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A hypothesis for Proterozoic-Phanerozoic supercontinent cyclicity, with implications for mantle convection, plate tectonics and Earth system evolution

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ABSTRACT

We present a conceptual model for supercontinent cycles in the Proterozoic-Phanerozoic Eons. It is based on the repetitive behavior of C and Sr isotopes in marine carbonates and U–Pb ages and εHf of detrital zircons seen during the Neoproterozoic-Paleozoic and Paleoproterozoic Eras, respectively. These records are considered to reflect secular changes in global tectonics, and it is hypothesized that the repetitive pattern is caused by the same type of changes in global tectonics. The fundamental premise of this paper is that such repetitive changes should also be recorded in orogenic belts worldwide. This carries the implication that Neoproterozoic-Paleozoic orogenic belts should have Paleoproterozoic equivalents. It is proposed that this is the case for the East African, Uralides and Ouachita–Alleghanian orogens, which have Paleoproterozoic analogs in the West African–Amazon, Laurentian and East European cratons, respectively. The Neoproterozoic-Paleozoic orogenic belts are not isolated features but occur in a specific global context, which correspond to the relatively well-constrained Neoproterozoic break-up of Rodinia, and the subsequent Late Paleozoic assembly of Pangea. The existence of Paleoproterozoic equivalents to Neoproterozoic-Paleozoic orogens requires that the same cycle defined the Paleoproterozoic. We therefore hypothesize that there were Paleoproterozoic supercontinents equivalent to Rodinia and Pangea, and that Proterozoic-Phanerozoic supercontinents are comprised of two basic types of configurations, equivalent to Rodinia (R-type) and Pangea (P-type). The Paleoproterozoic equivalent of Rodinia is likely the first supercontinent to have formed, and Proterozoic-Phanerozoic supercontinent cycles are therefore defined by R- to R-type cycles, each lasting approximately 1.5 Gyr. We use this cyclic pattern as a framework to develop a conceptual model that predicts the configuration and cycles of Proterozoic-Phanerozoic supercontinents, and their relation to mantle convection and Earth system evolution.

1. Introduction

The Earth constitutes a system that can be divided into four components; the geosphere, the atmosphere, the hydrosphere and the biosphere (Reddy and Evans, 2009; Skinner and Murck, 2011). Ever since its formation more than 4.5 billion years ago, the Earth system has been in constant flux. This change is largely driven by the thermal evolution of the geosphere, which encompasses the regolith, crust, mantle and core. The secular cooling of the Earth has had a profound effect on its evolution, and the Early Earth was undoubtedly very different from its present state.

A tectonic regime that involved subduction of oceanic crust may have begun to operate between 3.2 and 2.5 Ga, as lithological, geochemical and structural data of Archean and Paleo-Mesoproterozoic supracrustal belts and intrusive suites indicate that they formed through subduction processes (Cawood et al., 2006; Condie and Kröner, 2008; Dhuime et al., 2012; Næraa et al., 2012; Shirey and Richardson, 2011). However, "modern-style" subduction, characterized by widespread occurrences of unequivocal ophiolites and HP–LT metamorphism, appears to be restricted to the Neoproterozoic and Phanerozoic (Brown, 2006; Ernst, 2009; Hamilton, 2011; Stern, 2008).

The timing of the transition to plate tectonics is fundamental to models for the evolution of the Precambrian Earth (Cawood et al., 2006; Hamilton, 2011; Reddy and Evans, 2009; Stern, 2008; Windley, 1995). A central and controversial issue in Precambrian geology is the configuration, timing and cyclicity of supercontinents prior to the well-established Late Paleozoic-Early Mesozoic supercontinent Pangea (Bradley, 2011; Evans, 2013; Meert, 2012; Nance et al., 1988, 2014; Piper, 2013; Reddy and Evans, 2009). The controversies surrounding pre-Pangean supercontinents and supercontinent cycles stem from a range of factors, including the lack of a method capable of yielding unique solutions for paleogeographical reconstructions and uncertainty

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regarding the prevailing Precambrian tectonic regime. This is all compounded by the increasingly fragmentary geological record of the Proterozoic and Archean Eons.

There is general consensus that at least three supercontinents existed during Earth's history (e.g., Bradley, 2011; Evans, 2013; Meert, 2012), where a supercontinent includes >75% of the preserved continental crust at the time of formation, in a rigid or semi-rigid configuration (see Meert, 2012). These are Pangea in the Late Paleozoic-Early Mesozoic (Stampfli et al., 2013; Torsvik et al., 2012), Rodinia in the Late Mesoproterozoic-Early Neoproterozoic (Hoffman, 1991; Li et al., 2008), and the Late Paleoproterozoic-Mesoproterozoic supercontinent Columbia (or Nuna, see Meert, 2012; Rogers and Santosh, 2002; Zhao et al., 2004). The somewhat elusive Kenorland supercontinent is hypothesized to have existed in the Late Neoarchean-Early Paleoproterozoic although its configuration is poorly constrained (Campbell and Allen, 2008; Evans, 2013; Williams et al., 1991). Some of the proposed configurations (e.g., Williams et al., 1991) would not qualify as a supercontinent according to the definition by Meert (2012), but rather as large continents. Indeed, it has been proposed by many authors that the continental crust at this time was dispersed in multiple larger continents (Aspler and Chiarenzelli, 1998; Bleeker, 2003; Pehrsson et al., 2013; Rogers, 1996), which would make Columbia the oldest supercontinent.

Regardless of their specifics, a common denominator for all these reconstructions is that they explicitly or implicitly involve plate tectonics in some form. This provides a mean to break up and assemble supercontinents in different configurations during the course of successive supercontinent cycles. There are also dissenting views that argue for other models, for example stagnant lid tectonics that imply one long-lived supercontinent called Paleopangea throughout the Proterozoic, up and until Early Phanerozoic times (Piper, 2013).

The evolution of the "exogene" Earth, including the atmosphere, hydrosphere and biosphere, is strongly coupled with that of the geosphere (Bradley, 2011; Campbell and Allen, 2008; Nance et al., 2014; Reddy and Evans, 2009). Important factors in this interaction are volcanic activity, weathering and deposition of sedimentary rocks, all in conjunction with biological evolutionary leaps such as oxygenic photosynthesis (Farquhar et al., 2011; Och and Shields-Zhou, 2012). The evolving "exogene" Earth during the Precambrian has been attributed to both coupling with supercontinent cycles and global events in a lid tectonic regime (cf. Bradley, 2011; Piper, 2013). It seems clear however, that these changes are episodic – if not cyclic – in character (Bradley, 2011; Melezhik et al., 2013; Nance et al., 2014; Papinaeu, 2010), which models for the evolution of the Earth system must take into account.

The complexity of the Earth system makes it a challenging puzzle to solve; even more so the further one ventures back in time. A common approach to "fill in the blanks" regarding the Precambrian is to use modern Phanerozoic examples as analogs since they are comparatively well preserved and understood with regard to their formative processes (e.g., Glikson, 1981; Kusky et al., 2013; Windley, 1993; Windley and Garde, 2009). Such comparisons have been used to argue that similar processes (i.e., plate tectonics) operated in the Precambrian as in the Phanerozoic. However, this method is not without pitfalls, as different processes may conceivably produce the same results. Nevertheless, the use of modern analogs for the distant past remains a potent method as it can be used to formulate testable working hypotheses that can guide the investigator to new insights (e.g., Baker, 2014).

Here we aim to develop a model for supercontinent cycles in the Proterozoic-Phanerozoic Eons. The basis for the model is the repetitive behavior of C and Sr isotopes in marine carbonates and U–Pb ages and εHf of detrital zircons seen in the Neoproterozoic-Paleozoic (ca. 1.0–0.3 Ga) and Paleoproterozoic (ca. 2.5–1.8 Ga), respectively. We assume that these records directly reflect secular changes in global tectonics, and that the repetitive pattern suggests that the same changes took place during these two periods of time. The central point of this paper, discussed in Section 2, is that these repetitive changes in global tectonics should be recorded in orogenic belts. If the global tectonic evolution was the same during these two periods of time, then this carries the implication that Neoproterozoic-Paleozoic orogenic belts should have Paleoproterozoic analogs, which should record the same relative orogenic history. We propose in Section 3 that this is the case for the East African, Uralide and Variscan–Alleghanian–Ouachita orogens, which have Paleoproterozoic analogs in the West African–Amazon, Laurentian and East European cratons, respectively. The Neoproterozoic-Paleozoic orogenic belts are not isolated features but occur in a specific context, which correspond to the relatively well-constrained Neoproterozoic break-up of Rodinia, and the subsequent assembly of Gondwana, Laurussia, and finally Pangea during the Late Paleozoic. The existence of Paleoproterozoic analogs to Neoproterozoic-Paleozoic orogens suggests that a similar cycle defined the Paleoproterozoic. This provides a framework for developing a model that predicts the configuration and cycles of Proterozoic-Phanerozoic supercontinents, which will be discussed in Sections 4–5.

2. Secular changes in global tectonics — a means to infer past orogenic belts?

There are several isotopic records that, in their own way, may act as proxies for secular changes in global tectonics. These include the $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ composition of marine carbonates and global datasets of U–Pb ages and εHf from detrital zircons. The purpose of this section is to briefly review these records and to discuss how their repetitive behavior during the Paleoproterozoic and Neoproterozoic–Palaeozoic can be used to infer past supercontinent cycles.

2.1. $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ of marine carbonates

The Sr- and C-isotopic composition of unaltered marine carbonates is assumed to reflect the composition of their ambient seawater (e.g., Melezhik et al., 2013; Shields, 2007). $^{87}Sr/^{86}Sr$ of seawater is considered to reflect the relative input from continental weathering as river runoff and mantle-sourced volcanic activity at spreading ridges (Shields, 2007; Spencer et al., 2013). In addition to the isotopic evolution of the continental and mantle sources there are also other factors that affect the $^{87}Sr/^{86}Sr$ value, such as the number of spreading ridges, rate of continental weathering (dependent on atmospheric pCO_2), orogenic activity, and the composition of the weathering crust. The long term (>10–100 Myr) behavior of $\delta^{13}C$ is commonly attributed to the relative rate of burial and uplift-erosion of organic matter (with a negative $\delta^{13}C$) in sedimentary rocks (Campbell and Squire, 2010; Melezhik et al., 2013).

When normalized against the isotopic evolution of crustal and mantle sources, the Proterozoic-Phanerozoic record of $^{87}Sr/^{86}Sr$ marine carbonates show a fluctuating pattern with peaks of crustal contributions during the Mid Paleoproterozoic at ca. 2.0 Ga and the Early Paleozoic at ca. 0.5 Ga (Fig. 1A; Shields, 2007). $^{87}Sr/^{86}Sr$ increase also occurs during the late Cenozoic. Throughout the Proterozoic, the running average of $\delta^{13}C$ lies around 0‰ but is punctuated by positive excursions during the beginning and end of the Proterozoic Eons, each lasting approximately 200–300 Myr (Fig. 1A). The first positive excursion occurs during the Lomagundi–Jatuli Event between ca. 2.30–2.05 Ga (Martin et al., 2013; Melezhik et al., 2013) and the second in the Middle-Late Neoproterozoic between ca. 0.80–0.60 (Campbell and Allen, 2008; Shields and Veizer, 2002). In both these instances, the peak of the positive excursions in $\delta^{13}C$ predates peaks of $^{87}Sr/^{86}Sr$ by approximately 200 Myr (Fig. 1A).

The record of $\delta^{13}C$ during the Phanerozoic (<0.54 Ga) becomes more complex, reflecting the rise of animals and land plants following the Cambrian Explosion and their effect on the biogeochemical cycling of carbon (Fig. 1A; e.g., Campbell and Squire, 2010).