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Focus paper

The boring billion? – Lid tectonics, continental growth and environmental change associated with the Columbia supercontinent

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ABSTRACT

The evolution of Earth's biosphere, atmosphere and hydrosphere is tied to the formation of continental crust and its subsequent movements on tectonic plates. The supercontinent cycle posits that the continental crust is periodically amalgamated into a single landmass, subsequently breaking up and dispersing into various continental fragments. Columbia is possibly the first true supercontinent, it amalgamated during the 2.0–1.7 Ga period, and collisional orogenesis resulting from its formation peaked at 1.95–1.85 Ga. Geological and palaeomagnetic evidence indicate that Columbia remained as a quasi-integral continental lid until at least 1.3 Ga. Numerous break-up attempts are evidenced by dyke swarms with a large temporal and spatial range; however, palaeomagnetic and geologic evidence suggest these attempts remained unsuccessful. Rather than dispersing into continental fragments, the Columbia supercontinent underwent only minor modifications to form the next supercontinent (Rodinia) at 1.1–0.9 Ga; these included the transformation of external accretionary belts into the internal Grenville and equivalent collisional belts. Although Columbia provides evidence for a form of 'lid tectonics', modern style plate tectonics occurred on its periphery in the form of accretionary orogens. The detrital zircon and preserved geological record are compatible with an increase in the volume of continental crust during Columbia's lifespan; this is a consequence of the continuous accretionary processes along its margins. The quiescence in plate tectonic movements during Columbia's lifespan is correlative with a long period of stability in Earth's atmospheric and oceanic chemistry. Increased variability starting at 1.3 Ga in the environmental record coincides with the transformation of Columbia to Rodinia; thus, the link between plate tectonics and environmental change is strengthened with this interpretation of supercontinent history.

1. Introduction

The formation of supercontinents in the Earth's past is intrinsically linked with the evolution of the lithosphere, biosphere, atmosphere and hydrosphere (e.g. Worsley et al., 1985, 1986; Campbell and Allen, 2008; Santosh, 2010; Piper, 2013b; Young, 2013b). The concept of the supercontinent cycle, i.e. amalgamation and dispersal of continents, is based on evidence from the most recent supercontinents, e.g. Pangaea, Gondwana and Rodinia (see Nance et al., 2013 for a review). Tracing the supercontinent cycle back though deeper time leads to increasing difficulty, since the rock record becomes more fragmentary, rock units become more deformed, and the ability to constrain palaeopoles diminishes. Columbia (preferred name to Nuna; Meert, 2012), is perhaps the first true supercontinent (Senshu et al., 2009); its amalgamation is evident from the numerous collisional orogenic belts that can be found across most continental fragments with ages of 2.0–1.7 Ga. Maximum packing of this continent occurred at 1.9–1.85 Ga based on a peak of ages of collisional orogenesis (Rogers and Santosh, 2009), but amalgamation may have lasted until 1.6–1.5 Ga (Cutts et al., 2013). The configuration of Columbia is still debated due to a lack of well-constrained palaeopoles from the same period across all continental fragments (e.g. Evans and Mitchell, 2011). One key correlation that exists in nearly all configurations, is the connection between

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Laurentia (North America and Greenland), and Fennoscandia, known as the NENA connection (Gower et al., 1990). Break-up of the Columbia supercontinent is postulated to have occurred at 1.25–1.35 Ga, inferred from ages of dyke swarms (Hou et al., 2008b; Zhang et al., 2009b), but may have started as early as 1.6 Ga (Zhao et al., 2004), or even as early as 1.8 Ga (Senshu et al., 2009). Increasingly, however, it is becoming evident that this supercontinent may not have broken-up and dispersed fully; only partially breaking up before re-amalgamating into the next supercontinent Rodinia (Bradley, 2011; Evans and Mitchell, 2011).

The supercontinent cycle has been linked to patterns of crustal growth. Peaks in U–Pb crystallisation ages as well as juvenile granitoid ages correlate with the periods of supercontinent formation (Condie, 2004; Rino et al., 2004; Condie and Aster, 2010). This was suggested to be a consequence of events related to mantle convection, i.e. slab avalanches (Condie, 1998). More recently however, it has been suggested that the correlation represents preservation bias inherent in the supercontinent cycle (Hawkesworth et al., 2009; Cawood et al., 2013; Condie et al., 2011), whereby volumes of crust generated are greatest along subduction margins, but preservation of crust generated in collisional orogens is greater. Continental crust is largely formed at convergent margins, i.e. accretionary orogens (Cawood et al., 2009; Clift et al., 2009; Stern and Scholl, 2010). As well as being constructed at these margins, continental crust is also lost, via tectonic erosion, subduction erosion and sediment subduction (see Stern, 2011 for a review). The balance between growth and loss of continental crust across the globe at present is estimated to be roughly equal, or slightly in favour of greater loss (Scholl and von Huene, 2009; Stern and Scholl, 2010; Stern, 2011); since continental crust has grown over time since the Hadaean (Belousova et al., 2010; Hawkesworth et al., 2010), this balance must have favoured growth rather than loss for most of Earth's history. A deviation in calculated growth curves suggests growth was quicker up to 3.0 Ga (Dhuime et al., 2012). As well as decreasing over time, the balance between growth and loss will change in relation to the supercontinent cycle. Periods of supercontinent break-up will feature the greatest continental growth due to magmatism at retreating accretionary orogens and continental rift zones, and periods of supercontinent amalgamation will feature greatest loss, due to the increase in compressional accretionary orogens and collisional zones that host a greater volume of recycling into the mantle (Stern and Scholl, 2010; Yoshida and Santosh, 2011). This correlation was tested with a global compilation of zircon U–Pb–Hf data, using the Hf trend through time as a proxy for continental growth versus loss (Roberts, 2012); the data are compatible with increased continental loss during formation of Columbia, and increased growth during the subsequent ~500 million year period.

The period from ~1.85 to 0.85 Ga has been referred to as the 'boring billion' (Holland, 2006), and more recently 'barren billion' (Young, 2013a); this results from the lack of climatic events or dramatic changes in ocean and atmosphere composition. Tectonically, this period is far from boring, since it involved the formation of the Columbia supercontinent at its onset, and the formation of the Rodinia supercontinent during its latter half. What does seem apparent, however, is a lack of dramatic events within the earth system between ~1.7 Ga and 1.2 Ga, thus, there may be some coincidence between the tenure of the supercontinent Columbia, and the stability of the ocean and atmospheric systems. This paper looks at the Columbia supercontinent in terms of its age and tenure, mechanisms by which it broke up and formed the next supercontinent Rodinia, the plate tectonic regime and associated crustal growth during these events, and the correlation to other earth systems.

2. The Columbia supercontinent

Since its conception (Rogers and Santosh, 2002), numerous variations on Columbia palaeogeographies have been postulated. Two examples that are well-cited in the literature are those of Zhao et al. (2004) and Hou et al. (2008a), the core of these both feature well-known Laurentia, Baltica, Siberia and Australia connections. Many other palaeogeographic reconstructions use these continents at their core, but feature variable positions of other cratons, for example Congo (Ernst et al., 2013), India (Kaur et al., 2013; Pisarevsky et al., 2013), and North China (D'Agrella-Filho et al., 2012; Zhang et al., 2012). New palaeomagnetic poles are being published each year, which should eventually lead to some consensus on Columbia's palaeogeography. Fig. 1 shows four different recent Columbia reconstructions. The reconstruction of Piper (2013a,b) is based on a large database of palaeopoles, and constraints are not biased towards well-known geological connections. Some connections, such as Laurentia, Siberia, Baltica and Australia remain, but Amazonia resides on the other side of the supercontinent to Baltica. The reconstruction of Yakubchuk (2010) is also based on a large database of palaeopoles, but linkage between Grenvillian belts and Palaeoproterozoic belts is taken into consideration. The reconstruction of Zhang et al. (2012) is modified from that of Evans and Mitchell (2011), with new data from North China, and this original reconstruction is based on a rigorous critique of palaeopoles; because of this, many cratons are not included. The reconstruction of Kaur and Chaudhri (2013), is modified from that of Hou et al. (2008a), based on geological interpretations of Indian and Chinese cratons. A key difference in making reconstructions is that some are dominated by palaeomagnetic information, and some are based largely on geological interpretations. It is evident that both will need to be taken into account to provide all-inclusive and testable reconstructions that stand the test of time.

Common to nearly all Columbia configurations are the correlation of 1.8–1.3 Ga accretionary belts found across southern Laurentia, Southwest Fennoscandia and western Amazonia; the geological correlation of these belts was discussed by Johansson (2009) and named the SAMBA connection. In the Kaur and Chaudhri's (2013) type reconstruction, this margin is extended through India, North China and East Australia. Zhang et al. (2012) also noted the accretionary margin in North China, but do not extend it through Australia. However, although there is a difference in accretionary style, this margin is postulated to have extended from South Laurentia, to East Australia (Mawsonland) for at least the early part of Columbia's life (Betts et al., 2008). Thus, in the Zhang's reconstruction, the accretionary margin can be drawn around a large proportion of the included continents. Some continents lack evidence for this accretionary margin, i.e. Siberia, thus the accretionary margin may not have surrounded the entire supercontinent, and may even have been more one-sided (Fig. 1D). If we think of a modern example, this may represent something like the Americas, with the active Pacific margin on the west, and the passive Atlantic margin on the east. If we take this analogy further, then we can compare this long-lived accretionary belt with the entire Pacific rim. In this latter analogy, it is interesting to consider whether parts of the margin may represent an Andean-type margin (i.e. dominantly advancing accretionary orogeny; Cawood et al., 2009), or a Pacific-type margin (i.e. dominantly retreating accretionary orogeny).

3. Break-up

The break-up history of Columbia remains uncertain. Many authors have recorded mafic magmatism, typically as dykes, but sometimes as larger bodies, and felsic intrusions, and related these

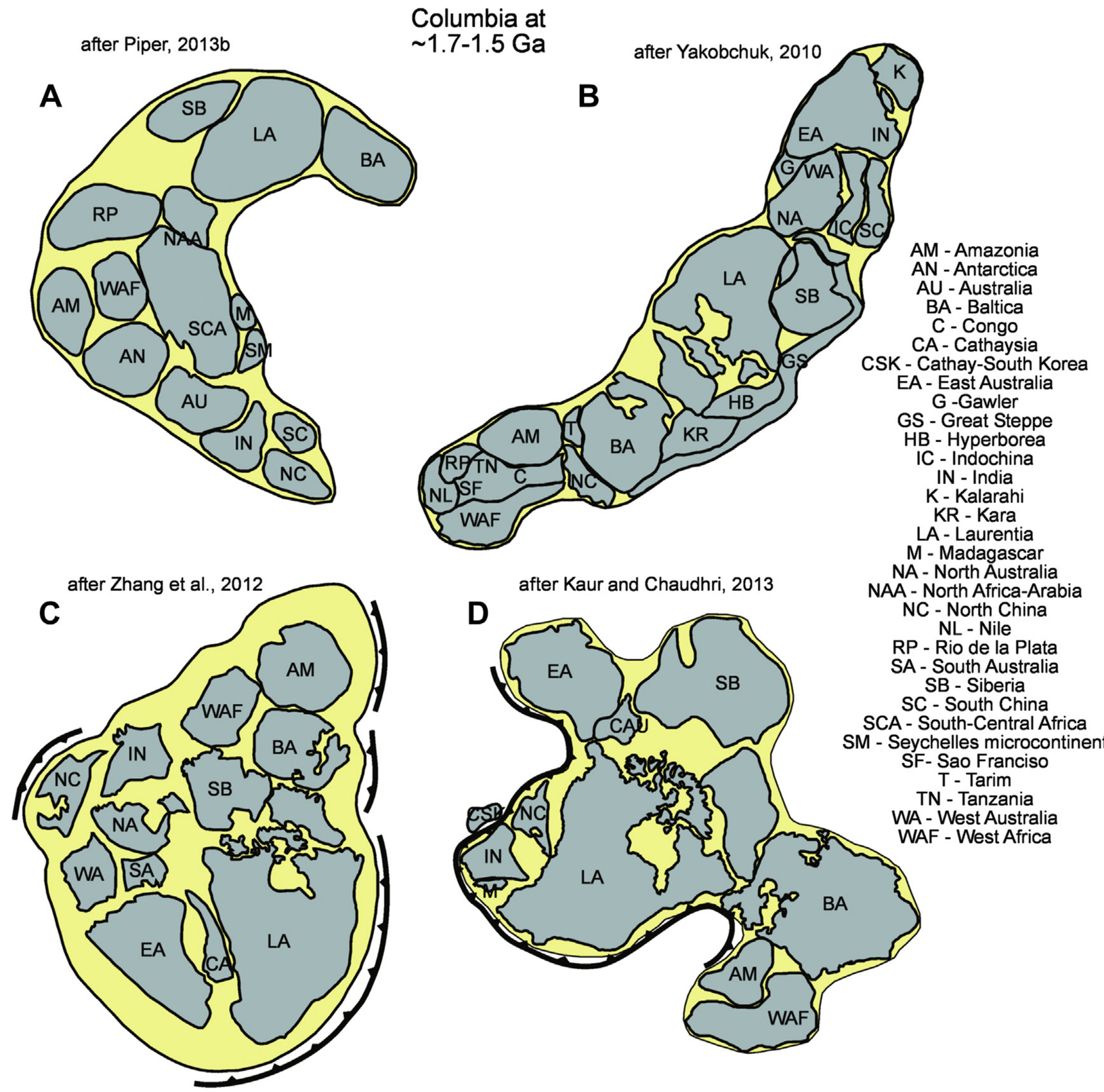

Figure 1. Palaeogeographic reconstructions of Columbia in the 1.7–1.5 Ga timeframe, after Piper (2013b), Yakubchuk (2010), Zhang et al. (2012) and Kaur and Chaudhri (2013). The subduction margin in C and D shows the approximate location of 1.8–1.3 Ga accretionary belts.

to possible break-up of the supercontinent. Dyke swarms occur in the 1.38–1.24 Ga period across many continents (e.g. Ernst et al., 2008 and references within; Hou et al., 2008b; Zhang et al., 2009b; Goldberg, 2010; El Bahat et al., 2012; Puchkov et al., 2013). These include large swarms such as the MacKenzie dyke swarm that are advocated as plume-related (Hou et al., 2008b). Earlier mafic intrusions are also found across many cratons of variable age, for example in South America at 1.59, 1.5 and 1.4 Ga (Bispo-Santos et al., 2012; Silveira et al., 2013; Teixeira et al., 2013), at 1.5 Ga in South China (Fan et al., 2013), at 1.46 Ga in India (Pisarevsky et al., 2013), and at 1.45 Ga in Baltica (Lubnina et al., 2010). Although, the continents record various episodes of mafic magmatism typically related to extensional tectonics, it is not clear that these provide evidence for break-up of the supercontinent Columbia. Some examples of the dykes, for example the 1.3–1.2 Ga dykes in Southwest Baltica, have been studied geochemically and isotopically, and interpreted as manifestations of active margin tectonics (Söderlund et al., 2005). These mafic intrusions thus relate to extensional tectonics associated with a convergent margin; the mafic dyke swarms may represent extension of brittle crust, whereas volcanosedimentary basins closer to the inferred convergent margin are interpreted as reflecting extension in warmer more mobile crust (Roberts et al., 2011). Another example where the dyke swarm is hypothesised to be unrelated to a mantle plume and supercontinent break-up is the Sudbury dyke swarm in Laurentia (Shellnutt and MacRae, 2012). Thus, many dyke swarms that occur towards craton margins rather than deep interiors may also be a consequence of plate-margin related processes – and not to the break-up of the supercontinent. The extent of this across the temporal and spatial range of dykes within Columbia remains to be investigated.

The evidence for break-up based on dyke swarms suggests rifting and extension throughout most of Columbia's lifespan. As a continental rift matures, it will eventually lead to passive margin sedimentation on its flanks. The record of passive margins throughout earth history has been investigated by Bradley (2008, 2011), and is shown in Fig. 4. Passive margin abundance is very low during Columbia's tenure, and start dates that would record the rifting of continents are non-existent until one at 1.25 Ga in North Laurentia and three at 1.0 Ga in East Baltica and South Siberia that coincide with Rodinia formation. This line of evidence suggests that Columbia didn't break-up into dispersed continents, as this would produce a large increase in passive margins.

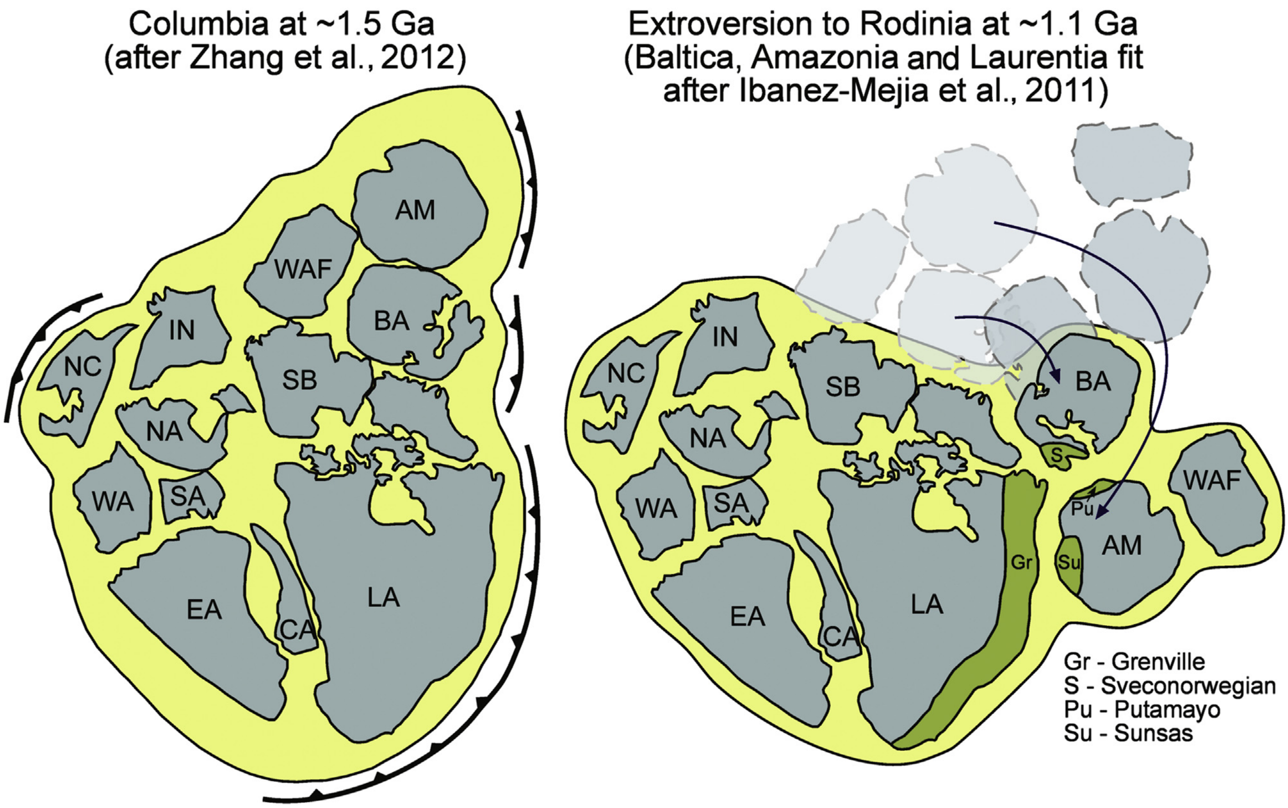

Figure 2. Simplified model for extroversion of Columbia into Rodinia. The movement of Baltica, Amazonia and the West African cratons is shown, but any potential movement of the cratons on the opposing side of Laurentia is omitted for simplicity.

Palaeomagnetic data also provide evidence that Columbia, or at least many of its cratonic components, were juxtaposed for much of the Mesoproterozoic, until at least 1.3 Ga. For example, palaeomagnetic data suggest Australia and Laurentia were contiguous from 1730 to 1595 Ma, but also allow for a continued association until ~1200 Ma (Payne et al., 2009). Siberia is linked with movements of Laurentia and Baltica from ~1600 to 1200 Ma (Salminen and Pesonen, 2007; Wingate et al., 2009; Lubnina et al., 2010; Pisarevsky and Bylund, 2010). North China also has a polar wander path compatible with connection to Laurentia–Siberia/Baltica to 1.35 Ga (Wu et al., 2005). Piper (2010, 2013a,b) takes this evidence to the extreme, suggesting that Columbia was a quasi-integral supercontinent for the entire period between 2.7 and 0.6 Ga. The palaeomagnetic record can be used to construct an estimate of plate velocity (Piper, 2013b), which during Columbia's lifespan records a period of low velocity (see Fig. 4). Thus, both the geological record and the palaeomagnetic evidence are indicative of a stable Columbia supercontinent from its formation at ~1.9 to ~1.3 Ga, whereupon continental movements may have increased.

4. Transformation to Rodinia

The Rodinia supercontinent that formed at 1.1–0.9 Ga, after Columbia's lifespan, also has a debated palaeogeographic configuration (e.g. Li et al., 2008). Except for Evans' (2009) and Pipers' (2013a,b) reconstruction, in which the Grenville belt originates as an exterior accretionary orogen, all reconstructions feature the Grenville Province as an interior orogenic belt within the centre of the supercontinent. This orogenic belt is typically extended into the Sveconorwegian domain on Fennoscandia, although structural evidence in Laurentia (Gower et al., 2008), and a re-interpretation of the Sveconorwegian orogen as non-collisional (Slagstad et al., 2013), suggest this may be an oversimplification. The Grenville belt is traditionally opposed to the Sunsas orogen of Amazonia (e.g. Tohver et al., 2002; Li et al., 2008), and the recently defined Putumayo orogen in Amazonia may have faced Baltica (Ibanez-Mejia et al., 2011). Since correlation of the Grenville–Sveconorwegian–Putumayo–Sunsas domains may have existed in the Columbia configuration also, it seems apparent that these continental fragments may have been adjacent throughout both the Columbia lifespan and Rodinia formation. To form the collisional Grenville belt, Fennoscandia and Amazonia must have rotated around so that they face each other, rather than facing the same ocean. This rotation is described by Yakubchuk (2010); in this model, in addition to the Laurentia/Baltica/Amazonia fragments (i.e. SAMBA) rotating around, the adjoined fragments that make up the rest of Columbia while remaining intact, also rotated around. Hence, supercontinents in this model are made up of various continental supergroups that appear to have remained intact for much of earth history; which fits with the quasi-integral continental lid hypothesis of Piper (2013a,b) also. Others have also noted the similarity between Columbia and Rodinia, and have suggested a lack of large-scale re-configuration between their formation (Evans and Mitchell, 2011), or have argued that the lack of evidence for continental movements in the geological record is indicative of this (Bradley, 2011).

It has been established that supercontinents may form by two end-member processes: introversion, where oceanic spreading along interior orogens is transformed to collision along the same orogens, and extroversion, where exterior accretionary orogens are transformed into interior collisional orogens (Murphy and Nance, 2003, 2013; Murphy et al., 2009). An addition to this, is a recent model of orthoversion (Mitchell et al., 2012), whereby a supercontinent forms orthogonal to its predecessor supercontinent, along the great circle defined by the subduction zones that encircle the previous supercontinent. This may represent a form of introversion if interior oceans are consumed to produce the collisional belts. The rotation of two large blocks (i.e. Nena and Atlantica), such that their exterior accretionary orogenic belts became an interior orogenic belt (i.e. Grenville), is compatible with a model of extroversion for Rodinia's formation (see Fig. 2). The history of the Ur continents, i.e. South Africa, India, Australia and Antarctica is less constrained. But based on evidence already discussed, it appears that any rapid movement required to form the Rodinia supercontinent from the Columbia supercontinent most likely happened after ~1.25 Ga.

What drives supercontinents to break-up and re-form is an ongoing debate and won't be discussed here; however, it has been approached from a variety of modelling techniques and studies of mantle behaviour (e.g. Gurnis, 1988; Condie, 1998; O'Neill et al., 2007; Zhong et al., 2007; Santosh et al., 2009; Senshu et al., 2009; Zhang et al., 2009a; Yoshida and Santosh, 2011). A process that features in many models is that of superupwellings and superdownwellings; the former can be thought of as superplumes. Supercontinents form at superdownwellings, and break-up when located over superupwellings (or geoid highs). Another concept is that of Y-shaped subduction zone junctions (Santosh et al., 2009). Where large subduction systems intersect these junctions, a downwelling of subducting slabs forms that refrigerates the mantle and in turn increases the convective downwelling; on the surface all continental materials are drawn together to form a supercontinent. What caused the shift from Columbia to Rodinia remains speculative. In the model of extroversion proposed here (Fig. 2), a downwelling may have occurred between Fennoscandia and Laurentia, such that these continents were dragged around and together. The opposing model would be that a geoid high developed over a superupwelling, and that this rifted the continents apart so that they could re-amalgamate over a geoid low. Given the tight rotation of the Baltica–Amazonia–Africa cratons recorded in most reconstructions, this scenario seems unlikely since the upwelling and downwelling would be very closely spaced. With increasing confidence and evidence for Columbia and Rodinia reconstructions, these hypotheses will become more amenable for testing.

5. Crustal growth

The record of continental growth has been linked to the supercontinent cycle. One group of models indicate that crustal growth is increased during formation of supercontinents due to increasing convergent margin magmatism and/or plume-related magmatism (e.g. Stein and Hofmann, 1994; Condie, 1998; Rino et al., 2004; Parman, 2007). Another opposing model suggests that crustal growth should decrease during supercontinent amalgamation, and increase during break-up (Stern and Scholl, 2010; Yoshida and Santosh, 2011). Finally, the record of continental growth is suggested to be biased, such that preservation of continental crust is greatest during supercontinent amalgamation (Hawkesworth et al., 2009; Cawood et al., 2013). Roberts (2012) suggested that the primary control of continental growth is defined by the extent of interior collisional orogenesis, to that of exterior accretionary orogenesis. The latter will feature greater crustal growth, and the former greater crustal recycling and loss. The secondary control is then defined as the ratio of advancing accretionary orogens, to those that are retreating, since the latter will feature greater volumes of new juvenile continental growth than the former (Roberts, 2012). Using detrital zircon Hf isotope data as a proxy for continental growth, Roberts (2012) showed that continental growth appears to be greater during periods of supercontinent break-up; however, one problem with this proxy, is that it shows relative changes in continental growth, but not absolute.

Fig. 3 shows a compilation of global detrital Hf data, and the derived growth curves based on mean and median trends from Roberts (2012). A distinct feature of this database, and of all detrital compilations (e.g. Belousova et al., 2010; Iizuka et al., 2010; Dhuime et al., 2012), is that the time period of Columbia's tenure (i.e. ~1.7–1.2 Ga), features a large proportion of juvenile (i.e. >CHUR) values, and a lack of evolved (i.e. <CHUR) values. Based on the concepts outlined in Roberts (2012), this is compatible with a lack of interior orogenic belts that involve large degrees of recycling of older crust, and of a greater ratio of retreating to advancing accretionary orogens. This also fits the observations of Collins et al. (2011), in that the increasing trend in ε_{Hf} is compatible with Pacific-type exterior margins. Accepting the caveats with this over-simplified approach, it appears that Columbia, although not breaking up till late in its history, was associated with an increase in continental growth rate after its formation.

Does an increase in continental growth rate relate to an actual increase in continental volume? Current thinking indicates that loss of continental crust back to the mantle is just as prevalent today as the growth of new continental crust (e.g. Clift et al., 2009; Scholl and von Huene, 2009); extrapolating the balance back through time between these processes remains elusive, since proxies for continental loss and growth lack absolute abundances. To help resolve this issue for the Columbia scenario, it is pertinent to return to the geological record. The detrital record is dominated by zircons derived from increasingly juvenile sources, this is compatible with the large accretionary orogenic system that wrapped around much of the supercontinent (see Fig. 1C and D). As this accretionary margin retreated away from the continents, it would have enabled growth of new continental crust in volcanic arcs. Arc terranes would have accreted to the supercontinent during periods of trench advance, or in some cases may have been lost by subduction erosion. If this was the only plate tectonic activity occurring during this time period, then continental volume is likely to have increased as the supercontinent expanded. This increase could be balanced if continental material was returned to the mantle via subduction. The lack of high-grade metamorphic events (see Fig. 4) in the geological record suggests that large-scale collisional orogenies were rare to absent during Columbia's tenure, this indicates that continental reworking and/or continental loss in this setting would have been minimal. If such events were existent, then they should produce detrital zircon data that would fill in the gap marked A in Fig. 3. The other way of balancing the expansion of the continents through retreating subduction zones, is by eroding the existing continents along advancing subduction margins. Although the preservation of this process may be low, an advancing subduction margin is likely to involve some magmatism that recycles the older crust that is being intruded and eroded; this would produce evolved isotopic signatures that are not prevalent in this time period. To summarise, either the geological record is biased such that the growth of new continental crust in accretionary margins is well preserved and the loss of continental crust is poorly preserved, in which case the record of increased continental growth is an artefact, or, the record is compatible with increased continental growth during Columbia's tenure. The issue of preservation remains critical to our further understanding of continental growth and plate tectonic processes through time.

6. Plate tectonics

The onset of plate tectonics and how plate tectonic regimes have changed through time remain hotly debated topics, with much

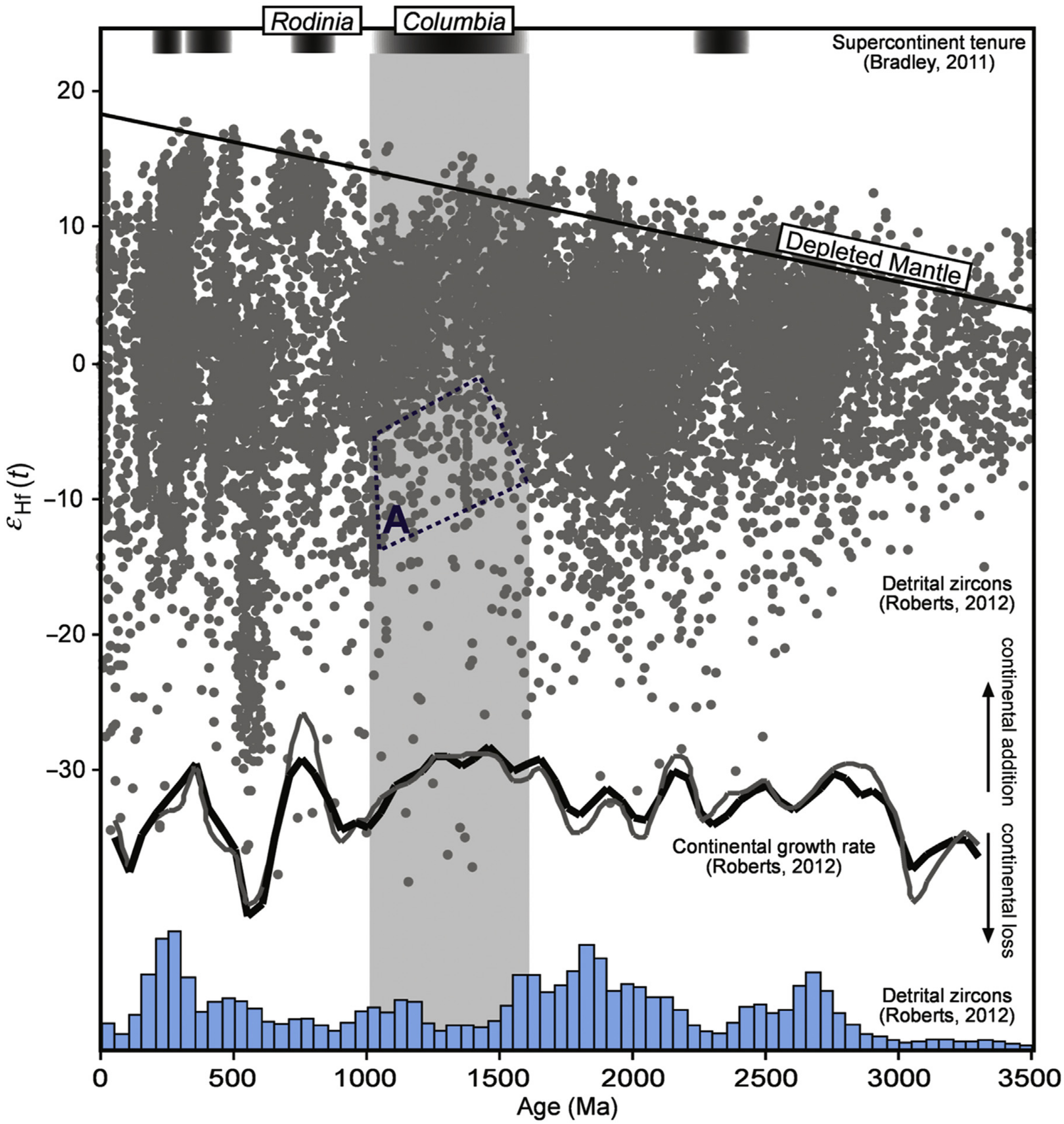

Figure 3. Compilation of global detrital zircon data and modelled trends (grey = median, black = mean) after Roberts (2012). The dashed box marked A shows the lack of zircons with evolved signatures that would counterbalance those with more juvenile signatures if crustal growth and loss were equal.

emphasis being placed on whether modern-day style plate tectonics began in the Archaean or more recently (e.g. Van Kranendonk, 2010; van Hunen and Moyen, 2012; Kusky et al., 2013; Santosh et al., 2013b). Whereas many researchers have advocated modern style plate tectonic processes, i.e. subduction, in Archaean domains, others believe that these processes didn't start until the Neoproterozoic (Stern, 2005; Hamilton, 2011; Piper, 2013a). Some ambiguity exists between what defines modern style plate tectonics, with Piper (2013a) defining three criteria: (1) mobility of the plates, (2) subduction processes, and (3) continent collision and break-up. Hamilton (2011) was happy to accept compression and extension of the plates to form the basins and orogens that are recorded in the Proterozoic and Archaean, but maintains that subduction and seafloor spreading didn't occur until ca. 850 Ma. Stern (2005) amongst others, noted the lack of well documented ophiolites, blueschists and UHP terranes before the Neoproterozoic, and suggested this relates to the lack of modern style subduction before this time.

The stability of the Columbia supercontinent, i.e. the lack of differential plate mobility, argues against plate tectonics according to Piper's criteria. Piper (2013a,b) extends the existence of this continental lid back as far as ~2.7 Ga, and as young as ~0.6 Ga. The potentially limited movement of continents between Columbia and Rodinia argues somewhat in Piper's favour. However, the existence of numerous collisional belts across most continental blocks (e.g. Zhao et al., 2002, 2004), including those that hosted subduction zones prior to collision (e.g. Trans-Hudson, Corrigan et al., 2009 and references therein), is indicative of large-scale plate motion during the formation of the Columbia supercontinent. Piper argues that such orogenic processes result from small-scale movements between crustal blocks. Whereas it would seem possible that small-scale movements may explain localised events within the interior

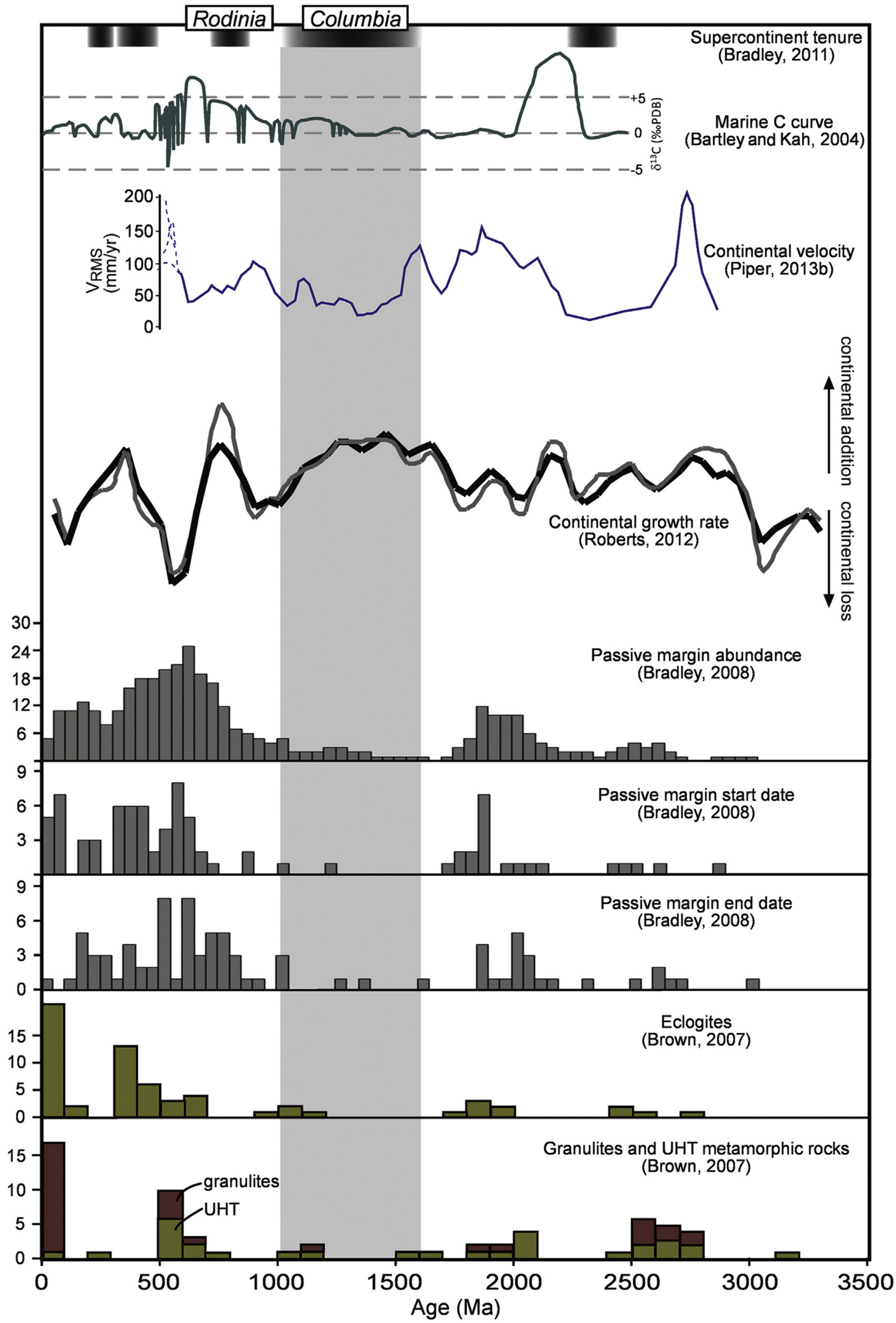

Figure 4. Compilation of geological records throughout Earth history (after Bartley and Kah, 2004; Brown, 2007; Bradley, 2008, 2011; Roberts, 2012; Piper, 2013b).

of the Columbia continental lid, it seems unlikely that the widespread orogenesis at 2.0–1.8 Ga is also a consequence of these. Stern (2008) noted that these periods of heightened orogenic activity may relate to some form of proto-plate tectonics, and that the intervening periods of stability are related to some form of continental lid tectonics.

Columbia thus appears to resemble some form of continental lid, formed during continental amalgamation between 2.0 and

1.8 Ga, lasting as a stable supercontinent until at least 1.3 Ga, and only partially breaking up before the maximum packing of the Rodinia supercontinent. However, this does not discount plate tectonic processes on the margins of this continental lid. As discussed previously, the margins of many continents record accretionary processes during Columbia's tenure. The best documents of these are in Laurentia and Baltica, where numerous arc domains have been defined and described. For example within the 1.8–1.2 Ga Labradorian, Pinwarian, Central Metasedimentary Belt, Central Gneiss Belt, and Composite Arc Belts, where arc, back-arc, rift and accretionary settings have been applied (e.g. Gower, 1996; Culshaw and Dostal, 1997, 2002; Rivers, 1997; Blein et al., 2003; Slagstad et al., 2004; Dickin and McNutt, 2007; Culshaw et al., 2013), and within the 1.8–1.2 Ga Transcandinavian Igneous, Gothian and Telemarkian Belts of Southwest Baltica (e.g. Brewer et al., 1998, 2004; Åhäll and Connelly, 2008; Roberts et al., 2011, 2013). These accretionary belts attest to plate tectonic (i.e. subduction-related) processes occurring on the edge of the Columbia supercontinent. The existence of numerous 'anorogenic' magmatic events during the timeframe of Columbia has been related to processes resulting from lid tectonics (Piper, 2013a), i.e. the effect of thermal blanketing of the mantle beneath the supercontinent (Anderson and Bender, 1989; Anderson and Morrison, 2005), or from mantle heat driven by a downwelling below the supercontinent (Vigneresse, 2005). However, the AMC (Anorthosite, Mangerite, Charnockite) and Rapakivi granites that are rather unique to this period of 'anorogenic' magmatism, are increasingly related to convergent margin settings, or at least to being a consequence of convergent margin tectonics (e.g. Åhäll et al., 2000; Bédard, 2009; Vander Auwera et al., 2011). Thus, with accounting for differences in crustal thickness and mantle temperature due to secular change within the Earth (e.g. Bédard, 2009), it seems that modern style plate tectonics can explain most or all features of the mid-Proterozoic period and the Columbia supercontinent.

7. A boring billion

The period roughly between 1.8 and 0.8 Ga has been referred to as the 'boring billion' (Holland, 2006), this results largely from the stability in the environment recorded by marine $\delta^{13}C$ (Brasier and Lindsay, 1998), and was more recently termed the 'barren billion' referring to the lack of major glaciations (Young, 2013a). Even earlier than this, the 1.6–1.0 Ga period was referred as the 'dullest time in Earth's history' (Buick et al., 1995), again referring to the lack of environmental, biological or geological events. Postulated links between environmental changes and the history of supercontinents have long been made (e.g. Squire et al., 2006; Campbell and Allen, 2008; Maruyama and Santosh, 2008; Meert and Lieberman, 2008). Various processes that affect the geochemistry of the oceans and atmosphere act together to provide a complex system, that combined with the secular changes in solar intensity and mantle cooling (e.g. Young, 2013a) mean it is particularly difficult to unravel cause and effect for particular environmental events.

The stability of the boring billion begins after the amalgamation of the supercontinent Columbia; it remains throughout Columbia's lifespan, and then includes the formation of Rodinia. Both the break-up of Rodinia and the formation of Gondwana are both postulated as strongly linked to the extreme climatic variations seen in the late Precambrian (for a review see Santosh et al., 2013a). In an idealised supercontinent cycle, Columbia would break-up and disperse during the early to mid-Mesoproterozoic, and then would re-amalgamate as Rodinia in the late Mesoproterozoic/early Neoproterozoic. The record of environmental events does not record any great changes or fluctuations that could be postulated as relating to this hypothesised break-up of Columbia and/or formation of Rodinia. This could be used as an argument against a direct link between supercontinent cycles and environmental change. Young (2013a) suggests that supercontinents have played a role, but postulates that it is the complex balance between solar radiation, atmospheric CO_2 and plate tectonics that has produced the two extreme climatic periods in Earth history. It is argued here that environmental stability is highly compatible with the history of Columbia. The ~1.8–1.2 Ga continental lid of Columbia and its minor re-configuration into Rodinia at ~1.2–0.9 Ga, and the prolonged rifting of Rodinia after 0.9 Ga, produce a history of continental movements that is in accord with the record of ocean and atmosphere stability.

Although the boring billion was initially extended to ~0.8 Ga, an increase in isotopic variability is seen after 1.3 Ga (e.g. Kah et al., 2001; Bartley and Kah, 2004; see Fig. 4); although this is only a slight rise in comparison to the extreme Neoproterozoic variations, it is comparable in size to the variations seen in Phanerozoic seawater, and may represent a moderate oxygenation increase in the biosphere (Kah et al., 2001). The onset of this isotopic variability is correlative with rifting events within Columbia, and subsequent Grenvillian mountain-building during transformation to Rodinia; further strengthening the potential links between plate tectonics and environmental change. Our knowledge of the evolution of life on Earth has suffered the same fate. Whereas most of the boring billion is seen as a time of limited cellular development and radiation, increasing evidence from scarce Mesoproterozoic outcrops has revealed some development in eukaryotes prior to the great radiation in the Neoproterozoic (e.g. Butterfield, 2001, 2005; Javaux et al., 2001, 2004; Leiming et al., 2005). That being said, the level of diversity is still much lower in the Mesoproterozoic than occurs in the Neoproterozoic (Javaux et al., 2004; Knoll et al., 2006). It is worth noting also, that although the great radiation of life occurred during the Neoproterozoic, the preceding period of stability is a possible driver of evolution; Brasier and Lindsay (1998) suggested it may have nurtured photosymbiosis within eukaryotes so that they could evolve into autotrophs. It is evident that the period referred to as 'boring', in fact remains rather interesting, as it provides clues on the relationship between tectonics, the environment and evolution.

8. Conclusions

The supercontinent Columbia formed at 2.0–1.7 Ga; maximum packing based on collisional orogenesis likely occurred at 1.95–1.85 Ga (Rogers and Santosh, 2009). This supercontinent remained as a quasi-integral continental lid for its entire duration. Break-up was attempted but not successful. Some differential plate movement was necessary after ~1.3 Ga to produce the next supercontinent (Rodinia) at 1.1–0.9 Ga; this occurred via a form of extroversion, whereby exterior accretionary belts were transformed into interior collisional belts, i.e. the Grenville and equivalent orogens. Continental growth outweighed continental loss during Columbia's lifespan as a result of accretionary processes along its margin. The stable continental lid and lack of differential plate movement during the 1.8–1.3 Ga period are linked to stability in the chemistry of the Earth's oceans and atmosphere, and strengthens a possible causal relationship. The evolution and radiation of life correlates with the environmental changes seen in the late Palaeoproterozoic to Neoproterozoic, i.e. a period of environmental stability, followed by a slow increase in variability after 1.3 Ga, and then by extreme variability after ~0.8 Ga that coincides with break-up of Rodinia. Since plate tectonics seem inextricably linked to the evolution of Earth's environment and life, it is necessary to unravel the past history of plate movements; it is apparent that the supercontinent cycle remains an over-simplification, with the role of lid versus plate tectonics changing though Earth's history.

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