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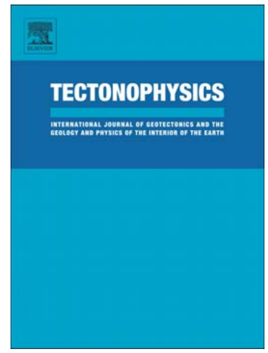
*Published in:*
Tectonophysics

*DOI:*
10.1016/j.tecto.2015.04.009

2015

# Accepted Manuscript

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PII: S0040-1951(15)00226-7
DOI: doi: 10.1016/j.tecto.2015.04.009
Reference: TECTO 126605

To appear in: *Tectonophysics*

Received date: 28 August 2014
Revised date: 6 April 2015
Accepted date: 21 April 2015

# 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 analogues 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.

## Keywords

- Supercontinent cycles
- Earth system evolution
- Mantle convection cells
- Rodinia
- Pangea

## Highlights

- Rodinia and Pangea represent the two basic types of supercontinent configurations
- True supercontinent cycles involve breakup-assembly of Rodinia-type supercontinents

- The convective pattern in the mantle is the same during each such cycle
- During these cycles, Pangea-type supercontinents are only transient stages
- Rodinia-type supercontinent break-ups coincide with atmospheric oxygenation events

## 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 3.2-2.5 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 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; Rogers and Santosh 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 analogues, 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 analogues 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 analogues 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 behaviour 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).

### 2.2. U-Pb ages and εHf of detrital zircon

The U-Pb ages and εHf of detrital zircon reflect a complex interplay of various process, including secular changes in magma composition, as well as spatiotemporal variations in uplift, erosion and crustal preservation (e.g. Cawood et al. 2013; Hawkesworth et al. 2009; Spencer et al. 2013). However, all such processes are related to the tectonic evolution of the source region from which the detrital zircons were derived. A representative dataset of detrital zircon could therefore – in theory – provide a record of secular changes in the tectonic evolution of any given source region.

The compilation of U-Pb ages from global datasets of detrital zircon shown in figure 1b (compiled from Belousova et al. 2010 and Campbell and Allen 2008) shows secular variation in the abundance of U-Pb ages. Prominent peaks occur between ca. 2.70-2.40, 2.00-1.50, 1.20-0.9, and 0.60-0.15 Ga. These peaks are in turn separated by troughs between ca. 2.40-2.20, 1.40-1.30, 0.90-0.65 and <0.15 Ga.

A compilation of detrital zircons that have been dated and analyzed for Hf-isotopes is also shown in figure 1b (data from Spencer et al. 2013, the εHf-curve shows the running average of initial zircon εHf). The εHf-curve shows that the Archean-Proterozoic Eons are characterized by periods in which the value of εHf is close to CHUR (fig. 1b), punctuated by periods between ca. 2.5-1.7 and 1.0-0.4 Ga where there is a transient shift towards negative εHf. The Mesozoic-Cenozoic is characterized by a transient shift towards positive εHf.

### 2.3. Repetitive changes in global tectonics and their implications

The $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ in marine carbonates and detrital zircon U-Pb and εHf display repetitive patterns during the Neoproterozoic-Paleozoic and the Paleoproterozoic (outlined by grey fields in figure 1). Specifically, these periods both span the positive excursions in $\delta^{13}C$ and increasing $^{87}Sr/^{86}Sr$ seen in figure 1a. They also encompass troughs in the relative abundance of U-Pb zircon ages and decreases in εHf (fig. 1b). There are no increases in $\delta^{13}C$

during the second half of the Paleoproterozoic (ca. <2.05 Ga) that are comparable to those seen in the Late Paleozoic (fig. 1a). However, the Late Paleozoic positive excursions occurred following the emergence of animals and land plants, and probably represent changes in the biosphere and its response to global tectonics, rather than any actual changes in global tectonics.

The behavior of the isotopic records of marine carbonates and detrital zircons is significant. Each of these records has the potential of reflecting secular changes in the global tectonics, and might therefore provide insights into supercontinent cycles. The occurrence of the same set of changes during the Neoproterozoic-Paleozoic and the Paleoproterozoic can be taken to suggest that the global tectonic evolution underwent the same changes during these two periods of time and are thus analogous.

This assumes that the isotopic composition of the marine carbonates and detrital zircons are ultimately controlled by global tectonics. It also assumes that the currently available datasets are representative samples of their global populations, and that they accurately capture the first order trends of these isotopic records. If so, these records may be treated as tracers of secular change in global tectonics. At this scale, it is not relevant what processes ultimately control their isotopic composition, as long as the processes are controlled by global tectonics.

Based on these assumptions, we hypothesize that the repetitive behavior of $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ in marine carbonates and U-Pb and εHf in detrital zircons during the Paleoproterozoic and the Neoproterozoic-Paleozoic indicate that the global tectonic evolution was the same during these two periods of time, which involved the break-up of Rodinia and subsequent assembly of Pangea in the latter case. As this global tectonic evolution should also be reflected in orogenic belts worldwide that formed during these periods, we further hypothesize that Neoproterozoic-Paleozoic orogenic belts should have Paleoproterozoic equivalents. This is the fundamental premise of this paper.

## 3. Inferring Paleo-Mesoproterozoic orogenic belts from Neoproterozoic-Phanerozoic analogues

The purpose of this section is to test the hypothesis developed above, namely that Neoproterozoic-Paleozoic orogens have Paleoproterozoic equivalents. If the hypothesis is correct, it should be possible to infer the existence of Paleoproterozoic orogens based only on knowledge of Neoproterozoic-Paleozoic orogenic belts and their relation to changes in e.g. the isotopic record of marine carbonates. The following sections will propose Paleoproterozoic equivalents to the Neoproterozoic to Palaeozoic Ouachita-Alleghanian, East African, and Uralide orogens.

### 3.1. A Paleoproterozoic analogue to the Ouachita-Alleghanian orogens

#### *3.1.1. The Ouachita-Alleghanian orogens*

The Ouachita-Alleghanian orogens formed the western section of the extensive orogenic belt that sutured Gondwana and Laurussia during the Late Paleozoic assembly of Pangea (fig. 2a; Nance et al. 2010; Stampfli et al. 2013; Torsvik et al. 2012). The eastern section corresponds to the Variscan Orogen in northern Africa and southern Europe. Gondwana assembled between ca. 650-530 Ma (e.g. Li et al. 2008; Stampfli et al. 2013), which coincided with the end of positive excursion of $\delta^{13}C$ in marine carbonates and simultaneous rise in $^{87}Sr/^{86}Sr$ (fig. 2a). Laurussia formed from amalgamation of Laurentia and the East European Craton, as well as Avalonian terranes rifted from the margin of Gondwana. This occurred between ca. 450-400 Ma (Nance et al. 2010; Stampfli et al. 2013; Torsvik et al. 2012), broadly coinciding with the Paleozoic peak in $^{87}Sr/^{86}Sr$.

The Variscan-Ouachita-Alleghanian orogeny marked the closure of the Rheic Ocean, which had opened following rifting of Avalonian terranes from the margin of West Gondwana (Nance et al. 2010; Torsvik et al. 2012). The Ouachita-Alleghanian section records an accretionary-collisional history extending from ca. 400 to 250 Ma, during which the Rheic ocean was closed and Laurussia and Gondwana were sutured (Keppie et al. 2008; Nance et al. 2010; Torsvik et al. 2012). This coincided with the development of an accretionary orogen outboard to the Ouachita-Alleghanian orogen at ca. 300 Ma (fig. 2a; Keppie et al. 2008; Nance et al. 2010). Altogether, this sequence of events coincided with a decrease in $^{87}Sr/^{86}Sr$ and a significant increase in $\delta^{13}C$ (fig. 2a).

#### *3.1.2. A Paleoproterozoic analogue – the Svecofennian-Central Russian orogens*

A Paleoproterozoic analogue to the Ouachita-Alleghanian orogens should exhibit the same relative spatial and temporal relationships between its orogenic belts. Most importantly, they should have the same relative relationship to the Paleoproterozoic positive excursion in $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ in marine carbonates. Based on these requirements, it is possible to infer the general structure of its Paleoproterozoic analogue, which is shown in figure 2b. If the model is correct, there should be a piece (or pieces) of continental crust with the same general structure. What remains is to interrogate the geological record to establish whether this is an accurate prediction.

We propose that the combined Svecofennian and Central Russian orogens in the East European Craton (fig. 2c; Bogdanova et al. 2008; Lahtinen et al. 2008) represent the Paleoproterozoic analogue to the Ouachita-Alleghanian orogens. The Svecofennian and Central Russian orogens assume a central position in the East European Craton, suturing the northern Norrbotten-Kola-Karelian cratons with the Volgo-Uralia and Sarmatia (Volgo-Sarmatia) blocks in the southeast (fig. 2c; Bogdanova et al. 2008). It is proposed here that the

Norrbotten-Kola-Karelian cratons are equivalent to a section of Laurussia, while the Volgo-Sarmatia provinces are equivalent to a section of Gondwana.

The Volgo-Sarmatia blocks contain Archean cratons sutured between ca. 2.05-2.00 Ga, while the Archean Norrbotten-Kola-Karelian cratons amalgamated between ca. 1.98-1.92 Ga (Bogdanova et al. 2008; Lahtinen et al. 2008, 2015). Together, the Svecofennian and Central Russian orogens record an accretionary-collisional history between ca. 1.95-1.75 Ga, which culminated with the amalgamation of the Fennoscandia and Volgo-Sarmatia blocks (Bogdanova et al. 2008; Lahtinen et al. 2008). Finally, a long-lived accretionary orogen also developed outboard to the sutured Fennoscandia and Volgo-Sarmatia blocks (fig. 2c) around 1.8 Ga.

The evolution of the orogenic belts and cratons in the East European Craton are strikingly similar in comparison to their proposed Neoproterozoic-Paleozoic analogues (cf. figs. 2a and c). They show the same relative timing and spatial relationships, and they relate in the same way to changes in the C and Sr isotopic record of marine carbonates.

## 3.2. A Paleoproterozoic analogue to the East African Orogen

### *3.2.1. The East African Orogen*

The East African Orogen formed during the Late Neoproterozoic-Early Paleozoic amalgamation of West and East Gondwana (fig. 3a; Fritz et al. 2013; Jacobs and Thomas 2004; Johnson et al. 2011; Stampfli et al. 2013). It is characterised by an early accretionary phase between ca. 800-650 Ma during which significant amounts of juvenile crust was formed, primarily in the northern part of the orogen (Fritz et al. 2013; Stern et al. 2010). This phase overlapped with the positive Neoproterozoic excursion in $\delta^{13}C$ (fig. 3a).

The accretionary phase was followed by a collisional phase as West and East Gondwana blocks were sutured, which coincided with a shift to lower $\delta^{13}C$ but an increase in $^{87}Sr/^{86}Sr$ (fig. 3a). The southern part of the orogen underwent high-grade metamorphism during crustal thickening, while the northern part was characterized by low-grade metamorphism and strike-slip shearing (Fritz et al. 2013; Johnson et al. 2011).

Following the East African Orogen, the Terra Australis accretionary orogen developed along the margin of Gondwana (fig. 3a; Cawood 2005). The development of the Terra Australis accretionary orogen broadly coincided with the Paleozoic peak in $^{87}Sr/^{86}Sr$.

### *3.2.2. A Paleoproterozoic analogue – the Birimian orogen*

Like the Paleoproterozoic analogue for the Ouachita-Alleghanian orogens, an analogue for the East African Orogen should exhibit the same relative spatial and temporal relationships between its orogenic belts, which in turn should have the same relative relationship to positive excursions in $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ of marine carbonates. Based on these requirements, it is possible to infer the general structure of the Paleoproterozoic analogue of the East African Orogen, shown in figure 3b.

We propose that the Birimian Orogen in the West African and Amazon Cratons represent a Paleoproterozoic analogue to the East African Orogen (fig. 3c). The two cratons are currently separated, but paleogeographic reconstructions places the Amazon Craton at the southern end of the West African Craton during the Paleoproterozoic (fig. 3c; Nomade et al. 2003; Onstott et al. 1984).

The Birimian Orogen contains large tracts of juvenile crust, located primarily in the northern West African Craton, which formed during an accretionary phase between ca. 2.35-2.15 Ga (e.g. Abouchami et al. 1990; Baratoux et al. 2011; Delor et al. 2003; Feybesse et al. 2006; Gasquet et al. 2003). This was followed by a collisional phase between ca. 2.15-2.05 Ga, during which the Birimian crust was sutured with Archean cratons on its western and eastern margins. High-grade metamorphism was largely restricted to the southern part of the orogen (e.g. Delor et al. 2003), while the northern part was subjected to low-grade metamorphism and strike-slip shearing. Following the collisional phase, a long-lived accretionary orogen developed outboard to the Birimian Orogen in the Amazon Craton (fig. 3c; Cordani and Teixeira 2007).

The accretionary stage of the Birimian Orogen coincided with the Paleoproterozoic positive excursion in $\delta^{13}C$, in the same manner as the East African Orogen (cf. figs 3a and 3c). The collisional phase coincided with an increase in $^{87}Sr/^{86}Sr$ but a decrease in $\delta^{13}C$, again equivalent to the collisional phase of the East African Orogen. Finally, the accretionary orogen that formed in the Amazon Craton coincided with the peak and subsequent decrease in $^{87}Sr/^{86}Sr$, in the same way as the Terra Australis orogen.

### 3.3. A Paleoproterozoic analogue to the Uralides

#### *3.3.1. The Uralides*

The ca. 350-250 Ma Uralides form an orogenic belt that sutured eastern Laurussia with the continental masses of the Central Asian Orogenic Belt and the Siberian Craton (fig. 4a; Brown et al. 2008; Ivanov et al. 2013; Pease et al. 2014). The collision coincided with a decrease in $^{87}Sr/^{86}Sr$ of marine carbonates and a short-lived peak in $\delta^{13}C$ (fig. 4a).

The main continental block on the Laurussian side of the Uralides was the East European Craton (fig. 4a). However, an assemblage of smaller continental blocks also existed north of this craton, which together have been referred to as Arctida (fig. 4a; Metelkin et al. 2014). Together, the East European Craton and the Arctida blocks record a Neoproterozoic rifting event between ca. 900-500 Ma (Cocks and Torsvik 2011; Metelkin et al. 2014), which coincided with the positive excursion in $\delta^{13}C$ (fig. 4a). This was followed by accretion and collision from ca. 500 Ma to 250 Ma, when the continental blocks of Arctida were accreted against the northeastern margin of the East European Craton and the Siberian Craton to the east (fig. 4a). This final stage coincided with an increase in $^{87}Sr/^{86}Sr$ of marine carbonates, coincident with a return to low values $\delta^{13}C$ (fig. 4a).

The Central Asian Orogenic belt represents an amalgam of juvenile arc crust and continental blocks, fringed to the north by the Siberian Craton (fig. 4a) and to the south by the North China and Tarim Cratons (Wilhelm et al. 2012; Windley et al. 2007). The Central Asian Orogenic Belt records a long history of accretionary and collisional orogenesis, starting in the Early Neoproterozoic at ca. 900 Ma and continuing until the final assembly of Pangea at ca. 300-250 Ma (fig. 4a; Wilhelm et al. 2012; Windley et al. 2007). As such, it spanned the positive excursions in both $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ of marine carbonates (fig. 4a). Following the assembly of Laurussia with the Asian continental blocks, an accretionary orogen developed outboard to this landmass, corresponding to the present-day Pacific "Ring of Fire" (fig. 4a; e.g. Seton et al. 2012; Torsvik et al. 2012).

#### *3.3.2. A Paleoproterozoic analogue – the Trans-Hudson Orogen*

A Paleoproterozoic analogue to the Uralides should exhibit two main assemblages of continental crust, equivalent to Laurussia-Arctida and Asia. In turn, these two assemblages should be separated by an orogen equivalent to Uralides. These units should have the same relative relationship to the Paleoproterozoic positive excursion in $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ in marine carbonates. Based on these requirements, it is possible to infer the broad structure of this Paleoproterozoic analogue, which is shown in figure 4b.

We propose that the Trans-Hudson Orogen in Laurentia and Greenland (fig. 4c; Corrigan et al. 2009; St-Onge et al. 2009; Whitmeyer and Karlstrom 2007) is the Paleoproterozoic equivalent to the northern part of the Uralides. In this context, the Superior and North Atlantic cratons are equivalent to the continental blocks of Arctida, while the composite Churchill Province (Corrigan et al. 2009) is equivalent to the Asian continental blocks, including the Central Asian Orogenic Belt and the Siberian Craton.

The Superior and North Atlantic cratons record a period of rifting between ca. 2.40-2.05 Ga (Lahtinen et al. 2008; Whitmeyer and Karlstrom 2007), followed by accretion and collision between ca. 2.0-1.8 Ga (fig. 4c; Corrigan et al. 2009; Whitmeyer and Karlstrom 2007). These stages have the same relative relationship to positive excursions in $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ of marine carbonates as their proposed equivalents in Arctida-Laurussia (fig. 4a). Meanwhile, the composite Churchill Province records a prolonged history between ca. 2.4-1.8 Ga of accretion and collision between juvenile crust and Archean continental blocks (Pehrsson et al. 2013; Whitmeyer and Karlstrom 2007), equivalent to the Central Asian Orogenic Belt.

The ca. 1.9-1.8 Ga Trans-Hudson Orogen sutured the Superior and North-Atlantic cratons with the amalgamated continental blocks of the Churchill Province (fig. 4c; Corrigan et al. 2009; Whitmeyer and Karlstrom 2007). The timing of the Trans-Hudson Orogen is equivalent to how the Uralides sutured the Laurussia-Arctida blocks with the amalgamated continental crust in Asia (fig. 4a). The New Quebec Orogen between the Superior and North Atlantic cratons (Corrigan et al. 2009; Whitmeyer and Karlstrom 2007) should be equivalent to the collisional belts along which the Arctida continental blocks were amalgamated during the final stages of the assembly of Pangea, at the same time as the Asian and Laurussian blocks collided along the Uralides (Metelkin et al. 2014).

The accretionary orogenic belts that developed outboard to the amalgamated Superior Craton, North Atlantic Craton, and Churchill Province (fig. 4c) should be equivalent to the accretionary orogen that formed outboard to Asia and Laurussia following their amalgamation (cf. figs 4a and 4c), and which is found today in Kamchatka and Alaska along the northern margin of the Pacific.

### 3.4. Implications

The most important aspect of the examples above is how it is possible to accurately predict the spatiotemporal distribution and orogenic style (accretionary, collisional, and extensional) of Paleoproterozoic orogenic belts, based only on knowledge of Neoproterozoic-Paleozoic orogenic belts and their relation to changes in the isotopic record of marine carbonates and detrital zircon. It could be argued that the geometric relationships between the orogenic belts discussed above only represent the general evolution of accretionary-collisional orogens. However, their temporal relationship with changes in the Sr- and C-isotopic record of marine carbonates is unique. This allows for the construction of unique models (figs. 2b, 3b, and 4b) that accurately predicts the first order structure of Paleoproterozoic orogenic belts. Notably, this can be done independently of any prior knowledge of their existence.

In detail, the orogenic belts might exhibit differences, but these could be considered as variations in the expression of the same underlying processes. However, it must be kept in mind that these types of predictions are restricted to large-scale features. It is not a question of predicting the existence of e.g. individual plutons or sedimentary basins, but instead the overall setting in which they occur and reflect.

The hypothesis that Neoproterozoic-Paleozoic orogens have Paleoproterozoic equivalents can therefore form the base for models that have a high predictive power. As will be discussed in the following sections, this can be extended beyond individual orogenic belts in the Paleoproterozoic, to predicting Proterozoic-Phanerozoic supercontinent configurations and cycles.

## 4. Implications for inferring supercontinent configurations and cycles

Orogenic belts do not form in isolation, but instead occur in a specific global context. The East African, Uralide and Ouachita-Alleghanian orogens discussed above were integral to the assembly of Gondwana and Pangea, respectively (figs. 2-4). It follows that if it is possible to predict Paleoproterozoic equivalents to these orogenic belts, then it should also be possible to predict the existence of Paleoproterozoic equivalents to Pangea, Laurussia, Gondwana and, by extension, Rodinia.

Altogether, this provides an opportunity to predict not only the existence of Paleoproterozoic orogenic belts, but also the configuration of supercontinents and their cyclic assembly and break-up. It can be further predicted that plate tectonics operated during the Paleoproterozoic, and that it would have been similar to “modern-style” plate tectonics (section 1), despite the apparent lack of features such as unequivocal ophiolites and LT-HP blueschist metamorphism. This is of course dependent on a solid understanding of the global tectonic evolution and paleogeography during the Neoproterozoic-Paleozoic, areas which unfortunately remain poorly constrained in many aspects. However, while any uncertainties regarding the Neoproterozoic-Paleozoic will naturally be transferred into the Paleoproterozoic when making these predictions, the uncertainties do not affect the underlying concept, namely that the Neoproterozoic-Paleozoic Eras may act as an analogue to the Paleoproterozoic. This has profound implications for how to view supercontinent cycles and the global tectonic evolution during the Proterozoic-Phanerozoic Eons, which will be further explored in the following sections.

### 4.1. Supercontinent types

The existence of the supercontinent Rodinia in the Early Neoproterozoic (ca. 1.0-0.9 Ga) is relatively well established, although the details regarding its assembly and break-up remain controversial (e.g. Evans 2013; Li et al. 2008). Nevertheless, it is inferred that its break-up initiated a rearrangement of continental blocks into Gondwana, Laurussia and, finally, the new supercontinent Pangea in the Late Paleozoic (ca. 0.3 Ga, e.g. Stampfli et al. 2013, Torsvik et al. 2012).

By analogy, the Paleoproterozoic should also have been defined by a supercontinent equivalent to Rodinia. It should have dispersed, as Rodinia did, only for its constituent continental blocks to reassemble into Paleoproterozoic equivalents of Gondwana, Laurussia, and Pangea. These Paleoproterozoic equivalents should have had the same general configuration or shape as their Neoproterozoic-Paleozoic counterparts, and should have assembled and broken up in the same manner.

The Paleoproterozoic equivalents of the Neoproterozoic-Paleozoic supercontinents Rodinia and Pangea should have had the same relative relationship to the positive excursions in C and Sr isotopes of marine carbonates (fig. 5a). From this, it is possible to predict that the Paleoproterozoic equivalent of Rodinia should have formed around 2.5 Ga, while the equivalent of Pangea should have formed around 1.8 Ga (fig. 5a). Based on previously proposed names for supercontinents at these periods of time, the Rodinia equivalent will from here on be referred to as Kenorland (fig 5a; after Williams et al. 1991), while the Pangea equivalent will be referred to as Columbia (fig. 5a; after Meert 2012; Rogers and Santosh 2002). Regarding Columbia, it is interesting to note that Rogers and Santosh (2002) recognized many similarities between their proposed reconstruction and Pangea.

As seen in the timeline in figure 5a, there appears to be a cyclic pattern, whereby supercontinents equivalent to Rodinia and Pangea alternate every 750 Myr since ca. 2.5 Ga. This suggests that the Proterozoic-Phanerozoic is defined by these two types of configurations. These will from here on be referred to as R- and P-type supercontinents, respectively. Most configurations for Rodinia suggest that it formed a circular aggregation of continental blocks (e.g. Evans 2013; Li et al. 2008) while Pangea reconstructions indicate that it assumed a crescent-like shape (e.g. Stampfli et al. 2013; Torsvik et al. 2012). It can therefore be inferred that these shapes define R- and P-type supercontinents, respectively.

Based on the alternating pattern of R- and P-type supercontinents, it can also be predicted that the next supercontinent should be an R-type, and that the proposed supercontinent Amasia will form some 500 Myr into the future (fig. 5a; Hoffman 2004).

## 4.2. Supercontinent cycles

### *4.2.1. Onset of supercontinent cycles*

The inferred cyclic pattern of R- and P-type supercontinents during the Proterozoic-Phanerozoic Eons appears to have started with the assembly of Kenorland at ca. 2.5 Ga (fig. 5a). There are no known positive excursions in C and Sr isotopes of marine carbonates in the Archean that would support the existence of R- and P-type supercontinents prior to 2.5 Ga. In addition, the inferred assembly of Kenorland followed an apparent transition period between 3.2-2.5 Ga, when plate tectonics similar to today might have been established (fig. 5a; e.g. Cawood et al. 2006; Condie and Kröner 2008; Dhuime et al. 2012; Keller and Schoene 2012; Næraa et al. 2012; Shirey and Richardson 2011). In addition, the end of this period also saw widespread cratonization and formation of subcontinental lithospheric mantle (Evans 2013; Griffin et al. 2014; Rogers 1996; Windley 1984, 1995).

The end of the transition period seems like a natural starting point for Proterozoic-Phanerozoic supercontinent cycles. As such, these cycles would be intimately tied to plate tectonics and the formation of cratonic lithosphere. Furthermore, as the lithosphere appears to form a boundary layer of the convecting mantle (e.g. Bercovici 2003), the repetitive pattern of R- and P-type supercontinents may be viewed as the surface expression of a convective pattern in the mantle, which was initiated following the transition period. Prior to the transition period, another convective pattern would have defined the mantle, perhaps involving some form of stagnant lid or episodic plate tectonics (fig. 5a; e.g. Cawood et al. 2006; Ernst 2009; Hamilton 2011).

If Kenorland was the first supercontinent, and reconstructions of Rodinia are accurate in the sense that it formed a circular aggregation of continental crust, then this shape becomes significant. From a global compilation of detrital zircon analyzed for Hf-isotopes, Griffin et al. (2014) found that the εHf composition of zircon between 2.9-2.5 Ga showed a spread towards both high and low values, indicating input from both juvenile and mature sources. This signature is found in orogenic belts that are subject to continuous accretion of continental blocks, as seen in the assembly of Gondwana and Eurasia (Collins et al. 2011; Spencer et al. 2013). Griffin et al. (2014) proposed that the data reflected the assembly of a supercontinent at ca. 2.5 Ga. If the data is representative for Neoarchean accretionary-collisional orogens, then the assembly of Kenorland at 2.5 Ga may have resulted from the continental crust being "sucked" into one place during the transition period.

The assembly of Kenorland could have had a stabilizing effect on the convective mantle, as most continental crust would have been located in one place. It could therefore be envisioned that the onset of plate tectonics that operated in a similar manner to today in the Meso-Neoarchean initiated a transitional convective pattern within the mantle. This convection ultimately led to the assembly of the first supercontinent, Kenorland, in the shape of a circular aggregation of crust. Its break-up would have marked the onset of Proterozoic-Phanerozoic supercontinent cycles.

#### *4.2.2. Nature of supercontinent cycles*

Evidence for supercontinents in the Archean remains elusive, so assuming that there were no R- or P-type supercontinents prior to around 2.5 Ga, Kenorland is left as the first supercontinent (fig. 5a). The inferred cyclic pattern of R- and P-type supercontinents would thus have begun with the break-up of an R-type supercontinent. In this context, the Proterozoic-Phanerozoic Eons can be said to be defined by R- to R-type (R-R) supercontinent cycles. The first such cycle corresponded to the break-up of Kenorland and assembly of Rodinia while the second and ongoing cycle span the break-up of Rodinia and the predicted future assembly of Amasia (fig. 5a). "Modern-style" plate tectonics (e.g. Stern 2008) appear to be associated with the Rodinia-Amasia cycle (fig. 5a).

The defining role of R-type supercontinents puts the P-type supercontinents in a subordinate role. As they form halfway through an R-R cycle, the P-type supercontinents may be viewed as marking the shift from break-up of the initial R-type supercontinent to assembly of the next one (fig. 5a). The “assembly” of a P-type supercontinent would in this situation correspond to the final stages of break-up of a preceding R-type supercontinent, while its “break-up” correspond to the assembly of the next R-type supercontinent.

This is not only a question of semantics, because when the R-R cycles are placed in relation to significant oxygenation events in Earth’s history, it is clear that these follow the break-up of R-type, but not P-type, supercontinents (fig. 5b). It has previously been noted that changes in biogeochemical cycles and atmospheric oxygenation during the Paleoproterozoic and Neoproterozoic-Paleozoic might have had the same cause, corresponding to break-up of supercontinents (e.g. Papineau 2010). However, the proposal here is more specific in that they are tied to the break-up of a particular type of supercontinent configuration.

The absence of atmospheric oxygenation events following P-type supercontinents (fig. 5b) could be explained by considering them as a transient stage during a given R-R cycle. Atmospheric oxygenation events are thus connected to a specific global geodynamic context, corresponding to the break-up of R-type supercontinents (e.g. Rodinia to Pangea). This setting must involve a combination of factors (such as the abundance, size and geographical position of rift zones, accretionary orogens, and collisional orogens), which facilitate the accumulation of oxygen in the atmosphere. These conditions must in turn be missing during the assembly of R-type supercontinents (e.g. Pangea to Amasia).

#### 4.3. Rodinia-Amasia – predicting a full R-R cycle

The purpose of this section is to briefly review the break-up history of Rodinia, and how its constituent continental blocks came to be rearranged into their current positions. In addition, an attempt will also be made to predict the configuration of the inferred future R-type supercontinent Amasia. This will provide a general picture of a full R-R cycle, which can act as a blueprint for the Kenorland-Rodinia cycle and make it possible to reverse engineer Columbia and Kenorland from Rodinia.

Of interest here are the major movements of continental blocks during the ongoing Rodinia-Amasia cycle. The Neoproterozoic-Phanerozoic paleogeographic history of individual continental blocks is generally not constrained well enough to accurately trace their movements step-by-step. However, there is enough data to broadly divide major continental blocks into crustal groups, each of which are characterized by a distinct history during the Neoproterozoic-Phanerozoic. By focusing on the relative motions of these crustal groups, rather than individual continental blocks, it is possible to broadly characterize their absolute and relative movements. These can subsequently be applied to the Kenorland-Rodinia cycle.

#### *4.3.1. Crustal groups in the Neoproterozoic-Phanerozoic*

The starting point for this division are the Phanerozoic Pangaea and Panthalassa whole-mantle convection cells proposed by Collins (2003), which permits the lithosphere to be divided into two domains. The Panthalassa cell only encompasses oceanic lithosphere, and corresponds to the current Pacific Ocean (fig. 6). In contrast, the Pangaea cell contains both continental and oceanic lithosphere. The boundary between the two cells is marked by semi-continuous accretionary orogens (the “Pacific Ring of Fire”), where oceanic crust within the Panthalassa cell is subducted beneath the Pangaea cell. While the model by Collins (2003) only covered the Phanerozoic, there seems to be no reason for why this first order division of the crust and mantle could not have been present during the Neoproterozoic, which we assume here.

The Pangaea cell can be further subdivided, based on long-lived associations among its constituent continental blocks. We here divide the Pangea cell into four crustal groups; corresponding to Laurussia, West Gondwana, East Gondwana, and Central Asia. The spatial distribution of these crustal groups in Pangea at 180 Ma and today are shown in figures 6a and

6b, respectively. The division is loosely based on Rino et al. (2008), who recognized long-lived associations of continental blocks on the basis of the distribution of detrital zircon ages.

The boundaries between the crustal groups are comprised of major orogenic belts related to the assembly of Pangea (fig. 6a), and which extends from the centre of the Pangaea cell towards its margin. These correspond to the Variscan-Alleghanian-Ouachita orogens (Nance et al. 2010), the Uralides (e.g. Brown et al. 2008; Ivanov et al. 2013), the East African Orogen (Fritz et al. 2013; Jacobs and Thomas 2004), and the Tethysides (Metcalfe 2013; Şengör 1987), which represent the collision zone of East Gondwanan blocks against Asia.

The crustal groups include the following major continental blocks, based on their relationship to the orogenic belts that define the crustal groups (fig. 6a).

- The Laurussia group: Laurentia and the East European Craton.
- West Gondwana group: Amazon, West African, Congo, Kalahari, São Francisco, and Rio de la Plata cratons
- East Gondwana group: Peninsular India, Australia, the Mawson Craton in Antarctica, and the Tarim Craton.
- Central Asian group: The Siberian, North China, and South China Craton.

As the crustal groups represent a subdivision of the Pangaea cell, they can also contain oceanic crust, as shown in figure 6. While the oceanic lithosphere is just as integral to these groups as the continental lithosphere, it is only the latter that survives over longer timescales (>200 Myr). The crustal groups represent a dynamic association of continental blocks, which may go through periods of rifting, drifting and collision over the course of a supercontinent cycle.

The concept of crustal groups is fundamental to the understanding of the supercontinent cyclicity as envisioned here. The inclusion of oceanic crust means that crustal groups differ from a coherent and rigid-semi-rigid continent. It creates a hierarchy in which continental blocks can drift relative to each other within crustal groups, which in turn move relative to each other. Therefore, while different apparent polar wander paths may show that two continental blocks were drifting separately, they may still have been part of the same crustal group. Furthermore, the inclusion of oceanic crust implies a connection between the crustal groups and the mantle, and the former may perhaps be seen as surface expressions of subcells within the greater Pangaea cell.

The movements of the crustal groups during the Rodinia-Amasia cycle represent a generalization of the movements of their constituent continental blocks. These can be used to define general rules that can subsequently be applied to the Kenorland-Rodinia cycle. However, the nature of the crustal groups also places constraints on how their constituent continental blocks can move during each cycle, as they must remain coherent as one unit comprised of continental and oceanic lithosphere. This is useful when dealing with continental blocks for which there are relatively few paleogeographic constraints, as their general movements can be inferred from other continental blocks in their crustal groups.

***4.3.2. Rodinia-Pangea***

The following simplified reconstruction is based on Li et al. (2008). It is intended to show the main movements of the crustal groups introduced above during the break-up of Rodinia (fig. 7a), up and until the assembly of Pangea (fig. 7d; after Seton et al. 2012). The paleogeographic reconstructions are complemented by conceptual sketches depicted the broad movements of the crustal groups. The reconstruction by Li et al. (2008) is chosen here only as an example to illustrate the behaviour of the crustal groups. The concept itself is equally applicable to other Rodinia configurations.

The breakup of Rodinia started shortly after 0.90 Ga as continental blocks in East Gondwana began to rift from what is today the western margin of Laurentia (fig. 7b; Hoffman 1991; Li et al. 2008). This was followed by a period between ca. 0.90-0.65 Ga when more blocks were rifted from Rodinia. Gondwana assembled between ca. 0.65-0.50 Ga when the blocks of East Gondwana were accreted against West Gondwana through the consumption of a series of oceans (fig. 7b-c).

The assembly of Gondwana coincided with the final breakup of Rodinia's core as the West Gondwana blocks rifted from the Laurussian blocks (fig. 7c; Li et al. 2008; Stampfli et al. 2013). This was followed by a period of convergence between 0.5-0.3 Ga during which Laurussia was formed through collision between Laurentia and the East European Craton (Stampfli et al. 2013; Torsvik et al. 2012). This period ended with the assembly of Pangea at ca. 0.3 Ga as Laurussia collided with Gondwana along the Variscan-Alleghanian-Ouachita Orogen (fig. 7d; Nance et al. 2010; Stampfli et al. 2013; Torsvik et al. 2012) and Central Asia was amalgamated (Wilhelm et al. 2012; Windley et al. 2007) and sutured with Laurussia along the Uralides (fig. 7d; Brown et al. 2008; Stampfli et al. 2013; Torsvik et al. 2012). The assembly of Gondwana also coincided with rifting of continental blocks from the northern margin of East Gondwana, which accreted against southern Asia along the Tethysides (fig. 7d; Metcalfe 2013; Şengör 1987).

The West and East Gondwana groups went through the most significant relative displacement during the break-up of Rodinia. From Rodinia to Pangea, the blocks rotated counter-clockwise relative to the Laurussian group. This left the East Gondwana group in Pangea (fig. 7d) on the opposite side of the Laurussia group compared to its position in Rodinia (fig. 7a). For the West Gondwana group, the rotation caused the West African Craton to become sutured with blocks from the Laurussian group in Pangea (fig. 7d). In Rodinia, the

West African Craton was separated from the Laurussian group by the Amazon Craton (fig. 7a).

The movement of the Central Asian group is very uncertain, owing to the poorly constrained Neoproterozoic history of its constituent continental blocks (e.g. Johansson 2014; Li et al. 2008). Based on their relative position in Rodinia and in Pangea (cf. figs. 7a and 7d) it might be inferred that the Central Asian group went through a net 180° clockwise rotation from Rodinia to Pangea. However, this is based on the tentative inclusion of the South China Craton into the Central Asian group. If it was rather included with the East Gondwana group, the Central Asian group would not have been subject to any net displacement from Rodinia to Pangea. The Laurussia group is otherwise alone in that significant relative displacement between its position in Rodinia and in Pangea did not occur (cf. figs. 7a and 7d).

#### *4.3.3. Pangea to Amasia*

The break-up of Pangea led to the opening of the Atlantic and Indian oceans, simultaneously with continued accretion of East Gondwanan blocks against Central Asia (Seton et al. 2012; Metcalfe 2013). This led to the present-day distribution of the crustal groups (fig. 8a), which is similar to their positions in Pangea (fig. 7d).

Based on the prediction that Amasia should be an R-type supercontinent, the crustal groups and their constituent continental blocks should rearrange from their current positions (fig. 8a) into a configuration equivalent to Rodinia. Considering the rotation of the crustal groups relative to each other during the break-up of Rodinia (fig. 7) it is clear that it will be impossible to assemble an exact replica of Rodinia within the allowed timeframe (ca. 500 Myr). However, it would be possible to assemble a supercontinent with the same shape as Rodinia, and in which the West and East Gondwana blocks assume the same relative position and orientation.

The assembly of such an equivalent to Rodinia could be achieved by closure of the Atlantic Ocean by suturing North and South America with Europe and Asia, suturing the continental blocks within the West Gondwana and Laurussia crustal groups (fig. 8b). Meanwhile, closure of the Indian Ocean would be achieved by accretion of Antarctica to southern Asia, while Australia should be accreted to Southeast Asia (fig. 8b). This would place the East Gondwana group outboard to the Central Asia group. Finally, South America and Africa (the West Gondwana group) should rotate relative North America and Europe (the Laurussia group) so that the Andes would collide with the North American Cordilleras (fig. 8b). Such movements could be accommodated by development of intracontinental strike-slip orogenic belts.

The movements proposed above would create a supercontinent with a general configuration equivalent to Rodinia (cf. figs 7a and 8b). However, it is important to remember that the predicted configuration of Amasia is entirely dependent on an accurate reconstruction of Rodinia. The following discussion has been based on the reconstruction by Li et al. (2008), but a different Rodinia configuration would yield a different Amasia configuration. Nevertheless, the fundamental concept of R-R cycles and crustal groups would remain the same.

Upon comparison, it is evident that Rodinia and the predicted configuration of Amasia are different, implying that consecutive R-type supercontinents are not identical in detail. This is the result of rotation of crustal groups during the break-up of Rodinia, which culminates with the formation of Pangea (fig. 7). While they have the same overall shape, the relative orientation and position (in the case of East Gondwana) of the crustal groups differs. The only exception is the West Gondwana group, which assumes the same relative position and orientation in the predicted Amasia configuration as in Rodinia.

## 5. A model for the assembly of Rodinia from Kenorland

The aim of this section is to outline a conceptual model for the Kenorland-Rodinia supercontinent cycle, using the Rodinia-Amasia cycle as a blueprint. Based on the latter, there are a number of constraints that must be taken into account when it is applied to the Kenorland-Rodinia cycle.

1) The break-up of Rodinia spanned the Neoproterozoic-Paleozoic Eras, and was associated with a set of positive excursions in $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ (fig. 5). As the same set of excursions developed during the Paleoproterozoic, it can be inferred that Kenorland broke up in the same manner as Rodinia, in order to generate the same signal in the isotopic record.
2) The Cenozoic increase in $^{87}Sr/^{86}Sr$ has been attributed to the Himalayan orogeny (Shields 2007), resulting from the collision between Peninsular India and southern Asia. By analogy with the Rodinia-Amasia cycle, an equivalent increase in $^{87}Sr/^{86}Sr$ should have taken place around 1.5 Ga, 500 Myr after the 2.0 Ga peak in $^{87}Sr/^{86}Sr$ (fig. 5). The fact that such an increase has not been detected indicates that an equivalent to the India-Asia collision did not occur in the Mesoproterozoic. From this, it can be inferred that the Paleo-Mesoproterozoic equivalent of Gondwana did not break-up following the formation of Columbia at ca. 1.8 Ga. By extension, it can be further inferred that there were no Paleo-Mesoproterozoic equivalents of the Atlantic and Indian Oceans. This is in contrast to the Mesozoic-Cenozoic break-up of Pangea and Gondwana (e.g. Metcalfe 2013; Seton et al. 2012).
3) By analogy with the Neoproterozoic-Phanerozoic, the Panthalassa and Pangaea whole-mantle convection cells would also have existed in the Paleo-Mesoproterozoic. This implies that the Panthalassa and Pangaea cells of Collins (2003) correspond to long-

lived features that form an integral part of the convective pattern that was initiated at 2.5 Ga.

4) As for the Rodinia-Amasia cycle, the Pangaea convection cell should be divided into four subcells, represented on the surface by crustal groups. All continental blocks within Rodinia should thus be distributed among the Paleo-Mesoproterozoic equivalents of the Laurussia, Central Asia, West Gondwana and East Gondwana crustal groups.

### 5.1. Crustal groups in the Paleo-Mesoproterozoic

The crustal groups during the Kenorland-Rodinia cycle should be defined by Paleo-Mesoproterozoic equivalents of the East African Orogen, Variscan-Alleghanian-Ouachita orogens, and the Uralides. The crustal groups are established during break-up of an R-type supercontinent and remain intact throughout an R-R cycle. It should therefore be possible to identify the crustal groups during the Kenorland-Rodinia cycle by determining the distribution of the Paleo-Mesoproterozoic equivalents of the East African Orogen, Variscan-Alleghanian-Ouachita orogens and the Uralides (see section 3) within a reconstruction of Rodinia (the version by Li et al. 2008 is used here).

#### *5.1.1. The Variscan-Alleghanian-Ouachita orogens*

The Svecofennian and Central Russian orogens were identified in section 3.1 as the Paleo-Mesoproterozoic equivalents of the Ouachita and Alleghanian orogens. It is further proposed here that the North China Craton may correspond to the Variscan Orogen, as its Paleoproterozoic history has many similarities with the Svecofennian Orogen (Kusky and Santosh 2009). The extent of the Svecofennian-Central Russian orogens and the North China Craton within Rodinia is shown in figure 9a, where it separates the Volga-Sarmatia blocks from Fennoscandia.

#### *5.1.2. The East African Orogen*

As proposed in section 3.2, the Paleo-Mesoproterozoic equivalent of the East African Orogen is the Birimian Orogen in the West African and Amazon cratons. This orogen can therefore be used to distinguish the boundary between the Paleo-Mesoproterozoic equivalents of the West and East Gondwana crustal groups, as shown in figure 9a.

#### *5.1.3. The Uralides*

As proposed in section 3.3, the Trans-Hudson Orogen in Laurentia and Greenland is considered to be the Paleoproterozoic equivalent to the northern section of the Uralides, separating the Superior and North Atlantic cratons (referred to as Superior in figure 9a) from the Churchill Province. As the Uralides mark the boundary between the Laurussian and Central Asian groups, the Trans-Hudson Orogen is also extended here between the Siberian Craton and the North China Craton (fig. 9a). Altogether, the extended Trans-Hudson Orogen separates the Churchill Province and the Siberian Craton from the North China and Superior cratons.

#### *5.1.4. Additional constraints on Paleo-Mesoproterozoic crustal groups*

The distribution of the crustal groups within Rodinia are constrained by the Grenville orogen between the Amazon Craton and Laurentia (Li et al. 2008; Johansson 2009), which should be equivalent to the predicted collision zone between the North American Cordilleras and the South America Andes during the assembly of Amasia (see section 4.3.3). That predicted collision zone should lead to juxtaposition of the West Gondwana and Laurussian groups (fig. 8b), and the Grenville Orogen may thus be inferred to mark the boundary between the Gondwana and Laurussian crustal groups during the Kenorland-Rodinia cycle (fig. 9a).

There is no distinct orogen between the Paleo- Mesoproterozoic equivalents of the East Gondwana and Central Asian groups, but the boundary is drawn here between the Kalahari Craton on the one hand and the Mawson Craton and Peninsular India on the other (fig. 9a), as this is also the boundary between the West and East Gondwana groups during the break-up of Rodinia (fig. 9b). It also coincide broadly with orogenic belts that developed during the assembly of Rodinia (Li et al. 2008), and which could potentially mark the collision between the Paleo- Mesoproterozoic equivalents of the East Gondwana and Central Asian groups.

#### *5.1.5. Distribution of continental blocks in crustal groups*

Based on their relationship to the defining orogenic belts (fig. 9a), the Paleo-Mesoproterozoic crustal groups (denoted with an * to distinguish them from their Neoproterozoic-Phanerozoic analogues) can be said include the following major continental blocks (other reconstructions of Rodinia could potentially lead to a different distribution).

- The Laurussia* group: Fennoscandia, Superior Craton, and the North China Craton
- The West Gondwana* group: Amazon and West African cratons, and the Volgo-Sarmatia blocks.
- The East Gondwana* group: Congo, São Francisco, Kalahari, and Rio de la Plata cratons
- The Central Asia* group: Peninsular India, Australia, the Mawson Craton in Antarctica, Siberian Craton, Churchill Province, South China Craton, and the Tarim Craton.

Figure 9 shows the distribution of continental blocks among the four crustal groups during the assembly of Rodinia (i.e. Kenorland-Rodinia cycle, figure 9a) and the break-up of Rodinia (Rodinia-Amasia cycle, figure 9b). While the same four crustal groups can be recognized during both cycles, it is clear that they do not always contain the same continental blocks. Indeed, the East Gondwana group during the Rodinia-Amasia cycle is entirely comprised of continental blocks that formed part of the Central Asian* group during the Kenorland-Rodinia cycle (cf. figs. 9a and 9b). However, in other crustal groups, the core continental blocks remain the same (e.g. Laurussia and West Gondwana).

The fact that the crustal groups during one R-R cycle do not survive intact into the next indicate that there is some form of break or "resetting" within the Pangaea cell when an R-type supercontinent is assembled. The crustal groups are established during break-up, but as each R-type supercontinent differs from its predecessor in how the crustal groups are distributed (see section 4.3.3), it becomes impossible to have continuous R-R cycles in which the crustal groups remain unchanged. Instead, in order for each R-type supercontinent to break-up in the same way, the Pangaea cell must be reset at the end of each R-R cycle. This might perhaps correspond to some form of stabilization of the convective pattern within the mantle, caused by the accumulation of all continental crust into one circular continent. As discussed in section 4.2.1, the same form of stabilization may have occurred at the end of the transition period at 2.5 Ga, when Kenorland assembled and the R-R cyclicity was first initiated.

### 5.2. Rodinia-Columbia

The assembly of Rodinia should have been similar, but not identical to, the proposed assembly of Amasia from Pangea. A central part of this prediction is that the Laurussian and West Gondwana groups should collide, juxtaposing the North American Cordilleras with the Andes. If the Grenville orogen is the Mesoproterozoic equivalent to this collision zone, then it becomes relatively straightforward to reconstruct Columbia from Rodinia, as the West Gondwana* and Laurussian* groups only need to be rotated away from each other into a position when their joint margins form a long-lived accretionary orogen equivalent to the "Pacific "Ring of Fire". This movement is illustrated in figures 10a-c.

Given the inference that the East Gondwana* group would not have dispersed like East Gondwana did in the Mesozoic-Cenozoic, it follows that it must have remained attached to the West Gondwana* group during assembly of Rodinia (figs. 10a-b). However, the rotation of the West and East Gondwana* groups relative to the Laurussia* group could be expected to trigger the development of intercontinental orogenic belts and rift zones in different parts of the Gondwana* groups (fig. 10b).

The effect of this rotation would have been particularly pronounced within the East Gondwana* group, which would have been required to move a greater distance compared to West Gondwana* during the assembly of Rodinia from Columbia (figs. 10a-c). The outer tip of the East Gondwana* group would in that case have fallen behind the rest of the joint Gondwana* groups. This could have subjected the East Gondwana* group to tensional stresses, which may have caused rifting and drifting of continental blocks, as the tension within the crustal group was accommodated by the formation of oceanic lithosphere (fig. 10b). This may be recorded by the Kalahari Craton, which appear to have drifted separately during parts of the Mesoproterozoic (Jacobs et al. 2008) and which would have been positioned at the outer tip of the East Gondwana* group (based on its position in Rodinia, see fig. 9a). Other blocks within the East Gondwana group, such as the São Francisco and Congo Cratons, appear to record mainly intracontinental rifting during the Mesoproterozoic (e.g. Danderfer et al. 2009; Fernandez-Alonso et al. 2012).

While the reconstruction proposed here for Columbia is entirely inferred based on the Rodinia-Amasia cycle, it is interesting to note that it has many similarities with paleomagnetically constrained models. Figure 11 shows three Late Paleoproterozoic to Mesoproterozoic (ca. 1.8-1.3 Ga) models of Columbia that are deemed compatible with paleomagnetic and other geological data. The continental blocks are divided according to the crustal groups identified above. Notably, the crustal groups assume the same relative position in these reconstructions as in the inferred reconstruction of Columbia in figure 10c. No continental blocks from the East Gondwana group* are shown in figure 11, but the reconstructions allow for the group to be positioned next to the West Gondwana* group.

The position of the North China Craton varies, and the reconstruction by Zhang et al. (2012) shows it as detached from the other Laurussian* blocks (fig. 11c). This might suggest that the North China Craton rather belong to the Central Asian* group. However, the reconstruction by Evans and Mitchell (2011) in figure 11b shows the North China Craton in a position where it forms an extension of the Fennoscandian block in the East European Craton. This reconstruction places the North China Craton in the position it would be expected to have as the Paleo-Mesoproterozoic equivalent of the Variscan Orogen (as proposed in section 5.1.1).

Although there may be differences in detail, the inferred reconstruction of Columbia in figure 10 is at the very least compatible with other paleomagnetically constrained reconstructions. The different positions of some continental blocks could be either due to an incorrect division of the crustal groups within Rodinia but also due to the non-unique nature of paleomagnetic data, which allows for contrasting reconstructions. However, at this stage, the differences do not affect the underlying concept.

### 5.3. Columbia-Kenorland

Columbia should have formed at the end of the break-up of Kenorland, which is inferred to have occurred in the same manner as Rodinia. Starting from the Columbia configuration in figure 10c, the Gondwana* groups should thus be rotated clockwise relative to the Laurussia* group (figs. 10d-e). This is needed in order to compensate for the counter-clockwise rotation that is inferred for these groups during the break-up of Kenorland (ca. 2.4-1.9 Ga), by analogy with the Gondwana groups during the break-up of Rodinia (fig. 7).

By analogy with the break-up of Rodinia, the Laurussian* group should not involve any relative displacement between Kenorland and Columbia. However, it would lead to a period of accretion and amalgamation between ca. 2.0-1.8 Ga (fig. 10d), which was preceded by rifting and drifting between ca. 2.4-2.0 Ga (fig. 10e). Considering the uncertainty that surrounds the behaviour of the Central Asian group during the break-up of Rodinia, it is problematic to apply it on the Kenorland-Rodinia cycle. However, if the Central Asian* group behaved in the same way, it would have to rotate 180° counter-clockwise from its position in Columbia in order to restore it to its original position in Kenorland (fig. 10c-f).

The East Gondwana group rifted from the western margin of Laurentia during the break-up of Rodinia, which later became the site of the North American Cordilleras (e.g. Li et al. 2008). By analogy, the continental blocks in the East Gondwana* group should have rifted from Laurussian* blocks, along whose margin a long-lived accretionary orogen should subsequently have developed. Among the Laurussian* continental blocks, such a long-lived accretionary orogen found in western Fennoscandia and eastern Laurentia, where it is represented by a series of Paleo-Mesoproterozoic orogenic belts (e.g. Bogdanova et al. 2008; Johansson 2009). These accretionary orogens would thus be Paleoproterozoic equivalents of the North American Cordilleras.

A simple reconstruction of the distribution of the crustal groups in Kenorland is shown in figure 10f. This places the West Gondwana* group in the same relative position as in Rodinia and the predicted configuration of Amasia (cf. figs 7a, 8b, 10b and 10f). Note that since the East Gondwana* group remained attached to the West Gondwana* group, it also came to assume the same position and orientation in Kenorland as it had had in Rodinia (cf. figs 10a and 10f). Within Kenorland, the East Gondwana* group is placed in contact with the Laurussia* group (fig. 10f), which should correspond to Archean crust in Fennoscandia and Laurentia, outboard to which long-lived accretionary orogenic belts developed in the Paleo-

Mesoproterozoic (Bogdanova et al. 2008; Whitmeyer and Karlstrom 2007). These orogenic belts would thus have formed on a rifted margin, equivalent to how the North American Cordilleras formed on the rifted margin of western Laurentia, along which the East Gondwana blocks had been attached in the Neoproterozoic (e.g. Hoffman 1991; Li et al. 2008). Finally, the Central Asian* group is placed on the opposite side of Laurussia* from the West Gondwana* group.

## 6. Summary

The main point of this paper is the hypothesis that the global tectonic evolution during the Neoproterozoic-Paleozoic and Paleoproterozoic Eras was principally the same. This implies that Paleoproterozoic orogenic belts should have Neoproterozoic-Paleozoic equivalents. From this, it is possible to make broader inferences relating to supercontinent configurations and cycles during the Proterozoic-Phanerozoic Eons.

Based on the above hypothesis, we have proposed a model that stipulates that the geosphere in the Proterozoic-Phanerozoic Eons was characterized by a cyclic convective pattern in the mantle. This is expressed in the lithosphere by supercontinent cycles, which alternate between two basic types of configurations, equivalent to Rodinia and Pangea. We refer to these as R- and P-type supercontinents, respectively.

The first supercontinent, Kenorland, formed after a transition period between 3.2-2.5 Ga, when the current convective pattern in the mantle was established. As Kenorland is inferred to have been an R-type supercontinent, the break-up and assembly of R-type supercontinents amount to “true” supercontinent cycles, each of which lasts approximately 1.5 Gyr. From this, we predict that the next supercontinent, Amasia, should be an R-type and assemble in some 500 Myr.

In this context, P-type supercontinents represent a transient stage during such cycles. It is therefore wrong to speak about the assembly and break-up of P-type supercontinents, as these processes rather record the break-up and assembly of two consecutive R-type supercontinents. Significant oxygenation events and perturbations of biogeochemical cycles (e.g. Holland 2006; Och and Shields-Zhou 2012; Papineau 2010) only occur during the break-up of R-type supercontinents.

Based on the hypothesis, it is also inferred that the Pangaea and Panthalassa whole-mantle convection cells of Collins (2003) are long-lived features, which form an integral part of the Proterozoic-Phanerozoic convective pattern in the mantle. Furthermore, we argue that the Pangaea cell may be subdivided into subcells, represented on the surface by crustal groups. Understanding the behaviour of the crustal groups during the Neoproterozoic-Phanerozoic makes it possible to constrain broad rules for their movements during the Rodinia-Amasia cycle. This knowledge can then be applied to “reverse engineer” Kenorland from a reconstruction of Rodinia.

The existence of crustal groups also provide an explanation for the continued juxtaposition of the same continental blocks in paleogeographical reconstructions, which has been noted previously by many authors (e.g. Bleeker 2003; Johansson 2009, 2014; Meert 2014; Pehrsson et al. 2013; Rogers 1996; Rogers and Santosh 2002). While crustal groups do not necessarily assume the same role during each R-R-cycle and may also lose or gain continental blocks, their cores represent long-lived associations of continental blocks that have persisted since 2.5 Ga. This implies that continental blocks that have been adjacent during the Phanerozoic were also likely adjacent in the Precambrian.

The inference that there was one supercontinent in the Early Paleoproterozoic is at odds with the commonly held view that the continental crust was dispersed in multiple large continents or supercratons at that time (Bleeker 2003; Perhsson et al. 2013; Rogers 1996), and that Columbia was the first supercontinent. However, by analogy with the Neoproterozoic-Paleozoic there should be a supercontinent in the Early Paleoproterozoic (Kenorland), which should be equivalent to Rodinia and thus have the same general configuration. The existence of crustal groups, which by definition have distinct geological histories, may account for the contrasting histories of the inferred supercratons. However, these contrasting histories would not prevent them from being assembled into one supercontinent, as exemplified by Rodinia.

The above inferences can be made without any data on the tectonic evolution and paleogeography during the Paleo-Mesoproterozoic. However, it requires a good understanding of Neoproterozoic-Phanerozoic paleogeography and tectonic evolution and, most importantly, the Proterozoic-Phanerozoic isotopic record of marine carbonates and detrital zircon.

The heavy reliance on isotopic records could be seen as problematic, as it is dependent on a number of assumptions regarding their representativeness and first order connection to global tectonics. For this reason, it is reassuring to see that all records display the same changes during the Neoproterozoic-Paleozoic and Paleoproterozoic, as they would be expected to do if the global tectonic evolution was the same during these periods (the exception being Late Paleozoic excursions in $\delta^{13}C$, but these could be attributed to changes in the biosphere). Furthermore, the fact that the current records can be used to accurately predict Paleoproterozoic orogenic belts also indicates that they reflect real changes in global tectonics.

In essence, the model proposed here for Proterozoic-Phanerozoic supercontinent cycles provides a link that allows previously proposed concepts and models concerning mantle convection cells (Collins 2003) and long-lived associations of continental blocks (Johansson 2014; Rino et al. 2008; Rogers 1996) to be merged into a model for the evolution of the geosphere in the Proterozoic-Phanerozoic. In turn, this provides a framework for understanding Earth system evolution as a whole.

## 7. Outlook

The proposed model makes predictions of supercontinent cycles during the Proterozoic-Phanerozoic Eras. These predictions are testable, and one obvious means of testing them is with paleomagnetic data. The proposed movements of the crustal groups during the Paleo-Mesoproterozoic (fig. 10) should, if correct, be permitted by available paleomagnetic data. The availability of paleoGIS software such as GPlates (Williams et al. 2012), together with a simplified global tectonic GIS, should make such testing relatively straightforward, technically speaking. However, this remains the subject of future work.

Taken together, the model presented here would act as a qualitative framework, while paleomagnetic data would provide absolute latitudinal constraints. Approximate longitude could potentially be derived from the position of the equatorial lower mantle African and Pacific Large Low Shear-Wave Velocity Provinces (LLSVPs, e.g. Garnero and McNamara 2008; Lekic et al. 2012), which currently coincide spatially with the Pangaea and Panthalassa cells, respectively. By analogy, a similar relationship can be inferred to have existed in the Paleo-Mesoproterozoic, and the current position of the LLSVPs could thus be used to "guesstimate" the longitude of continental blocks at that time. For example, the longitude of Pangea at ca. 0.3 Ga, constrained by the spatial coincide of Large Igneous Provinces with the margins of the African LLSVP (Burke and Torsvik 2004), should be analogous to that of Columbia at ca. 1.8 Ga. Combined with a tectonic GIS that incorporates crustal growth and orogenic activity, it would be possible reconstruct Kenorland from Rodinia and make a paleogeographic model spanning the Proterozoic-Phanerozoic Eons. However, it remains important to further constrain the Rodinia-Amasia cycle and, in particular, the configuration and break-up history of Rodinia, which is the key to understanding Kenorland and the Paleoproterozoic.

The model highlights the need to consider the dynamic nature of supercontinent cycles, and that it is necessary to consider their evolution as a whole, on timescales of billions of years. It is not enough to consider the configuration of a limited set of continental blocks during a brief period of time, as it is necessary to also account for how they came to be in that position, and how they evolved from there to reach their present positions. As pointed out by Johansson (2014), "…supercontinent configurations should not be regarded as isolated snapshots of the Earth, as map drawings in a paper may erroneously suggest, but as part of a continuously evolving geodynamic scenario".

The proposed model can provide a spatiotemporal framework for models concerning any aspect of the Proterozoic-Phanerozoic Earth. Notable areas include mantle convection, crustal growth/destruction, ore genesis, and perturbations in biogeochemical cycles. In addition, a successful reconstruction of Kenorland would also provide a springboard for understanding the evolution and paleogeography during the 3.2-2.5 Ga transition period, by illuminating the spatial relationships of Archean accretionary, collisional and extensional orogens within Kenorland.

A consequence of the R-R cycles is that the Neoproterozoic and Phanerozoic Eras appear to be related with respect to supercontinent cyclicity, as they formed part of the Rodinia-Amasia cycle. If the hypothesis withstands further testing, there might be reason to adjust the geological timescale to reflect these cycles. This could be done by extending the Phanerozoic Eon back to ca. 1.0 Ga. This would leave the Proterozoic Eon to represent the Kenorland-Rodinia cycle, whereas the Phanerozoic Eon represent the current Rodinia-Amasia cycle. These Eons may subsequently be divided into Eras in which each unit represents half-cycles, i.e. R-P cycles, and vice versa. This would mean that the division of the Eons and Eras in the geological timescale would be based solely on the evolution of the geosphere. Ranks lower than Eras (i.e. Periods, Epochs and Ages) would in contrast reflect the joint evolution of the atmosphere, biosphere, hydrosphere, and lithosphere. Such a distinction would emphasize the importance of the evolution of the geosphere for the evolution of the Earth system as a whole.

However, before getting too carried away with models that might become speculative it is important to remind oneself that the key to all this lies – as in all areas of Earth science – in detailed field work, followed by careful analysis and interpretation. Indeed, this paper would not have been possible to write without the hard field- and labwork by a multitude of geologists through the ages. Although the names and faces of many of these workers may have faded away from the contemporary geological discourse, their contributions live on by forming the foundation for those who have come after them. This may be the natural order of things, but every now and then it may be good to commemorate the effort of those who have spent much of their careers in the field, to the benefit of generations of Earth scientists (and hopefully to themselves!). This is especially true in a paper like this, which draws its conclusions entirely from previously collected data.

Among these geologists, Brian F. Windley (fig. 12) takes a prominent position. He is of course not alone, nor was he the first, but his career and achievements provide an excellent example of what characterizes a great practicing field geologist – a genuine interest in the Earth and the processes that has shaped it, together with a willingness to conduct field work in challenging locations and, not least of all, enthusiastically sharing the fruits of these efforts through supervision, teaching and publication; not least through his many editions of his book on the Evolving Continents that have been read by many budding geologists over the years. While our current understanding of the Earth cannot possibly be attributed to a single person it is safe to say that Brian has made significant contributions, which this paper has benefited from considerably.

## 8. Acknowledgements

The authors wish to thank reviewer Å. Johansson for detailed and constructive comments. An anonymous reviewer is also thanked for comments on the manuscript. Editor T. Kusky is thanked for patient handling of the manuscript and for giving it a second chance, despite initial verdicts from the reviewers that were less than enthusiastic. AS acknowledge financial support by the Swedish Research Council through grant #2012-5431.

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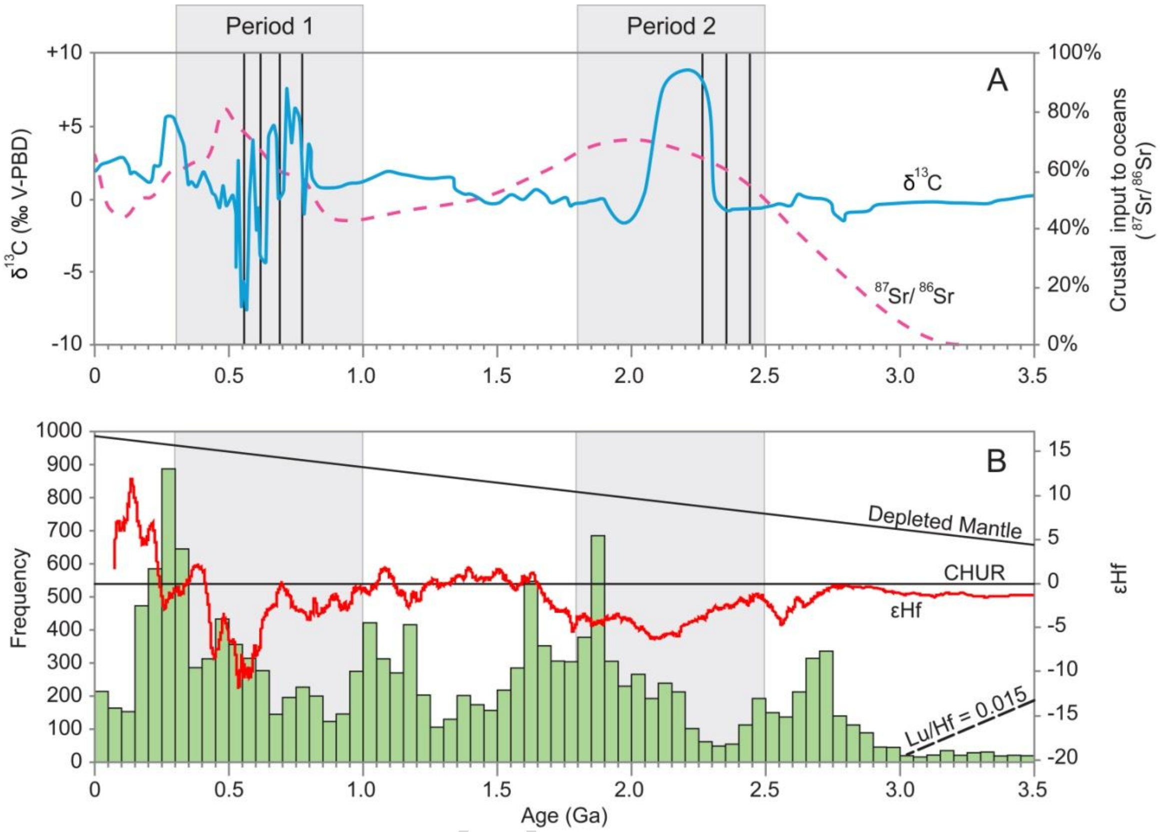


Fig. 1. <3.5 Ga secular evolution of the isotopic record of marine carbonates and detrital zircon. Vertical grey fields labeled Period 1 and Period 2 highlight stages during the Neoproterozoic-Paleozoic and Paleoproterozoic, respectively, when the records exhibit the same type of changes. **A)** C and Sr isotopes of marine carbonates. The $^{87}Sr/^{86}Sr$ curve is from Shields (2007), and is normalized to show the contribution (0-100%) of continental weathering (river runoff) to the average seawater composition. The $\delta^{13}C$ curve (running mean) is after Campbell and Allen (2008), with the exception of the interval 2.5-1.9 Ga, which is after the "least-assumption" reconstruction of Melezhik et al. (2013). The smoother shape of the $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ curves >1 Ga reflect a poorer temporal resolution in current datasets. Black vertical lines show the timing of major Proterozoic glaciations. Neoproterozoic glaciations after Campbell and Allen (2008) and Paleoproterozoic ditto after Hoffman (2013). **B)** The <3.5 Ga secular evolution of U-Pb ages and εHf running average of detrital zircons. U-Pb ages compiled after Belousova et al. (2010) and Campbell and Allen (2008). εHf curve from Spencer et al. (2013).

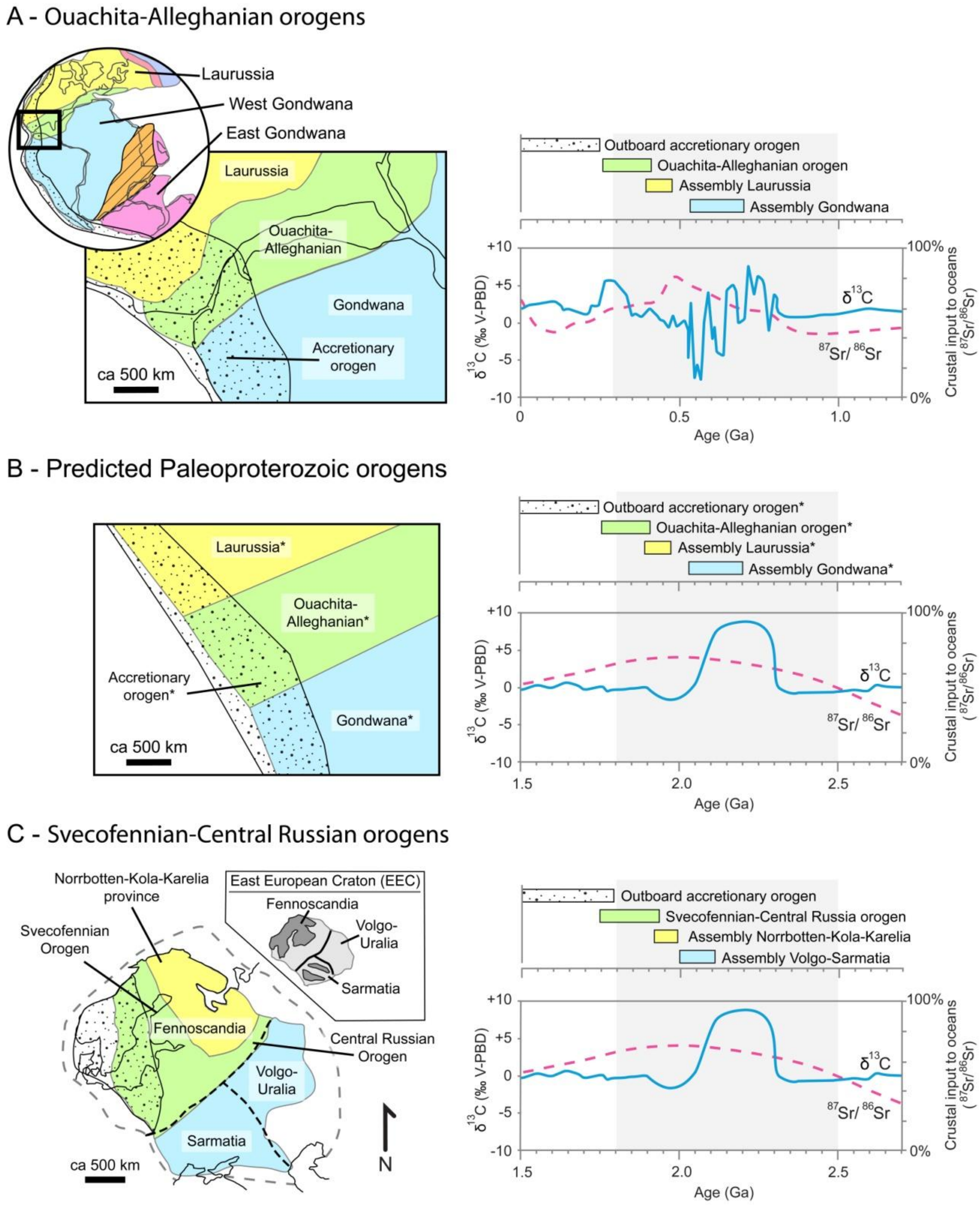


Fig. 2. **A)** A simplified map of the Ouachita-Alleghanian orogens and adjacent continental blocks (modified after Nance et al. 2010). The temporal extent of orogenic activity for each unit is shown in the graph, relative to the C and Sr isotopic record of marine carbonates during the Neoproterozoic-Paleozoic (see figure 1 for references). See section 3.1 for further discussion. Inset show the position of the Ouachita-Alleghanian orogens in Pangea.

Reconstruction modified after Nance et al. (2010). **B)** Model of the inferred Paleoproterozoic equivalent of the Ouachita-Alleghanian orogens (units denoted with *). The graph shows the predicted temporal extent of orogenic activity for each unit, based on their Neoproterozoic-Paleozoic equivalents (see graph in **A**). This model is derived independently of any Paleo-Mesoproterozoic geological data, other than Sr- and C-isotopes from marine carbonates. What remains is to test this model against other Paleo-Mesoproterozoic data, which amounts to the ground truth. **C)** Simplified geological map of the East European Craton (EEC; modified after Bogdanova et al. 2008). Inset show the main blocks of the EEC, dark areas highlight exposures of the EEC basement. Note that the orogenic belts and continental blocks within the EEC have the same spatial and temporal relationships as the model in **B**. On a first order scale, the model in **B** thus fits the Paleo-Mesoproterozoic ground truth.

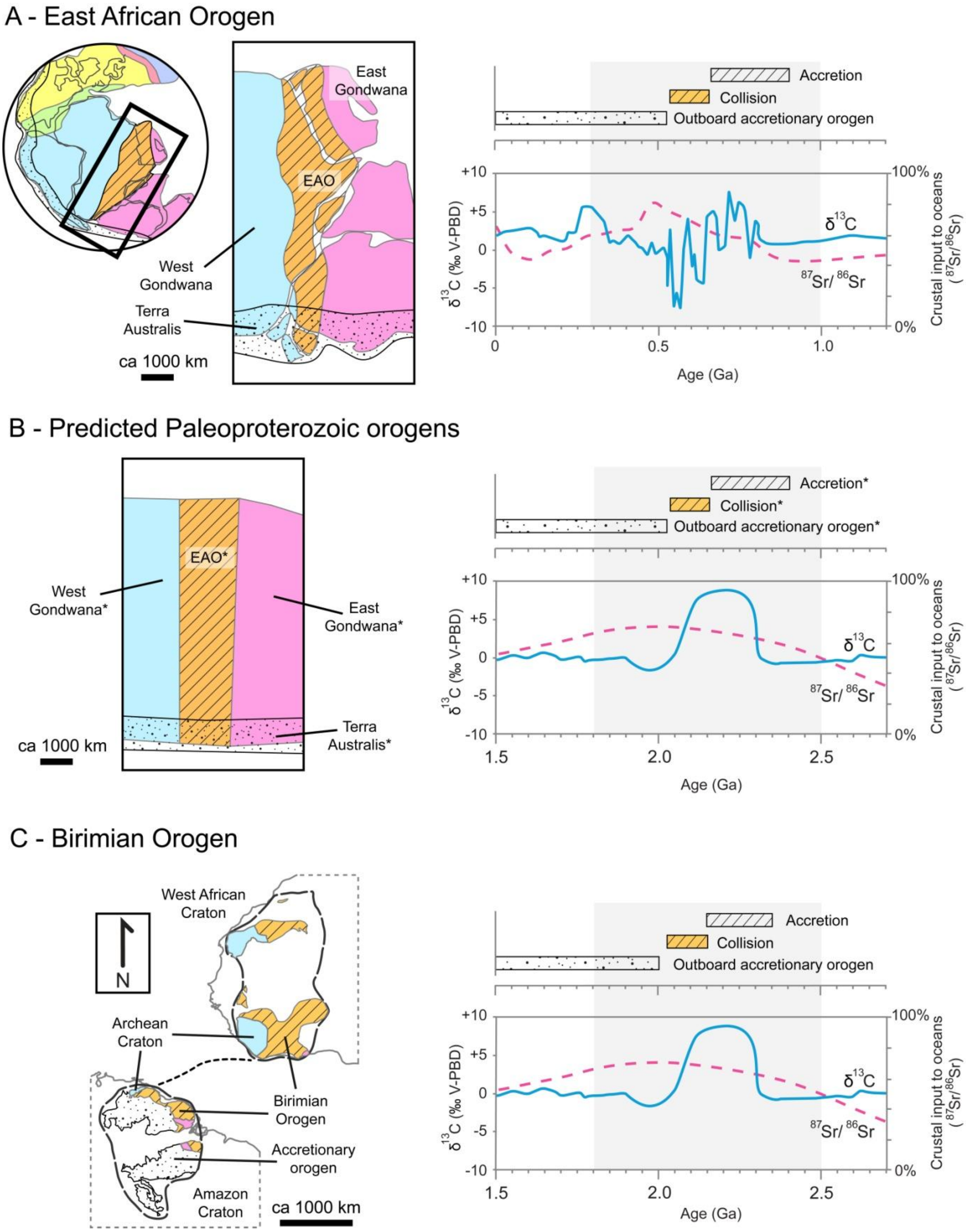


Fig. 3. **A)** A simplified map of the East African Orogen and adjacent continental blocks (modified after Jacobs and Thomas 2004). The temporal extent of orogenic activity for each unit is shown in the graph, relative to the C and Sr isotopic record of marine carbonates

during the Neoproterozoic-Paleozoic (see figure 1 for references). See section 3.2 for further discussion. Inset show the position of the East African Orogen in Pangea. Reconstruction modified after Nance et al. (2010). **B)** Model of the inferred Paleoproterozoic equivalent of the East African Orogen (units denoted with *). The graph shows the predicted temporal extent of orogenic activity for each unit, based on their Neoproterozoic-Paleozoic equivalents (see graph in **A**). This model is derived independently of any Paleo-Mesoproterozoic geological data, other than Sr- and C-isotopes from marine carbonates. What remains is to test this model against other Paleo-Mesoproterozoic data, which amounts to the ground truth. **C)** Simplified geological map of the Birimian Orogen in the West African and Amazon cratons (modified after Abouchami et al. 1990, Feybesse et al. 2006 and Cordani and Teixeira 2007). Dashed line show inferred connection between the West African and Amazon Cratons (after Onstott et al. 1984). Note that the orogenic belts and continental blocks within the West African and Amazon cratons have the same spatial and temporal relationships as the model in **B**. On a first order scale, the model in **B** thus fits the Paleo-Mesoproterozoic ground truth.

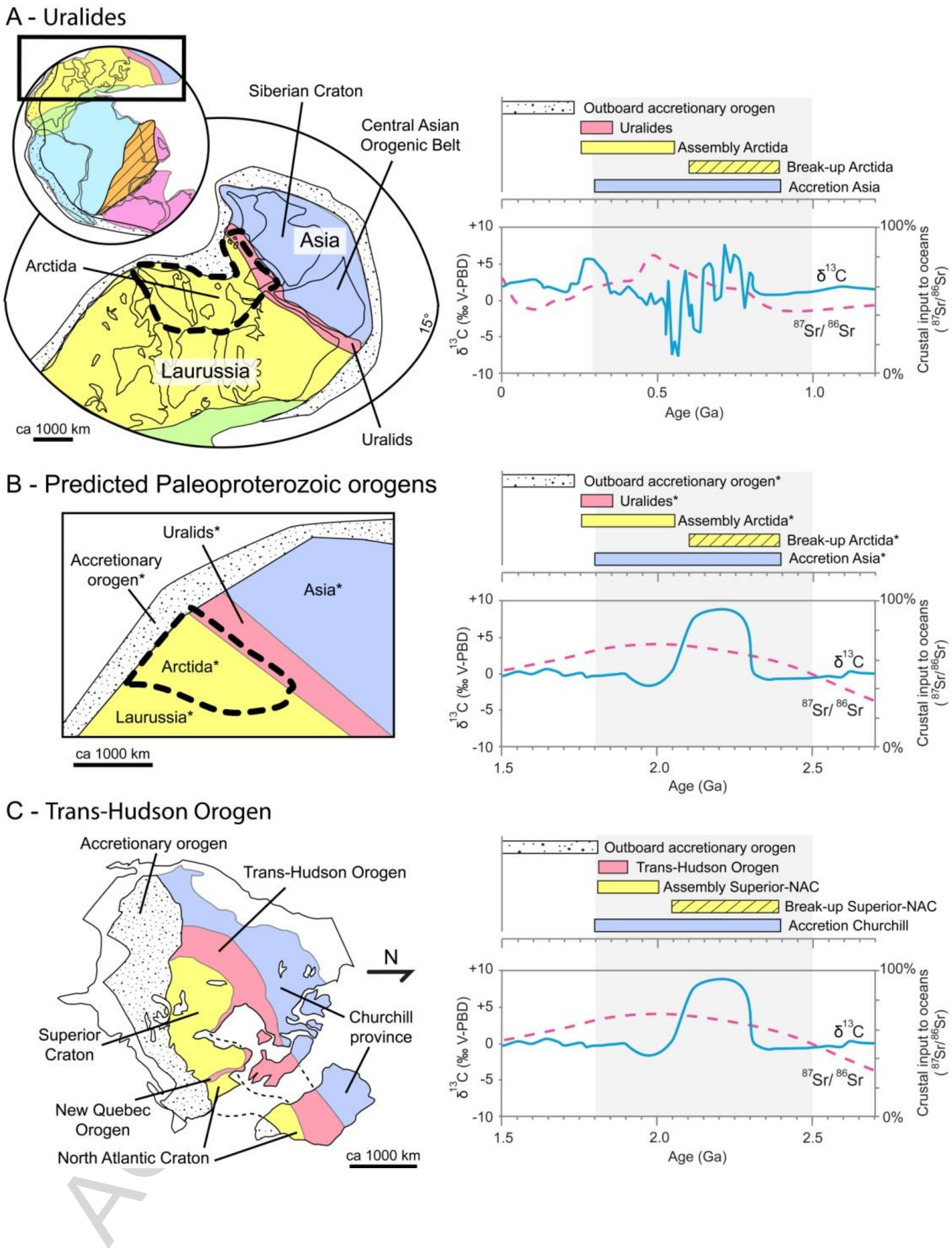


Fig. 4. **A)** A simplified map of the Uralides and adjacent continental blocks (modified after Metelkin et al. 2014). The temporal extent of orogenic activity for each unit is shown in the graph, relative to the C and Sr isotopic record of marine carbonates during the Neoproterozoic-Paleozoic (see figure 1 for references). See section 3.3 for further discussion. Inset show the position of the Uralides in Pangea. Reconstruction modified after Nance et al. (2010). **B)** Model of the inferred Paleoproterozoic equivalent of the Uralides (units denoted with *). The graph shows the predicted temporal extent of orogenic activity for each unit,

based on their Neoproterozoic-Paleozoic equivalents (see graph in **A**). This model is derived independently of any Paleo-Mesoproterozoic geological data, other than Sr- and C-isotopes from marine carbonates. What remains is to test this model against other Paleo-Mesoproterozoic data, which amounts to the ground truth. **C)** Simplified geological map of the Trans-Hudson Orogen in Laurentia (modified after Corrigan et al. 2009 and Whitmeyer and Karlstrom 2007). Note that the orogenic belts and continental blocks within Laurentia have the same spatial and temporal relationships as the model in **B**. On a first order scale, the model in **B** thus fits the Paleo-Mesoproterozoic ground truth. *Abbreviation*: **NAC** – North Atlantic Craton.

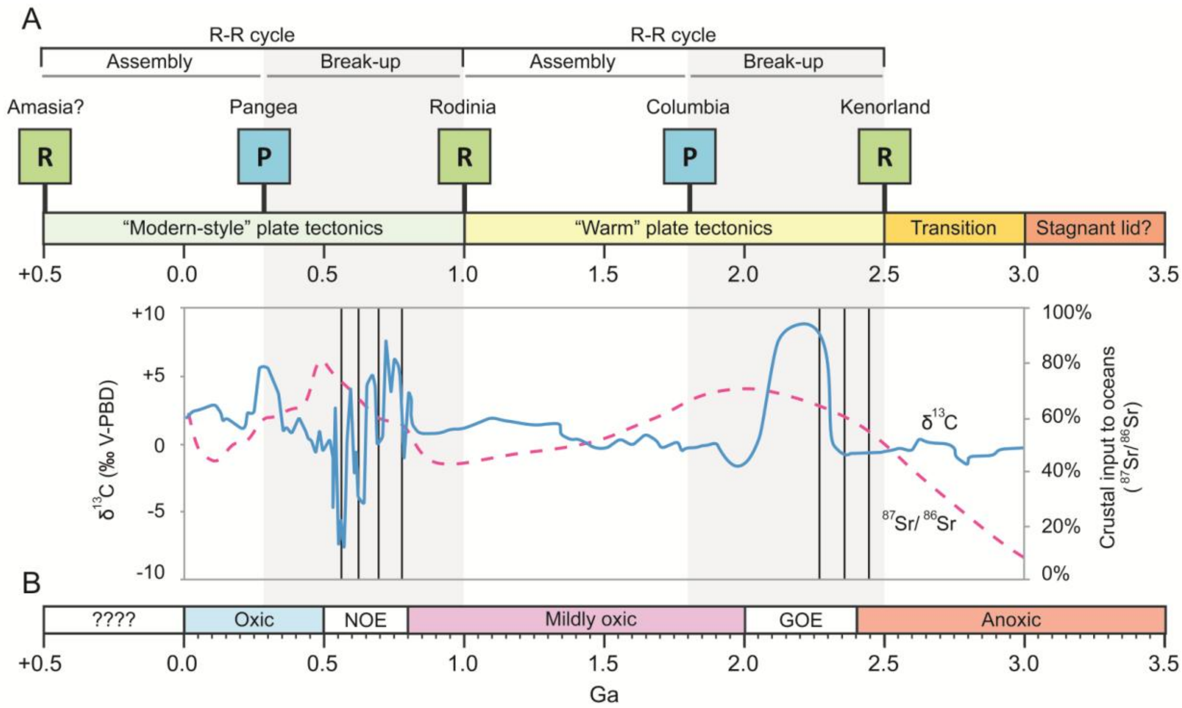


Fig. 5. The temporal distribution of supercontinent cycles, tectonic regimes and significant oxygenation events relative to changes in the isotopic record of marine carbonates (see references in figure 1a) **A)** The inferred distribution of R- and P-type supercontinents in Proterozoic-Phanerozoic, shown relative to the inferred temporal distribution of Precambrian tectonic regimes (see section 1). R-R cycles refer to the break-up of one R-type and the assembly of the subsequent iteration. In this context, P-type supercontinents are only a transient stage during this cycle, marking the shift from break-up of one R-type supercontinent and the assembly of the next. The predicted next R-type supercontinent, Amasia, is inferred to assemble in ca. 500 Myr. **B)** The temporal distribution of significant oxygenation events during the Paleoproterozoic and Neoproterozoic. Great Oxidation Event (GOE) after Holland (2006) and Neoproterozoic Oxygenation Event (NOE) after Och and Shields-Zhou (2012). Note how GOE and NOE coincide with the break-up of R-type supercontinents.

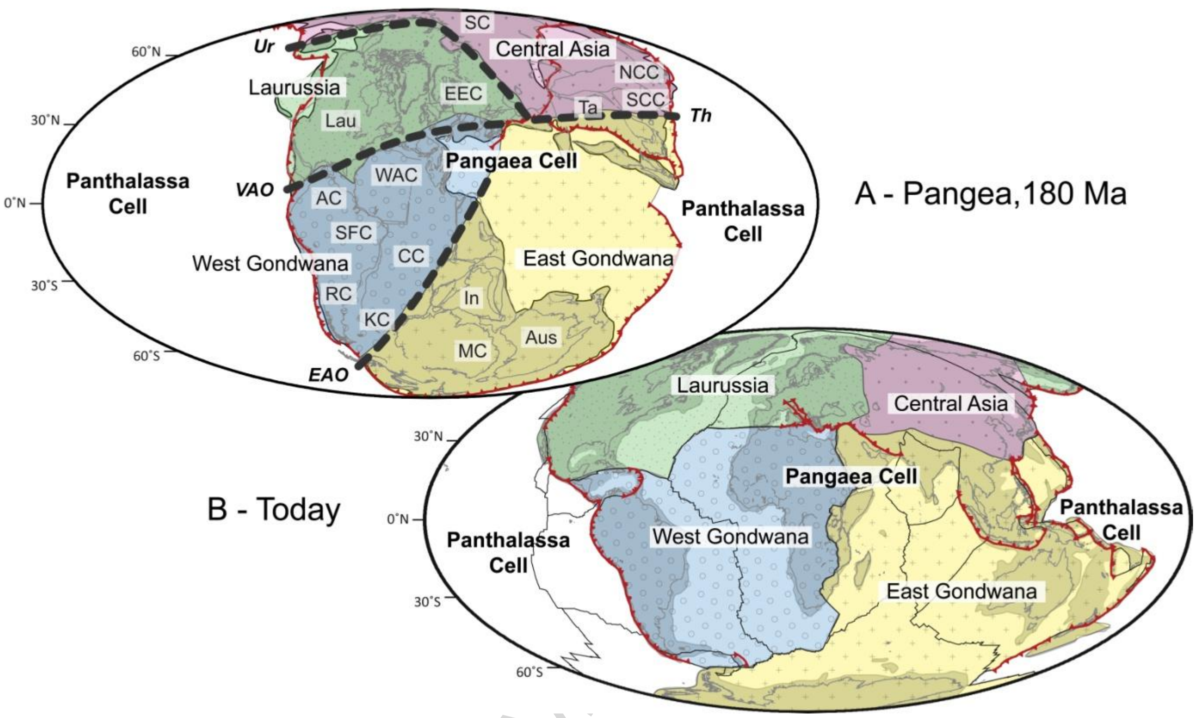


Fig. 6. Distribution of the Pangaea and Panthalassa cells of Collins (2003) in Pangea at 180 Ma **(A)** and today **(B)**. Reconstructions modified after Seton et al. (2012). The extent of the Laurussian, Central Asian, West Gondwana, and East Gondwana crustal groups are shown in both figure **A** and **B**. Figure **A** shows the orogenic belts that are used to delineate the crustal groups as thick dashed lines. Tagged red and thin black lines represent convergent margins and spreading centers, respectively. Shaded areas represent continental crust. *Abbreviations*: **VAO** – Variscan-Alleghanian-Ouachita orogens; **EAO** – East African Orogen; **Ur** – Uralides; **Th** – Tethysides. Figure **A** also shows the position of major continental blocks that form part of the respective crustal groups. *Abbreviations*: **AC** – Amazon Craton; **Ant** – Antarctica; **Aus** – Australia; **CC** – Congo Craton; **EEC** – East European Craton; **In** – Peninsular India; **KC** – Kalahari Craton; **Lau** – Laurentia; **MC** – Mawson Craton; **NCC** – North China Craton; **RC** – Rio de la Plata Craton; **SC** – Siberian Craton; **SCC** – South China Craton; **SFC** – São Francisco Craton; **Ta** – Tarim; **WAC** – West African Craton.

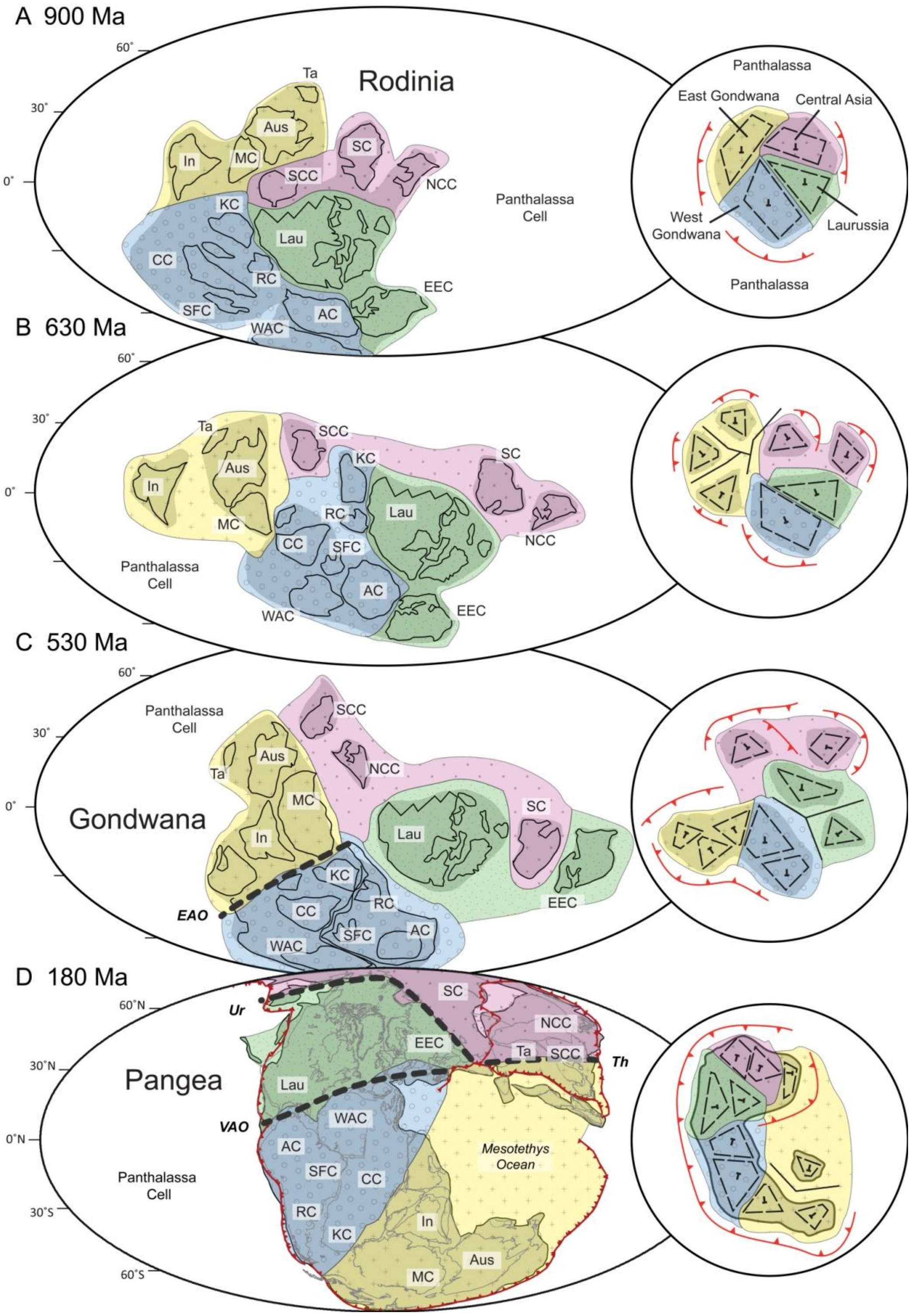


Fig. 7. Reconstruction of the break-up of Rodinia and subsequent formation of Gondwana and Pangea, showing the behaviour and distribution of the Laurussian, West Gondwana, East Gondwana and Asian crustal groups. Paleogeographic reconstructions on the left show the location of the Pangaea and Panthalassa cells of Collins (2003) and the crustal groups, as well

as continental blocks and orogenic belts from figure 6a. Schematic sketches on the right show the general movements of the crustal groups. See section 4.3 for further discussion. Symbols and abbreviations as in figure 6. Paleogeographic reconstructions in **A-C** after Li et al. (2008), **D** after Seton et al. (2012).

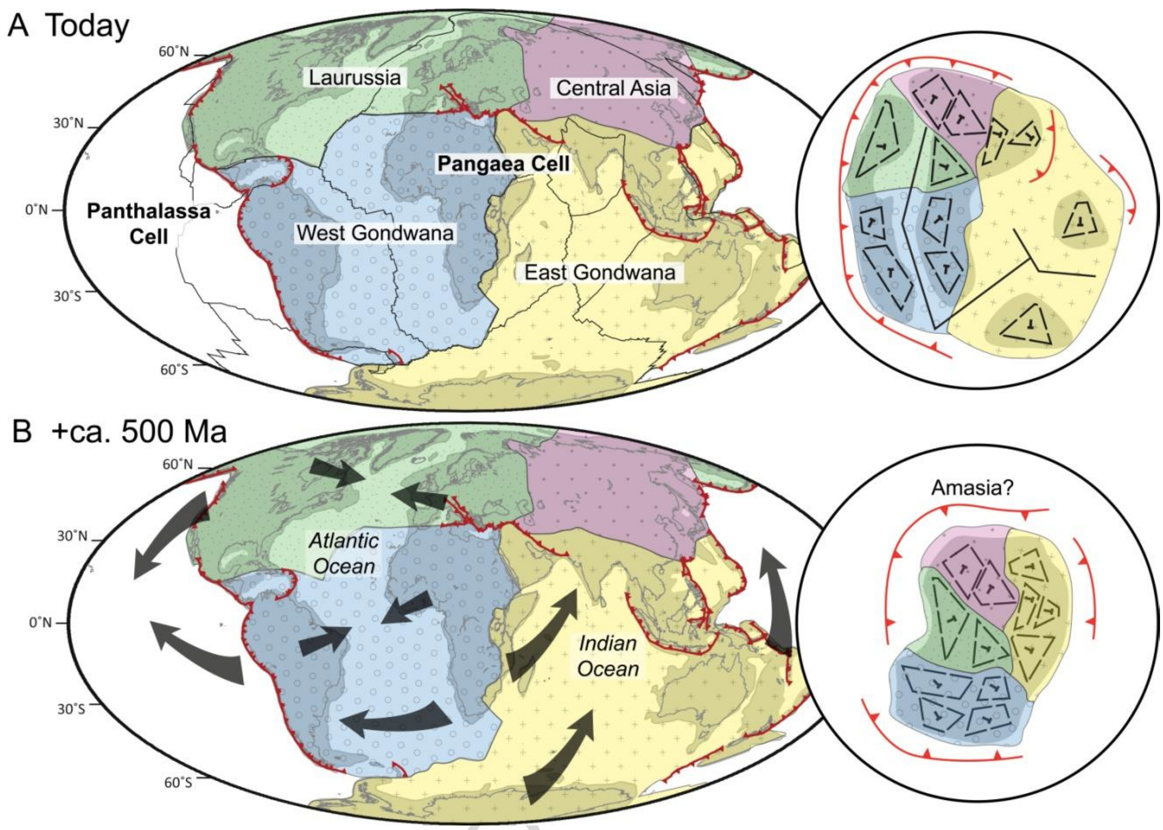


Fig. 8. The present distribution of continental crust and crustal groups (A) and the movements required to assemble Amasia in ca. 500 Myr (B), based on the prediction that it should correspond to an R-type supercontinent. See further discussion in section 4.3.3. Paleogeographic reconstructions on the left (after Seton et al. 2012) show the location of the Pangaea and Panthalassa cells of Collins (2003) and the Laurussian, West Gondwana, East Gondwana and Asian crustal groups. Schematic sketches on the right show the general movements of the crustal groups.

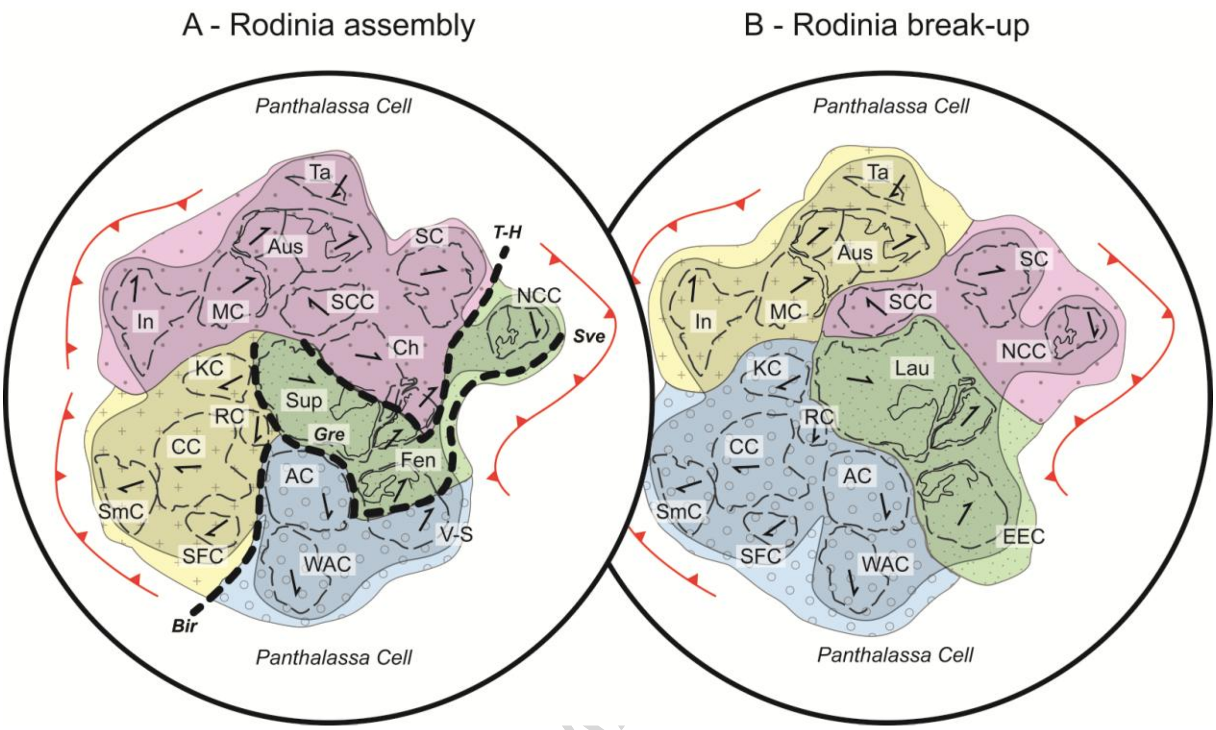


Fig. 9. A comparison between the distribution of continental blocks among the crustal groups during the assembly **(A)** and break-up **(B)** of Rodinia. The purpose of this figure is to delineate the spatial extent of the Paleoproterozoic equivalents of the East African Orogen, Uralides and Variscan-Alleghanian-Ouachita orogens. By identifying their position within Rodinia (B), it becomes possible to broadly determine what crustal groups the major continental blocks belonged to in the Paleo-Mesoproterozoic. Note that in many instances, continental blocks did not form part of the same crustal group in the Neoproterozoic-Phanerozoic (A) as in the Paleo-Mesoproterozoic (B). See further discussion in section 5.1.5. *Abbreviations*: **Bir** – Birimian Orogen; **Ch** – Churchill province; **Gre** – Grenville Orogen; **SmC** – Saharan Metacraton; **Sup** – Superior; **Sve** – Svecofennian-Central-Russian orogens; **T-H** – Trans-Hudson Orogen; **V-S** – Volgo-Sarmatia. Other abbreviations and symbols as in figure 6. Arrows in continental blocks indicate present-day north.

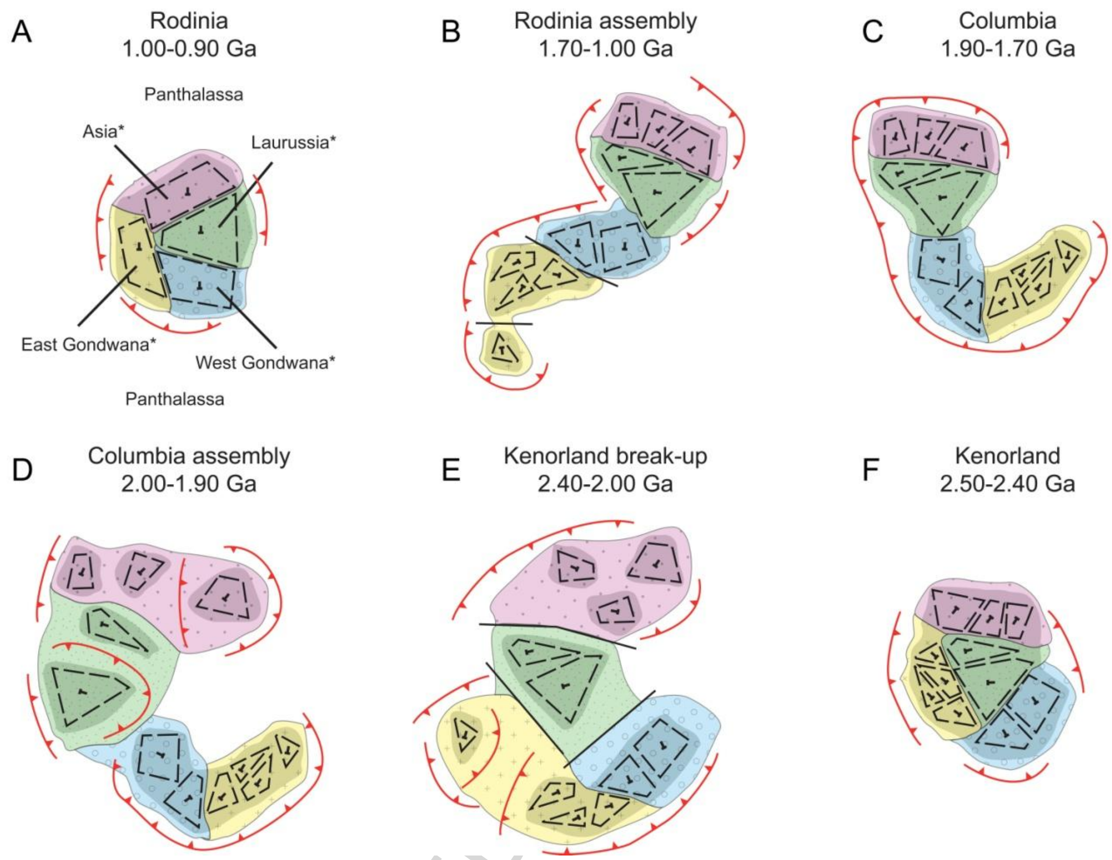


Fig. 10. A reconstruction of the Kenorland-Rodinia cycle. The basis of the reconstruction is the behaviour of the crustal groups during the break-up of Rodinia and assembly of Amasia (figs. 7 and 8), which can applied to reverse engineer Columbia and Kenorland. See further discussion in section 5. Symbols as in figure 6.

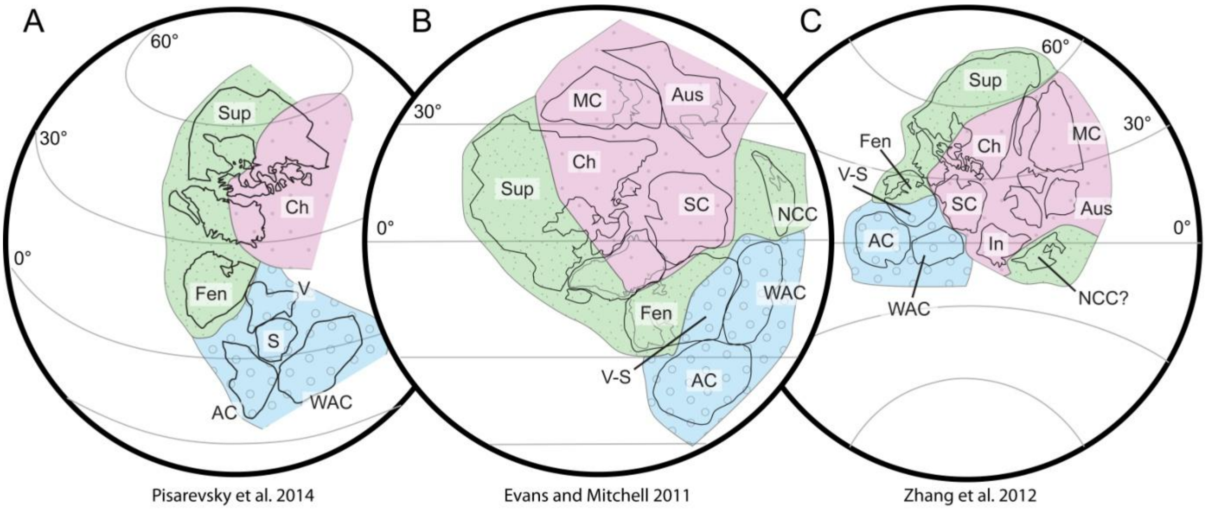


Fig. 11. Paleomagnetically constrained Late Paleoproterozoic to Mesoproterozoic (ca. 1.8-1.3 Ga) reconstructions of Columbia by **A)** Pisarevsky et al. (2014), **B)** Evans and Mitchell (2011), and **C)** Zhang et al. (2012). The continental blocks have been divided into the Laurussian*, West Gondwana*, and Central Asian* crustal groups, based on the division in figure 9. Note that the general distribution of the crustal groups is the same as in the inferred reconstruction in figure 10c. No continental blocks from the East Gondwana group* are shown in figure 11, but the reconstructions allow for the group to be positioned next to the West Gondwana* group. Abbreviations as in figures 6 and 9.

Fig. 12. Brian (left) and Tomas Næraa eating their lunch on the Ikkatoq gneiss during the 2008 GEUS fieldwork in southern West Greenland. Photo by Anders Scherstén.

## Highlights

- Rodinia and Pangea represent the two basic types of supercontinent configurations
- True supercontinent cycles involve breakup-assembly of Rodinia-type supercontinents
- The convective pattern in the mantle is the same during each such cycle
- During these cycles, Pangea-type supercontinents are only transient stages
- Rodinia-type supercontinent break-ups coincide with atmospheric oxygenation events