Rio de la Plata (light blue) poles rotated to the Laurentian framework using parameters listed in Table 1; (b) Paleogeographic fit of Congo-Sao Francisco, Rio de la Plata and the North China Block to Laurentia using rotation parameters listed in Table 1; filled purple, pink or light blue poles have good spatial and temporal fits with the Laurentian reference path.

Fig 12. 1450 Ma reconstruction of Columbia using paleomagnetic data listed in Table 1. Rotation parameters are as follows (Euler pole latitude, longitude, rotation angle where - clockwise, +counterclockwise). Laurentia; 0°, 307°, -101.4°; Baltica; 1.4°, 94.6°, +90.8°; Siberia; 31.5°, 59.9°, +175°; Amazonia; 54.1°, 60.7°, +87.8°; India; 15.8°, 12.2°, -134.5°; Australia; 0.8°, 90.6°, -174°; Sao Francisco 43.2°, 188.8°, -177.7°; Congo; 27.5°, 217.3°, +175.8°; North China Block; 5.9°, 108.4°, +83°.

Author Vitae

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Pangea (~260 Ma)

(a)

Rodinia (McMenamin and McMenamin, 1990)

(b)

(c)

(a) **Columbia**
(Rogers & Santosh, 2002)

(b)

"Columbia"
(Zhao et al., 2004)

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Australia (Cawood and Korsch, 2008)

(a)

India (Meert and Pandit, 2015)

(b)

Basin Names: MB=Marwar Basin; VB=Vindhyan Basin; ChB=Chhattisgarh Basin; CuB=Cuddapah Basin; KBB=Kaladgi-Bhima Basin; IB=Indravati Basin | **Tectonized Regions:** NSL=Narmada-Son Lineament; AFB=Aravalli Fold Belt; DFB=Delhi Fold Belt; CIS=Central Indian Suture; CITZ=Central Indian Tectonic Zone; SMB=Satpura Mobile Belt; EGMB=Eastern Ghats Mobile Belt; PCSZ=Palghat-Cauvery Shear Zone; KGB=Karimnagar Granulite Belt; BPG=Bhopalpatnam Granulite Belt | **Other Abbreviations:** CG=Closepet Granite; WDD=Western Dharwar Domain; EDD=Eastern Dharwar Domain; SIB=Southern Indian Blocks (Dharwar, Bastar and Singhbhum); NIB=Northern Indian Blocks (Aravalli-Bundelkhand)

Antarctica (Boger, 2011)

(c)

Amazonian Craton (Tassinari and Macambira, 1999)

Congo-Sao Francisco (De Waele et al., 2008)

Amazonian Poles

Laurentian Poles

Australia Poles

Laurentian Poles

(a) ■ SIB India Poles ■ Laurentian Poles

(c)

(e)

(b)

(d)

(f)

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**Paleomagnetically Permissible
Columbia Reconstruction at
1450 Ma**