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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