



Linking collisional and accretionary orogens during Rodinia assembly and breakup: Implications for models of supercontinent cycles



Peter A. Cawood ^{a,*}, Robin A. Strachan ^b, Sergei A. Pisarevsky ^c, Dmitry P. Gladkochub ^d, J. Brendan Murphy ^e

^a Department of Earth Sciences, University of St. Andrews, Irvine Building, North Street, St. Andrews, Fife KY16 9AL, UK

^b School of Earth and Environmental Sciences, University of Portsmouth, Portsmouth PO1 3QL, UK

^c Institute for Geoscience Research (TIGeR), Department of Applied Geology, Australian Research Council Centre of Excellence for Core to Crust Fluid Systems (CCFS), Curtin University, GPO Box U1987, Perth, WA 6845, Australia

^d Institute of the Earth's Crust, Siberian Branch of the Russian Academy of Sciences, 128 Lermontov Street, 664033 Irkutsk, Russia

^e Department of Earth Sciences, St. Francis Xavier University, Antigonish, Nova Scotia B2G 2W5, Canada

ARTICLE INFO

Article history:

Received 4 April 2016

Received in revised form 24 May 2016

Accepted 28 May 2016

Available online 8 June 2016

Editor: A. Yin

Keywords:

Rodinia
supercontinent
top down
bottom up
Neoproterozoic

ABSTRACT

Periodic assembly and dispersal of continental fragments has been a characteristic of the solid Earth for much of its history. Geodynamic drivers of this cyclic activity are inferred to be either top-down processes related to near surface lithospheric stresses at plate boundaries or bottom-up processes related to mantle convection and, in particular, mantle plumes, or some combination of the two. Analysis of the geological history of Rodinian crustal blocks suggests that internal rifting and breakup of the supercontinent were linked to the initiation of subduction and development of accretionary orogens around its periphery. Thus, breakup was a top-down instigated process. The locus of convergence was initially around north-eastern and northern Laurentia in the early Neoproterozoic before extending to outboard of Amazonia and Africa, including Avalonia–Cadomia, and arcs outboard of Siberia and eastern to northern Baltica in the mid-Neoproterozoic (~760 Ma). The duration of subduction around the periphery of Rodinia coincides with the interval of lithospheric extension within the supercontinent, including the opening of the proto-Pacific at ca. 760 Ma and the commencement of rifting in east Laurentia. Final development of passive margin successions around Laurentia, Baltica and Siberia was not completed until the late Neoproterozoic to early Paleozoic (ca. 570–530 Ma), which corresponds with the termination of convergent plate interactions that gave rise to Gondwana and the consequent relocation of subduction zones to the periphery of this supercontinent. The temporal link between external subduction and internal extension suggests that breakup was initiated by a top-down process driven by accretionary tectonics along the periphery of the supercontinent. Plume-related magmatism may be present at specific times and in specific places during breakup but is not the prime driving force. Comparison of the Rodinia record of continental assembly and dispersal with that for Nuna, Gondwana and Pangea suggests grouping into two supercycles in which Nuna and Gondwana underwent only partial or no break-up phase prior to their incorporation into Rodinia and Pangea respectively. It was only after this final phase of assembly that the supercontinents then underwent full dispersal.

© 2016 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Profound influences on the evolution of Earth's crust, atmosphere, hydrosphere and life have been exerted since the late Archean by repeated cycles of supercontinent amalgamation and dispersal (Nance et al., 2014; Worsley et al., 1986). Key to evaluating these influences is the understanding of the relative timing

of tectonic events within and between the different aspects of the Earth system, particularly in the fragmentary rock archive of the Precambrian. Temporal relations across supercontinents between interior collisional and peripheral accretionary orogens suggest a linked history, most likely related to global plate kinematic adjustments (Cawood and Buchan, 2007; Collins and Pisarevsky, 2005). Quantifying global changes in the movement of lithospheric plates and links to other aspects of the Earth system is only possible for the modern Earth with its relatively complete record of oceanic crust and seafloor spreading. Hence such links have been best eval-

* Corresponding author.

E-mail address: peter.cawood@st-andrews.ac.uk (P.A. Cawood).

uated for the Earth since the break-up of Pangea beginning in the early Mesozoic (Nance et al., 2014). A related issue centres on the mechanisms for supercontinent break-up: is this primarily driven by extensional stresses resulting from the development of encircling and retreating subduction zones ("top-down") or from the generation of mantle plumes and hot spots within the supercontinent ("bottom-up")? Most recent work, based on the break-up of Pangea (Buiter and Torsvik, 2014; Keppe, 2015a, 2015b) and the results of numerical modelling (Bott, 1992; Heron et al., 2015; Lowman and Jarvis, 1995), favours the view that the development of subduction zones around a supercontinent is a pre-requisite for break-up. The development of encircling subduction zones shuts off the mantle region in the centre of the supercontinent from subduction, often leading to rising hot mantle, which may then facilitate break-up, although development of plumes and hot spots is not a pre-requisite (Condie, 2005).

Analysis of the pre-Pangea parts of Earth history is limited to a qualitative analysis derived from the rock record generated in orogenic belts and resultant interpretations of plate boundary evolution and interactions. Thus, accurately deciphering the geological records of orogenic belts is key to determining global paleogeography in deep time, unravelling links between periods of continental assembly and dispersal (supercontinent cycle) with major changes in the Earth's surficial environments (e.g., oceans, atmosphere, biosphere), and determining links to deep Earth processes, including evaluating the roles of top-down versus bottom-up tectonic processes (Murphy and Nance, 2003; Murphy et al., 2009, 2013). Increasing availability of precise age, geochemical and isotopic data has enabled a detailed understanding of the individual records within, and global correlations between, orogens. The aim of this paper is to demonstrate how collisional orogenic systems associated with the assembly of Rodinia at c. 1.0–0.9 Ga were followed by global plate adjustments that led to the development of accretionary orogens around a significant part of the supercontinent. Furthermore, these accretionary orogenic processes were coeval with multistage rifting events in the interior of the supercontinent, leading to its eventual break-up during Cryogenian and Ediacaran to early Cambrian times. This linked history between the interior and exterior of the supercontinent, together with the lack of widespread development of plumes and hot spots during break-up, suggests a dominance of top-down tectonic processes, similar to the current generally accepted model for the break-up of Pangea.

2. Lithotectonic record of supercontinent assembly and breakup

Orogenic belts record a long history of sediment accumulation, commonly in association with igneous activity, across a variety of plate margins (divergent, convergent, strike-slip) and intraplate settings, prior to stabilisation through one or more short pulses of tectonothermal activity (orogenesis). The position of stabilisation with respect to a plate boundary type enables division of orogens into collisional, accretionary and intracontinental (Cawood et al., 2009; Murphy and Nance, 1991). Collisional orogens form through collision of continental lithospheric fragments and occupy interior locations within the assembled continental mass. Accretionary orogens form at sites of continuing oceanic plate subduction and occupy exterior (or peripheral) locations with respect to continental fragments. Intracratonic orogens lie within a continent, away from an active plate margin with orogenic activity inferred to be driven by transmission of far-field stresses from a plate-margin.

From the end of the Mesoproterozoic to the beginning of the Neoproterozoic, collisional suturing of continental fragments including Australia–Antarctica and Amazonia onto a keystone assemblage of Laurentia, Baltica and Siberia resulted in the formation of the supercontinent of Rodinia (Hoffman, 1991; Li et al., 2008). The

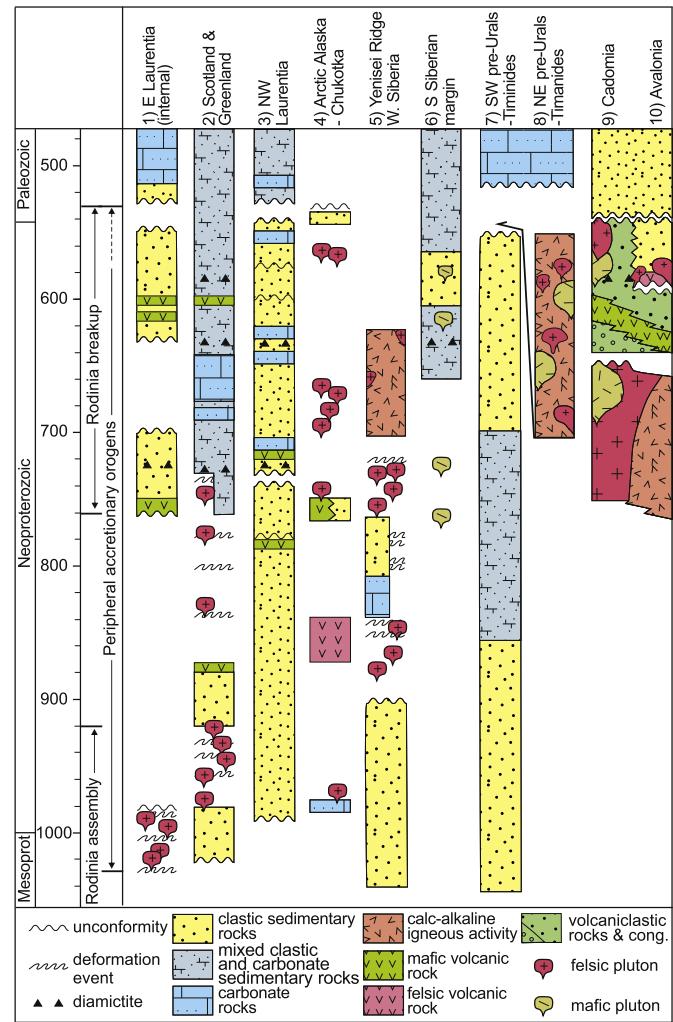


Fig. 1. Time–space plot for various continental fragments of Rodinia for the period from the end of the Mesoproterozoic to the early Paleozoic. Sources of data for individual columns given in text. Location of numbered columns shown in Fig. 2. Abbreviation: Mesoprot – Mesoproterozoic.

subsequent development of passive margin assemblages around all or parts of Laurentia, Baltica and Siberia indicates that the supercontinent had broken apart by the beginning of the Paleozoic (e.g., Bond et al., 1984). These two events of supercontinent assembly and dispersal bookend a complex Neoproterozoic geological record of evolving plate boundaries. Fig. 1 is a time–space plot covering the time interval from final assembly of Rodinia until its breakup (ca. 1000–500 Ma). Our analysis of this record focuses on the evolution of Laurentia but incorporates data from Baltica, Siberia and peri-Gondwanan terranes outboard of South America and West Africa (e.g., Avalonia–Cadomia).

2.1. Collisional assembly of Rodinia

Final assembly of Rodinia is best documented for the east Laurentia–southwest Baltica margin (present day coordinates used throughout) where a long lived, late Paleoproterozoic to Mesoproterozoic convergent plate margin (Fig. 2A; e.g., Condie, 2013; Pisarevsky and Blylund, 2010; Zhao et al., 2002) was terminated through suturing of a continental block, generally considered to be Amazonia (Fig. 2B; Dalziel, 1997; Hoffman, 1991; Park, 1992). Orogenesis commenced as early as 1.4 Ga in northeast Laurentia (e.g., Dickin et al., 2010), peaking at 1.08 to 0.98 Ga here and in Baltica and Amazonia (Fig. 1; Grenville–Sveconorwegian–

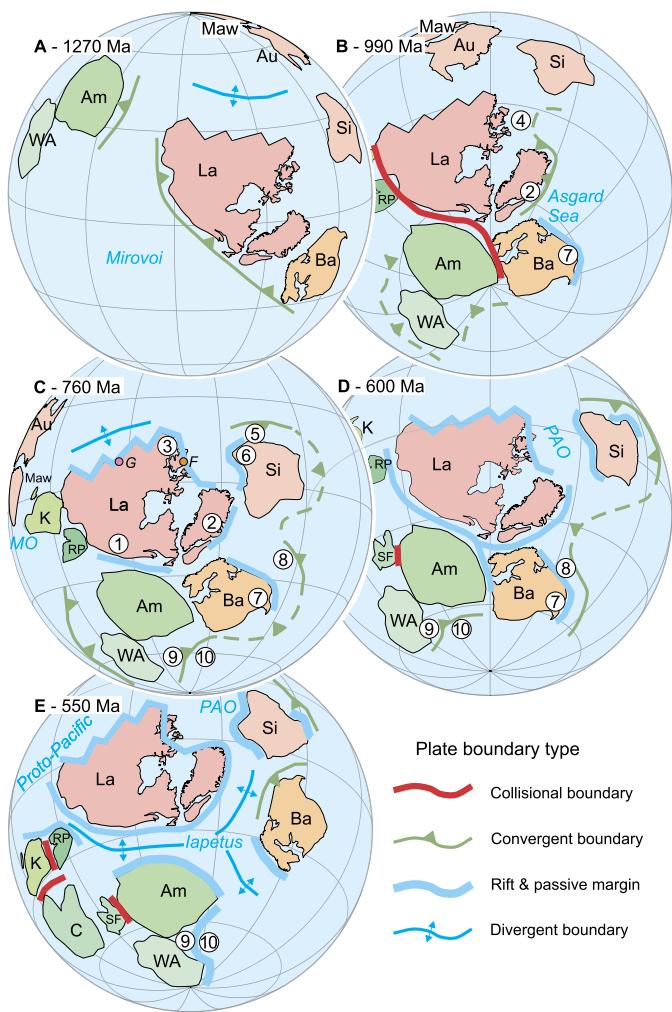


Fig. 2. Paleogeographic reconstructions for the time period from 1270 Ma to 550 Ma, covering the assembly and dispersal of Rodinia (Supplementary Table 1 provides a list of Euler poles used for the reconstructions). Numbers 1–10 refer to columns in Fig. 1. New age dates for paleopoles (Evans et al., 2016) along with geological data (De Waele et al., 2008) suggest the Congo–San Francisco craton may not have been part of Rodinia and it is not shown on the 760 Ma and older reconstructions. The inferred position of the plume heads for the ca. 780 Ma Gunbarrel (G) and 720 Ma Franklin (F) igneous provinces are shown on the 760 Ma reconstruction. Abbreviations: Am – Amazonia, Au – Australia, BA – Baltica, C – Congo, K – Kalahari, La – Laurentia, Maw – Mawson, RP – Rio de la Plata, SF – São Francisco, Si – Siberia, WA – West Africa, MO – Mozambique Ocean, PAO – Paleo-Asian Ocean.

Sunsas orogeny), followed by exhumation and cooling continuing to around 0.92 Ma (Bingen et al., 2008; Gower and Krogh, 2002; Hynes and Rivers, 2010; Tohver et al., 2004). These sites of collisional suturing occupied interior locations within Rodinia and were isolated from subsequent tectonic activity until the final stage of Rodinia breakup in the Ediacaran.

2.2. Evidence for development of exterior accretionary orogens

End Mesoproterozoic collisional orogenesis in part overlaps with the establishment of the Valhalla accretionary orogen (1025–730 Ma) along the northeast margin of Laurentia (Figs. 1, 2; Cawood et al., 2010). The geological history of this orogen is fragmentary due to Phanerozoic tectonic disruption but its record is preserved in isolated blocks in Scotland, east Greenland, Svalbard and Norway. The orogen is characterised by end Mesoproterozoic to mid-Neoproterozoic pulses of siliciclastic sedimentation and magmatic activity (1025–980 Ma and 920–870 Ma) punctuated by tectonothermal events associated with subduction

and crustal thickening at 980–920 Ma and 840–730 Ma (Cawood et al., 2010, 2015). Detrital zircon provenance record of the siliciclastic successions indicates derivation from Laurentia and the calc-alkaline geochemistry of the magmatic activity suggests initiation of plate convergence outboard of northeast Laurentia around 1000 Ma. Petrological studies in Scotland indicate medium-pressure Barrovian-style metamorphism at c. 950 Ma in a regime of moderate crustal thickening (Cutts et al., 2009, 2010).

Initiation of the Valhalla Orogen corresponds with 95° clockwise rotation of Baltica with respect to Laurentia, which on paleomagnetic constraints occurred after 1265 Ma, and likely after 1122 Ma, but before 990 Ma (Cawood et al., 2010). This rotation resulted in the opening of the Asgard Sea between northeast Laurentia (outboard of Greenland) and northern Baltica. The stabilised Valhalla succession is overlain by mixed siliciclastic, carbonate and volcanic rock units (e.g. Dalradian and Eleonore Bay supergroups) with an inferred age for the base of the succession of around 760 Ma (Prave et al., 2009). In northern Norway, the mid- to late Neoproterozoic record of the Kalak Nappe complex of the Valhalla Orogen records younger deformational and magmatic events including syn-deformational magmatism at 710 Ma and 670 Ma, and magmatic activity at 600 Ma, 570–560 Ma and 530–520 Ma (Kirkland et al., 2008). The 600 Ma and younger events probably reflect rift-related magmatism associated with Rodinia breakup.

Fragmentary Neoproterozoic successions occur in a number of continental blocks bordering the Arctic Ocean, including northern Alaska (Brooks Range and Seward Peninsula), Chukotka and the New Siberian Islands, and have been variously referred to as Arcadia and the Arctic Alaska–Chukotka terrane (Amato et al., 2014; Metelkin et al., 2015; Miller et al., 2011). The main lithologies are felsic igneous rocks that have been dated at 970 Ma, 870 Ma, 750–740 Ma, 700–640 Ma and 570–540 Ma (Fig. 1; Amato et al., 2014). The tectonic affinities of the older magmatism are uncertain but the younger two phases have been related to arc and rift-related activity, respectively. Malone et al. (2014, and references therein) extend the Valhalla accretionary orogen northwards to incorporate units bordering the Arctic Ocean. They note the presence of 980–960 Ma orthogneiss, which was a source of detritus for younger Neoproterozoic strata, and 710–635 Ma detritus likely derived from the Timanian arcs and related units. They argue that a convergent plate margin lay outboard of the passive margin of northeast to northern Laurentia and northern Baltica for much of the Neoproterozoic with the continental blocks lying on the upper plate.

Around the margins of Siberia are a series of isolated structural blocks dominated by Neoproterozoic igneous and metamorphic assemblages. These include the Yenisei Ridge on the western margin of Siberia (Figs. 1, 2), the Dariv–Shishkhid–Gargan zone in southwest Siberia, and the Baikal–Muya zone of southern Siberia (Gladkochub et al., 2006; Kröner et al., 2015; Likhanov et al., 2015b; Sovetov et al., 2007; Vernikovsky and Vernikovskaya, 2006). These blocks record a series of accretionary and collisional events that developed outboard of the Siberian craton and have been correlated with the Valhalla Orogen (Likhanov et al., 2015a, 2015b), as exemplified along the Yenisei Ridge where convergent plate margin activity commenced around 900 Ma and provide a record of tectonothermal events (Fig. 1; Gladkochub et al., 2006).

The Neoproterozoic history of the east and northeast portion of Baltica consists of an inboard rift and passive margin siliciclastic–carbonate succession that ranges in age from late Mesoproterozoic to Ediacaran and an outboard clastic succession interstratified with 700–550 Ma calc-alkaline basalt to rhyodacitic volcanic rocks, which, together with their intrusive equivalents, are interpreted to represent a supra-subduction zone assemblage (Kuznetsov et al., 2015, 2010). Ocean closure led to ultimate collisional emplacement of the outboard upper plate arc system onto the passive margin to

form the pre-Uralides-Timanide orogen around 540 Ma (Kuznetsov et al., 2015).

Cadomia and Avalonia (Fig. 1) consist of mid- to late Neoproterozoic (Fig. 1, 760–570 Ma) volcanic and volcanioclastic rock units and their intrusive equivalents, which display supra-subduction zone geochemical affinities (Murphy et al., 2013, and references therein). Their main arc phase (630–570 Ma) developed along the periphery of northern South America and West Africa (Fig. 2). Subduction terminated diachronously between ~600 Ma and ~550 Ma and the tectonic setting changed to rift and transpressional-related environments prior to establishment of a stable platform around 530 Ma. East Africa includes a series of supra-subduction arc terranes that were active from at least 870 Ma to 630 Ma, with further localised subduction-related magmatic activity extending back to ca. 955 Ma (Fritz et al., 2013, and references therein; Robinson et al., 2015).

2.3. Record of Rodinia breakup

The breakout of Laurentia from the core of Rodinia was associated with the development of extension-related rift and passive margin successions around its margins and those of conjugate continental blocks (e.g. eastern Australia, cratonic blocks of western South America) and Baltica and Siberia (Bond et al., 1984). We interpret this protracted rifting history to be linked kinematically with subduction along the periphery of the supercontinent. Lithostratigraphic relations in West Laurentia (Figs. 1, 2) indicate a protracted history of rifting (Yonkee et al., 2014) possibly involving two stages of continental breakup (Colpron et al., 2002; Prave, 1999). The first occurred in the mid-Neoproterozoic, around 750 Ma, based on the record in the Windermere Supergroup in the northern Cordillera, which unconformably overlies an intracontinental basinal succession (Ross, 1991; Strauss et al., 2015). The inferred conjugate margin, preserved in the Adelaidian succession of East Australia, records a similar history related to the opening of the proto-Pacific (Cawood, 2005, and references therein). A second break-up event, recorded in the strata of the southeastern Canadian Cordillera and Death Valley, occurred around 570 Ma and represents final opening of the proto-Pacific (although the specific block that broke away at this time is unknown) and development of a passive margin succession along the entire western margin of Laurentia (Yonkee et al., 2014).

The east Laurentian margin records a protracted history of Neoproterozoic rift-related sedimentation and magmatism commencing around 760 Ma (Fig. 1). In northeast Laurentia, these deposits include the Dalradian and Eleonore Bay supergroups and their correlative (Anderton, 1982, 1985; Prave et al., 2009; Sonderholm et al., 2008; Soper, 1994), and are characterised by siliciclastic-dominated strata that occurred initially in a series of (half) grabens unconformably onlapping basement highs (Anderton, 1985; Banks et al., 2007; Smith et al., 1999) of the stabilised Valhalla Orogen. Further south in the Appalachians, the early record of extension is restricted and best developed in the vicinity of the Blue Ridge with mid-Neoproterozoic (760–680 Ma) sedimentation and associated igneous units resting unconformably on Mesoproterozoic rocks of the Grenville Orogen (Aleinikoff et al., 1995; Novak and Rankin, 2004). During the late Neoproterozoic, sedimentation patterns indicate renewed pulses of basin deepening related to lithospheric extension locally interstratified with and intruded by mafic and silicic extension-related magmatic activity (Anderton, 1985; Cawood et al., 2007a, 2007b; Chew et al., 2010; Volkert et al., 2015). Rift-related magmatic activity occurred largely in the range 620–570 Ma but includes bodies as young as 550 Ma in the northeastern segment of the east Laurentian margin and 520 Ma in the southeastern segment (Cawood et al., 2001; Thomas, 2011). The final break-up history of the East Laurentian

margin from the conjugate western Baltica and Amazonian margins was long and complex based on constraints from the ages of the youngest rift-related magmatism, the change from rift to passive margin sedimentation, and from paleomagnetic data. Opening of the northern Iapetus Ocean associated with the separation of Baltica occurred in the 590–570 Ma timeframe (Abdelmalak et al., 2015; Bingen et al., 1998; Cawood et al., 2001; Pisarevsky et al., 2008a). Separation of opposing continental blocks is inferred to have occurred around 570–550 Ma but final development of the East Laurentian passive margin did not take place until the early Cambrian at around 530 Ma (Cawood et al., 2001). Along the southeastern margin of Laurentia, a further pulse of rifting associated with the separation of microcontinental ribbons (e.g., Precordillera, Chilenia) occurred around 530–520 Ma (Astini, 1998; Thomas, 2011; Thomas and Astini, 1996).

The timing of breakup on the northern margin of Laurentia is less well constrained but probably occurred around 570 Ma based on mapping in the Canadian Arctic (Dewing et al., 2004; Lane and Gehrels, 2014). Lithotectonic relations indicate that a carbonate-dominated passive margin was well established by the Early Cambrian and overlies a thick sequence of late Neoproterozoic rift related clastic rocks.

Recent dating, provenance and paleomagnetic studies from the southern margin of Siberia suggest rifting to form the Paleo-Asian ocean commenced after 760 Ma, probably at about 720 Ma, which correlates with the Franklin igneous event in northern Laurentia (Ernst et al., 2016; Gladkochub et al., 2013; Pisarevsky et al., 2013). The eastern and northern Siberian margins consist of Mesoproterozoic sedimentary rocks inferred to have accumulated in passive margin settings (Pisarevsky et al., 2008b) unconformably overlain by Ediacaran strata. Detrital zircons with ages spanning 790–590 Ma occur in the Ediacaran succession and are thought to be derived from the Central Taimyr accretionary belt (Khudoley et al., 2015).

3. Discussion

3.1. Linking processes of supercontinent assembly and dispersal in space and time

The near synchronicity of changes in lithotectonic assemblages related to phases of lithospheric compression and extension within and around Rodinia (Fig. 3) suggests a history controlled by linked plate kinematic interactions. Final collisional suturing at the end Mesoproterozoic corresponds with the initiation of subduction in northeast and northern Laurentia (Cawood et al., 2015; Malone et al., 2014) and possibly East Africa (Fritz et al., 2013). The subsequent early Neoproterozoic subduction record around the Rodinia margin is fragmentary, in part reflecting poor preservation due to reworking during subsequent orogenic events. Nonetheless, the available data indicate widespread subduction around the margins of Rodinia throughout the Neoproterozoic but with the record of subduction activity within the Mirovoi Ocean propagating from areas such as the Valhalla orogen and its continuations in the early Neoproterozoic to incorporate Avalonia, Cadomia, Siberia, the pre-Urals and Timanides in the mid-Neoproterozoic around 760 Ma.

The duration of subduction around the margins of Rodinia precisely spans the time interval for the lithospheric extension within the supercontinent that led to its breakup. A major phase of rifting related to lithospheric extension commenced at around 760 Ma. But final development of passive margin successions around Laurentia, Baltica and Siberia was not completed until the end of the Neoproterozoic to early Paleozoic in the timeframe 570–530 Ma. This latter timeframe corresponds with the termination of convergent plate interaction in many regions (Fig. 1).

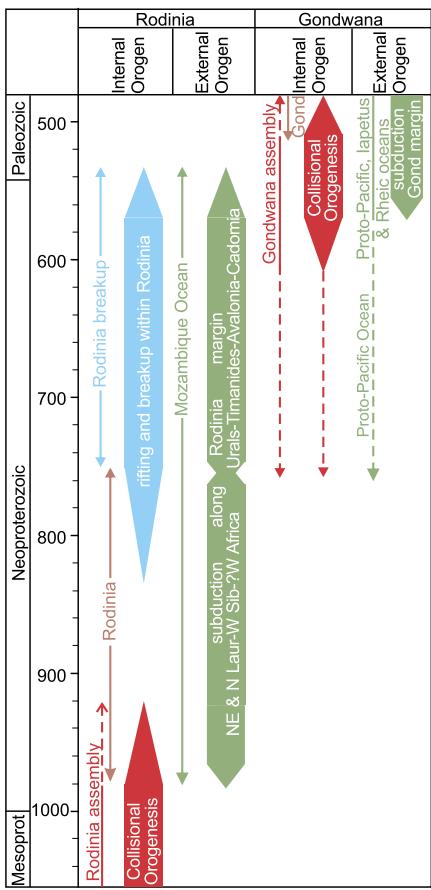


Fig. 3. Summary of timing events associated with continental collision and convergent and divergent plate margin activities related to assembly and dispersal of Rodinia and subsequent assembly of Gondwana. Abbreviations: Mesoprot – Mesoproterozoic; Gond – Gondwana; Laur – Laurentia; Sib – Siberia.

Breakup of Rodinia through a combination of internal lithospheric extension and external convergence led to closure of the surrounding Mozambique Ocean and the assembly of continental fragments within Gondwana (Collins and Pisarevsky, 2005). As collisional suturing of the Gondwana fragments (not shown in Fig. 2 but see Murphy et al., 2004; Nance et al., 2008) occurred, subduction zones between the converging continents were replaced by subduction zones around its periphery i.e. in the Mirovoi Ocean (Murphy and Nance, 1991). The terminal stages of Gondwana assembly occurred between ca. 570 Ma and 530 Ma, and were coeval with opening of Iapetus and the initiation of subduction in the proto-Pacific, as exemplified by the accretionary Terra Australis Orogen (Fig. 3; Cawood, 2005; Cawood and Buchan, 2007).

3.2. Top-down vs. bottom-up tectonics and the supercontinent cycle

The correlation of periods of lithospheric extension and compression within and around the margins of a supercontinent respectively has implications for geodynamic processes. In particular, it has the potential to provide insights into the relative roles of lithospheric plate interactions (top-down) versus mantle plume influenced (bottom-up) processes in controlling periods of continental aggregation and dispersal (Gurnis, 1988; Murphy and Nance, 2013).

A key tenet of plate tectonic theory is that the Earth's rigid lithospheric plates are in a state of constant dynamic adjustment such that changes in Euler pole locations must be accommodated across plate boundaries through changes in rate and direction of movement. The periodic assembly of continental fragments into

supercontinents leads to the widespread termination of convergent plate boundaries over a relatively short time interval at sites of collisional suturing. This termination is accommodated by an adjustment in the nature of remaining plate boundaries such as increasing rates of subduction at convergent plate boundaries, decreasing rates of spreading at divergent boundaries, or the initiation of new sites of convergence. Changes in spreading rate are difficult to evaluate on the pre-Mesozoic Earth due to the absence of oceanic crust older than Jurassic and changes in rates of convergence are difficult to quantify in preserved orogenic records. However, the initiation of lithospheric subduction along the margins of Rodinia (and subsequently Gondwana and Pangea) suggests that this is the principal method of accommodating the changing global plate kinematic framework in response to continental suturing (i.e. transfer of convergence from between the converging continents during collisional suturing to the periphery of the supercontinent). The subsequent temporal link between subduction of dense oceanic lithosphere around the margins of the supercontinent and internal lithospheric extension leading to breakup is consistent with the concept that subduction places the overriding supercontinent in extension. This in turn implies that final breakup of the supercontinent Rodinia was subduction-driven, i.e. a top-down process.

Magmatic activity associated with Rodinia break-up has been related to the impingement of a plume or superplume beneath the supercontinent (Li et al., 2003; Nosova et al., 2011; Puffer, 2002). The 780 Ma Gunbarrel magmatic event and the 720 Ma Franklin Large Igneous Province (LIP) are present in northwest Laurentia and related to mantle plumes (Ernst et al., 2013, 2016, 2008). The former event has been related to magmatic activity associated with rifting during opening of the proto-Pacific (Harlan et al., 2003), although recently Li et al. (2013) have argued that breakup did not commence until after 720 Ma. One or both of these events may be temporally equivalent to phases of rifting along the Laurentian margin but their links to geodynamic drivers associated with Rodinia breakup are less clear given the general uncertainty in the rift history of the margins (Colpron et al., 2002; Lane and Gehrels, 2014; Lane et al., 2016; Prave, 1999).

Late Neoproterozoic (Ediacaran) magmatic activity spanning the range 630–550 Ma along the East Laurentian margin has also been linked to a plume source based on the similarities to ocean island basalts (Puffer, 2002). However, Fettes et al. (2011) argue that the geochemistry of plumes is non-unique and an enriched mantle source does not necessitate a plume origin. They show that the rift-related basalts in Ireland and Scotland resulted from normal and enriched mid-ocean ridge basalt sources, with some contamination with continental crust for younger samples. Critically, there is no evidence that magmatism at the Scottish promontory (the nexus of Laurentia–Baltica–Amazonia) resulted from a mantle plume. Nor is there any evidence for uplift here or elsewhere along the margin above a plume head. Indeed the converse is the case with units such as the 600 Ma Tayvallich Volcanic rocks (Halliday et al., 1989) in Scotland extruded during a phase of rapid basin subsidence associated with lithospheric extension (Anderton, 1985). Furthermore, the magmatic activity occurs in a linear belt for over 4000 km from the US Appalachians to the Greenland and Scandinavian Caledonides that is parallel to the axis of Iapetus Ocean opening. In combination, the linear extent of the magmatic activity, the lack of evidence for syn-magmatic uplift, and its geochemical character are consistent with adiabatic melting of a variable mantle source associated with lithospheric extension (cf. Abdelmalak et al., 2015; Fettes et al., 2011). Any plume-related magmatic activity associated with the opening of the Iapetus Ocean is probably minor and localised within a long linear belt of rift-related melting.

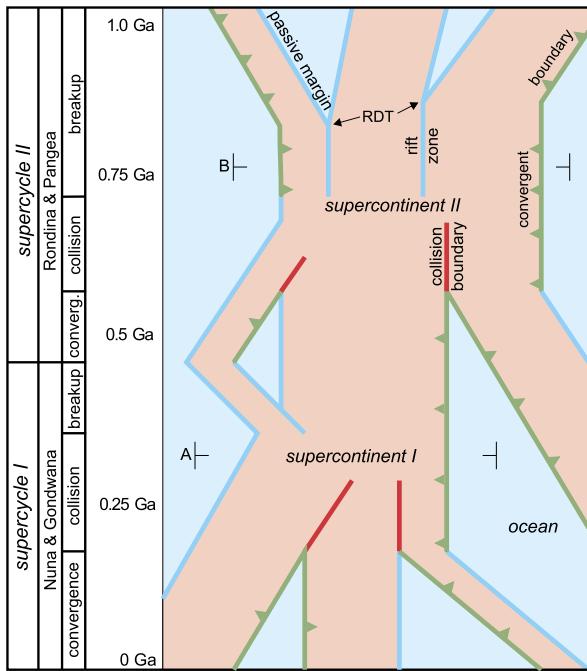


Fig. 4. Schematic time-space plot for proposed supercycles I and II involving continental assembly and breakup. Convergence results in aggradation of continental blocks to form a supercontinent. Termination of subduction zones through continental collision results in initiation of subduction along the margin of the supercontinent. The development of convergent plate margins at, or near, opposing sides of the supercontinent in supercycle II results in the continental lithosphere being placed in tension leading to the development of rift zones. These will be sites of adiabatic decompression melting and may also be the locus of any plumes beneath the continental lithosphere. Rifting during supercycle II ultimately leads to complete continental breakup and the formation of passive margins, and the formation of ocean basins between the dispersed continental fragments. Colours of plate boundaries same as Fig. 2. Lines A and B show location of schematic cross sections in Fig. 5. Abbreviations: converg. – convergence; RDT – rift to drift transition.

The Neoproterozoic record of Rodinia is consistent with a top-down, rather than a bottom-up driven process in which subduction along its margins drove lithospheric extension within its interior leading to breakup and passive margin development. Top-down driven breakup of Rodinia is consistent with the model of extroversion (Murphy and Nance, 2005, 2013) in which breakup of Rodinia occurs over a geoid high and continents are dispersed towards a geoid low.

3.3. Application to other supercontinent cycles

As with Rodinia, the period of Gondwana assembly corresponds with initiation of subduction along the east Gondwana margin in the late Neoproterozoic around 580 Ma (Cawood and Buchan, 2007). But in marked contrast to Rodinia, subduction did not result in contemporaneous extension and breakup of the overriding plate until closure of the interior Iapetus and Rheic oceans and consequent collisional assembly of Laurussia and Gondwana in the Mesozoic to form Pangea. For Gondwana, subduction was largely limited to one (eastern) margin, analogous to present day South America, whereas Pangea was largely surrounded by subduction zones and experienced extension and ultimate break-up (Figs. 4, 5). This is similar to the model proposed by Bott (1982), that continental splitting is driven by the suction force acting on the overriding plate when subduction roll-back occurs on opposite sides of a large continental mass. He cited the breakup of Pangea as an example of this process. Our analysis suggests that such a model is also applicable to Rodinia breakup with subduction extending from its southern (Cadomian) to northwestern (Siberia)

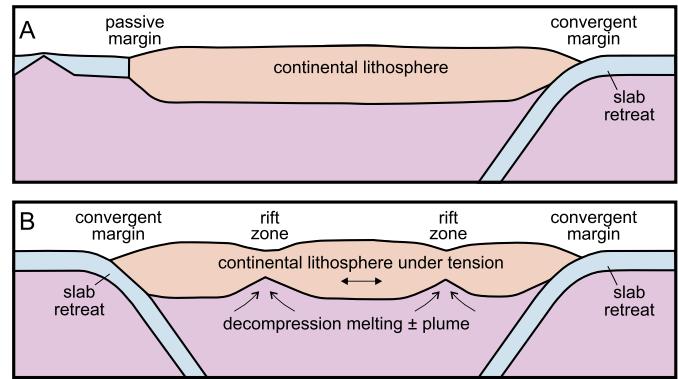


Fig. 5. Schematic cross sections across supercycles I and II along the lines A and B in Fig. 4 showing. Line A corresponds with supercycle I, which is proposed to correspond with assembly of Nuna and Gondwana with section B representing supercycle II and corresponding with Rodinia and Pangea. Rift zones leading to supercontinent breakup are inferred to reflect continental lithospheric extension resulting from slab retreat at the margins of the supercontinent.

margins in a kinematically linked series of arc systems (Fig. 2D). On the basis of finite element modelling, Bott (1992) subsequently argued that a mantle plume could not provide sufficient horizontal tension to drive lithospheric extension but that the suction force (= roll-back) of subduction around the margins of a supercontinent, either alone or in combination with a plume, could drive splitting. Recent numerical modelling continues to emphasise the role of marginal subduction driving lithospheric extension of a supercontinent with plume-related activity, if present, playing a subordinate role and in part controlled by the marginal subduction zones (Heron et al., 2015).

Evaluating geodynamic drivers in pre-Rodinian supercontinents is hindered by decreasing resolution in paleogeographic reconstructions. Thus, a variety of models have been proposed for the disposition of continental fragments around the margin of Nuna (Amazonia, India, Australia) (Evans and Mitchell, 2011; Johansson, 2009; Zhang et al., 2012; Zhao et al., 2002). But there is general agreement that the core components of the supercontinent – Laurentia, Baltica and Siberia – remained together in the transition into Rodinia (Pisarevsky et al., 2014, and references therein). Indeed a long lived convergent plate margin occurred along the east Laurentia and south Baltica margins from around 1.8 Ga until termination through end Mesoproterozoic Grenville–Sveconorwegian–Sunsas collisional orogenesis (Åhall and Connolly, 1998; Cawood et al., 2007b; Gower, 1990; Karlstrom et al., 2001; Zhao et al., 2002). The maintenance of Nuna's cratonic core during protracted convergent plate interaction along its margin is analogous to Gondwana and the subduction record of the accretionary Terra Australis Orogen along its proto-Pacific margin (Cawood, 2005; Cawood et al., 2009). In both cases it was only after further continental accretion and the conversion of Nuna to Rodinia and Gondwana to Pangea, along with the development of inward-dipping subduction zones around the margins of the supercontinent that lithospheric tension was sufficient to drive breakup. Thus, the assembly and dispersal of continental blocks through the Proterozoic and Phanerozoic can be grouped into two supercycles (Fig. 4). The first involves assembly of most, but not all (Pisarevsky et al., 2014), of the major Archean cratons in the Paleoproterozoic to form Nuna, followed by partial dispersal of marginal cratons, before reassembly into Rodinia in the late Mesoproterozoic. The second supercycle involved the aggregation, at the end of the Neoproterozoic, of some of the continental blocks derived from Rodinia breakup (the so-called southern continents) to form Gondwana, followed by the further addition of Laurussia at the end of the Paleozoic to form Pangea, with its dispersal commencing in the mid-Mesozoic.

4. Conclusions

Our synthesis of the geological record preserved in peri-Rodinia orogens provides insights into the geodynamic controls on supercontinent breakup and the relative importance of subduction-related (top down) versus plume-related (bottom-up) tectonic processes. Collisional assembly of Rodinia at c. 1.1–1.0 Ga following the Grenville–Sveconorwegian orogeny led to initiation of subduction and development of accretionary orogens around the periphery of the supercontinent. Subduction occurred throughout the Neoproterozoic, its earliest record (\sim 1000–950 Ma) being preserved in north-eastern and northern Laurentia and possibly East Africa, with younger subduction zones (post \sim 760 Ma) developing outboard of Amazonia and West Africa, producing Avalonia–Cadomia, and arcs outboard of Siberia and western to northern Baltica. The duration of subduction around the periphery of Rodinia coincided with the interval of lithospheric extension within the supercontinent, including a major phase commencing at around 760 Ma attributed to the opening of the proto-Pacific and the commencement of rifting in east Laurentia. Final development of passive margin successions around Laurentia, Baltica and Siberia was not completed until the end of the Neoproterozoic to early Paleozoic (ca. 570–530 Ma), which corresponds with the termination of convergent plate interaction in many regions and the migration of subduction zones to the periphery of Rodinia. The temporal link between external subduction with internal extension suggests that breakup of Rodinia was a top-down process driven by accretionary processes along the periphery of the supercontinent. Magmatism was synchronous with rifting during breakup. Although some pulses of this magmatic activity have a mantle plume signature, most of the magmatism is probably due to extension-related decompression melting and plume-related magmatism was not a major driver of breakup. Our conclusions mirror those proposed by other workers studying the break-up of Pangea, suggesting that the main mechanisms for supercontinent break-up have remained unchanged for the last 1.0 Ga. Numerical models of continental breakup imply that widespread peripheral subduction is the primary control on, and is necessary for, supercontinent break-up; formation of plumes often accompanies breakup, but this is not a pre-requisite (Figs. 4 and 5). This interpretation is substantiated not only by the geological record of the Earth's most recent supercontinent of Pangea (Buiter and Torsvik, 2014; Keppe, 2015a, 2015b) but also by that of Rodinia. Furthermore, comparison of the Rodinia record of continental assembly and dispersal with that for Nuna, Gondwana and Pangea suggests grouping into two supercycles. Supercycle I is represented by Nuna and Gondwana and involves some but not all available continental blocks, which then underwent partial (Nuna) or no break-up (Gondwana), prior to their incorporation into Rodinia and Pangea (Supercycle II). It was only at the end of this second supercycle that the supercontinents underwent complete dispersal.

Acknowledgements

We thank journal reviewers David Chew and Alan Collins, along with Jeff Amato, Kent Condé, David Evans and Tony Prave, for discussion and comment, and we acknowledge support from our respective funding agencies (NERC grant NE/J021822/1, and NSERC Canada). This is publication 815 from the ARC Centre of Excellence for Core to Crust Fluid Systems (<http://www.ccfs.mq.edu.au>) and a contribution to IGCP 648.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at <http://dx.doi.org/10.1016/j.epsl.2016.05.049>.

References

- Abdelmalak, M.M., Andersen, T.B., Planke, S., Faleide, J.I., Corfu, F., Tegner, C., Shephard, G.E., Zastrophnov, D., Myklebust, R., 2015. The ocean–continent transition in the mid-Norwegian margin: insight from seismic data and an onshore Caledonian field analogue. *Geology* 43, 1011–1014.
- Åhall, K.I., Connelly, J., 1998. Intermittent 1.53–1.13 Ga magmatism in western Baltica, age constraints and correlations within a postulated supercontinent. *Precambrian Res.* 92, 1–20.
- Aleinikoff, J.N., Zartman, R.E., Walter, M., Rankin, D.W., Lytle, P.T., Burton, W.C., 1995. U–Pb ages of metarhyolites of the Catoctin and Mount Rogers formations, central and southern Appalachians: evidence for two phases of lapetus rifting. *Am. J. Sci.* 295, 428–454.
- Amato, J.M., Aleinikoff, J.N., Akinin, V.V., McClelland, W.C., Toro, J., 2014. Age, chemistry, and correlations of Neoproterozoic–Devonian igneous rocks of the Arctic Alaska–Chukotka terrane: an overview with new U–Pb ages. *Spec. Pap., Geol. Soc. Am.* 506, 29–57.
- Anderton, R., 1982. Dalradian deposition and the late Precambrian–Cambrian history of the N Atlantic region: a review of the early evolution of the lapetus Ocean. *J. Geol. Soc.* 139, 421–431.
- Anderton, R., 1985. Sedimentation and tectonics in the Scottish Dalradian. *Scott. J. Geol.* 21, 407–426.
- Astini, R.A., 1998. Stratigraphical evidence supporting the rifting, drifting and collision of the Laurentian Precoardillera terrane of western Argentina. In: Pankhurst, R.J., Rapela, C.W. (Eds.), *The Proto-Andean Margin of Gondwana*. *Geol. Soc. (Lond.) Spec. Publ.* 142, 11–33.
- Banks, C.J., Smith, M., Winchester, J.A., Horstwood, M.S.A., Noble, S.R., Ottley, C.J., 2007. Provenance of intra-Rodinian basin-fills: the lower Dalradian supergroup, Scotland. *Precambrian Res.* 153, 46–64.
- Bingen, B., Demaiffe, D., van Breemen, O., 1998. The 616 Ma old Egersund Basaltic Dike Swarm, S.W. Norway and Late Neoproterozoic Opening of the lapetus Ocean. *J. Geol.* 106, 565–574.
- Bingen, B., Nordgulen, Ø., Viola, G., 2008. A four-phase model for the Sveconorwegian orogeny, SW Scandinavia. *Norwegian J. Geol.* 88, 43–72.
- Bond, G.C., Nickerson, P.A., Komlinz, M.A., 1984. Breakup of a supercontinent between 625 and 555 Ma: new evidence and implications for continental histories. *Earth Planet. Sci. Lett.* 70, 325–345.
- Bott, M.H.P., 1982. The mechanism of continental splitting. *Tectonophysics* 81, 301–309.
- Bott, M.H.P., 1992. The stress regime associated with continental break-up. In: Storey, B.C., Alabaster, T., Pankhurst, R.I. (Eds.), *Magmatism and the Causes of Continental Break-up*. Geological Society of London, London, pp. 125–136.
- Buiter, S.J.H., Torsvik, T.H., 2014. A review of Wilson cycle plate margins: a role for mantle plumes in continental break-up along sutures? *Gondwana Res.* 26, 627–653.
- Cawood, P.A., 2005. Terra Australis Orogen: Rodinia breakup and development of the Pacific and lapetus margins of Gondwana during the Neoproterozoic and Paleozoic. *Earth-Sci. Rev.* 69, 249–279.
- Cawood, P.A., Buchan, C., 2007. Linking accretionary orogenesis with supercontinent assembly. *Earth-Sci. Rev.* 82, 217–256.
- Cawood, P.A., Kröner, A., Collins, W.J., Kusky, T.M., Mooney, W.D., Windley, B.F., 2009. Accretionary Orogens through Earth history. In: Cawood, P.A., Kröner, A. (Eds.), *Earth Accretionary Systems in Space and Time*. *Geol. Soc. (Lond.) Spec. Publ.* 318, 1–36.
- Cawood, P.A., McCausland, P.J.A., Dunning, G.R., 2001. Opening lapetus: constraints from the Laurentian margin in Newfoundland. *Geol. Soc. Am. Bull.* 113, 443–453.
- Cawood, P.A., Nemchin, A.A., Strachan, R.A., 2007a. Provenance record of Laurentian passive-margin strata in the northern Caledonides: implications for paleo-drainage and paleogeography. *Geol. Soc. Am. Bull.* 119, 993–1003.
- Cawood, P.A., Nemchin, A.A., Strachan, R.A., Prave, A.R., Krabbendam, M., 2007b. Sedimentary basin and detrital zircon record along East Laurentia and Baltica during assembly and breakup of Rodinia. *J. Geol. Soc.* 164, 257–275.
- Cawood, P.A., Strachan, R., Cutts, K., Kinny, P.D., Hand, M., Pisarevsky, S., 2010. Neoproterozoic orogeny along the margin of Rodinia: Valhalla orogen, North Atlantic. *Geology* 38, 99–102.
- Cawood, P.A., Strachan, R.A., Merle, R.E., Millar, I.L., Loewy, S.L., Dalziel, I.W.D., Kinny, P.D., Jourdan, F., Nemchin, A.A., Connelly, J.N., 2015. Neoproterozoic to early Paleozoic extensional and compressional history of East Laurentian margin sequences: the Moine Supergroup, Scottish Caledonides. *Geol. Soc. Am. Bull.* 127, 349–371.
- Chew, D.M., Fallon, N., Kennelly, C., Crowley, Q., Pointon, M., 2010. Basic volcanism contemporaneous with the Sturtian glacial episode in NE Scotland. *Earth Environ. Sci. Trans. R. Soc. Edinb.* 100, 399–415.
- Collins, A.S., Pisarevsky, S.A., 2005. Amalgamating eastern Gondwana: the evolution of the Circum-Indian Orogens. *Earth-Sci. Rev.* 71, 229–270.
- Colpron, M., Logan, J.M., Mortensen, J.K., 2002. U–Pb zircon age constraint for late Neoproterozoic rifting and initiation of the lower Paleozoic passive margin of western Laurentia. *Can. J. Earth Sci.* 39, 133–143.
- Condé, K.C., 2005. *Earth as an Evolving Planetary System*. Elsevier, Amsterdam.

- Condie, K.C., 2013. Preservation and recycling of crust during accretionary and collisional phases of Proterozoic orogens: a bumpy road from Nuna to Rodinia. *Geosciences* 3, 240–261.
- Cutts, K.A., Hand, M., Kelsey, D.E., Wade, B., Strachan, R.A., Clark, C., Netting, A., 2009. Evidence for 930 Ma metamorphism in the Shetland Islands, Scottish Caledonides: implications for Neoproterozoic tectonics in the Laurentia–Baltica sector of Rodinia. *J. Geol. Soc.* 166, 1033–1047.
- Cutts, K.A., Kinny, P.D., Strachan, R.A., Hand, M., Kelsey, D.E., Emery, M., Friend, C.R.L., Leslie, A.C., 2010. Three metamorphic events recorded in a single garnet: integrated phase modelling in situ LA-ICPMS and SIMS geochronology from the Moine Supergroup, NW Scotland. *J. Metamorph. Geol.* 28, 249–267.
- Dalziel, I.W.D., 1997. Neoproterozoic–Paleozoic geography and tectonics: review, hypothesis, environmental speculation. *Geol. Soc. Am. Bull.* 109, 16–42.
- De Waele, B., Johnson, S.P., Pisarevsky, S.A., 2008. Palaeoproterozoic to Neoproterozoic growth and evolution of the eastern Congo Craton: its role in the Rodinia puzzle. *Precambrian Res.* 160, 127–141.
- Dewing, K., Harrison, J.C., Pratt, B.R., Mayr, U., 2004. A probable late Neoproterozoic age for the Kennedy Channel and Ella Bay formations, northeastern Ellesmere Island and its implications for passive margin history of the Canadian Arctic. *Can. J. Earth Sci.* 41, 1013–1025.
- Dickin, A.P., McNutt, R.H., Martin, C., Guo, A., 2010. The extent of juvenile crust in the Grenville Province: Nd isotope evidence. *Geol. Soc. Am. Bull.* 122, 870–883.
- Ernst, R.E., Bleeker, W., Söderlund, U., Kerr, A.C., 2013. Large Igneous Provinces and supercontinents: toward completing the plate tectonic revolution. *Lithos* 174, 1–14.
- Ernst, R.E., Hamilton, M.A., Soderlund, U., Hanes, J.A., Gladkochub, D.P., Okrugin, A.V., Kolotilina, T., Mekhonoshin, A.S., Bleeker, W., LeCheminant, A.N., Buchan, K.L., Chamberlain, K.R., Didenko, A.N., 2016. Long-lived connection between southern Siberia and northern Laurentia in the Proterozoic. *Nat. Geosci.* 9, 464–469.
- Ernst, R.E., Wingate, M.T.D., Buchan, K.L., Li, Z.X., 2008. Global record of 1600–700 Ma Large Igneous Provinces (LIPs): implications for the reconstruction of the proposed Nuna (Columbia) and Rodinia supercontinents. *Precambrian Res.* 160, 159–178.
- Evans, D.A.D., Mitchell, R.N., 2011. Assembly and breakup of the core of Paleoproterozoic–Mesoproterozoic supercontinent Nuna. *Geology* 39, 443–446.
- Evans, D.A.D., Trindade, R.I.F., Catelani, E.L., D’Agrella-Filho, M.S., Heaman, L.M., Oliveira, E.P., Söderlund, U., Ernst, R.E., Smirnov, A.V., Salminen, J.M., 2016. Return to Rodinia? Moderate to high palaeolatitude of the São Francisco/Congo craton at 920 Ma. *Geol. Soc. (Lond.) Spec. Publ.* 424, 167–190.
- Fettes, D.J., Macdonald, R., Fitton, J.G., Stephenson, D., Cooper, M.R., 2011. Geochemical evolution of Dalradian metavolcanic rocks: implications for the break-up of the Rodinia supercontinent. *J. Geol. Soc.* 168, 1133–1146.
- Fritz, H., Abdelsalam, M., Ali, K.A., Bingen, B., Collins, A.S., Fowler, A.R., Ghebreab, W., Hauzenberger, C.A., Johnson, P.R., Kusky, T.M., Macey, P., Muhongo, S., Stern, R.J., Viola, G., 2013. Orogen styles in the East African Orogen: a review of the Neoproterozoic to Cambrian tectonic evolution. *J. Afr. Earth Sci.* 86, 65–106.
- Gladkochub, D., Pisarevsky, S.A., Donskaya, T., Natapov, L.M., Mazukabzov, A., Stanevich, A.M., Sklyarov, E., 2006. Siberian Craton and its evolution in terms of Rodinia hypothesis. *Episodes* 29, 169–174.
- Gladkochub, D.P., Stanevich, A.M., Mazukabzov, A.M., Donskaya, T.V., Pisarevsky, S.A., Nicoll, G., Motova, Z.L., Kornilova, T.A., 2013. Early evolution of the Paleoasian ocean: LA-ICP-MS dating of detrital zircon from Late Precambrian sequences of the southern margin of the Siberian craton. *Russ. Geol. Geophys.* 54, 1150–1163.
- Gower, C.F., 1990. Mid-Proterozoic evolution of the eastern Grenville Province, Canada. *Geol. Fören. Stockh. Förh.* 112, 127–139.
- Gower, C.F., Krogh, T.E., 2002. A U-Pb geochronological review of the Proterozoic history of the eastern Grenville Province. *Can. J. Earth Sci.* 39, 795–829.
- Gurnis, M., 1988. Large-scale mantle convection and the aggregation and dispersal of supercontinents. *Nature* 332, 695–699.
- Halliday, A.N., Graham, C.M., Aftalion, M., Dymoke, P., 1989. The deposition age of the Dalradian Supergroup: U-Pb and Sm-Nd isotopic studies of the Tayvallich Volcanics, Scotland. *J. Geol. Soc.* 146, 3–6.
- Harlan, S.S., Heaman, L., LeCheminant, A.N., Premo, W.R., 2003. Gunbarrel mafic magmatic event: a key 780 Ma time marker for Rodinia plate reconstructions. *Geology* 31, 1053–1056.
- Heron, P.J., Lowman, J.P., Stein, C., 2015. Influences on the positioning of mantle plumes following supercontinent formation. *J. Geophys. Res., Solid Earth* 120, 3628–3648.
- Hoffman, P.F., 1991. Did the breakout of Laurentia turn Gondwanaland inside-out? *Science* 252, 1409–1412.
- Hynes, A., Rivers, T., 2010. Protracted continental collision – evidence from the Grenville Orogen. *Can. J. Earth Sci.* 47, 591–620.
- Johansson, Å., 2009. Baltica, Amazonia and the SAMBA connection—1000 million years of neighbourhood during the Proterozoic? *Precambrian Res.* 175, 221–234.
- Karlstrom, K.E., Ahall, K.-I., Harlan, S.S., Williams, M.L., McClelland, J., Geissman, J.W., 2001. Long-lived (1.8–1.0 Ga) convergent orogen in southern Laurentia, its extensions to Australia and Baltica, and implications for refining Rodinia. *Precambrian Res.* 111, 5–30.
- Keppie, D.F., 2015a. How the closure of paleo-Tethys and Tethys oceans controlled the early breakup of Pangaea. *Geology* 43, 335–338.
- Keppie, F., 2015b. How subduction broke up Pangaea with implications for the supercontinent cycle. *Geol. Soc. (Lond.) Spec. Publ.* 424.
- Khudoley, A., Chamberlain, K., Ershova, V., Sears, J., Prokopiev, A., MacLean, J., Kazakova, G., Malyshev, S., Molchanov, A., Kullerud, K., Toro, J., Miller, E., Veselovskiy, R., Li, A., Chiplay, D., 2015. Proterozoic supercontinental restorations: constraints from provenance studies of Mesoproterozoic to Cambrian clastic rocks, eastern Siberian Craton. *Precambrian Res.* 259, 78–94.
- Kirkland, C.L., Daly, J.S., Whitehouse, M.J., 2008. Basement-cover relationships of the Kalak Nappe Complex, Arctic Norwegian Caledonides and constraints on Neoproterozoic terrane assembly in the North Atlantic region. *Precambrian Res.* 160, 245–276.
- Kröner, A., Fedotova, A.A., Khain, E.V., Razumovskiy, A.A., Orlova, A.V., Anosova, M.O., Perelyaev, V.I., Nekrasov, G.E., Liu, D.Y., 2015. Neoproterozoic ophiolite and related high-grade rocks of the Baikal–Muya belt, Siberia: geochronology and geo-dynamical implications. *J. Asian Earth Sci.* 111, 138–160.
- Kuznetsov, N.B., Alekseev, A.S., Belousova, E.A., Romanyuk, T.V., Reimers, A.N., 2015. First results of U/Pb isotope dating (LA-ICP-MS) of detrital zircons from sandstones of the low Cambrian Brusov formation of the Southeastern White Sea region: a constraint for the lower age limit of the beginning of the Arctida–Baltica collision. *Dokl. Earth Sci.* 460, 28–32.
- Kuznetsov, N.B., Natapov, L.M., Belousova, E.A., O'Reilly, S.Y., Griffin, W.L., 2010. Geochronological, geochemical and isotopic study of detrital zircon suites from late Neoproterozoic clastic strata along the NE margin of the East European Craton: implications for plate tectonic models. *Gondwana Res.* 17, 583–601.
- Lane, L.S., Gehrels, G.E., 2014. Detrital zircon lineages of late Neoproterozoic and Cambrian strata, NW Laurentia. *Geol. Soc. Am. Bull.* 126, 398–414.
- Lane, L.S., Gehrels, G.E., Layer, P.W., 2016. Provenance and paleogeography of the Neruokpuk Formation, northwest Laurentia: an integrated synthesis. *Geol. Soc. Am. Bull.* 128, 239–257.
- Li, Z.-X., Evans, D.A.D., Halverson, G.P., 2013. Neoproterozoic glaciations in a revised global palaeogeography from the breakup of Rodinia to the assembly of Gondwanaland. *Sediment. Geol.* 294, 219–232.
- Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimmons, I.C.W., Fuck, R.A., Gladkochub, D.P., Jacobs, J., Karlstrom, K.E., Lu, S., Natapov, L.M., Pease, V., Pisarevsky, S.A., Thrane, K., Vernikovsky, V., 2008. Assembly, configuration, and break-up history of Rodinia: a synthesis. *Precambrian Res.* 160, 179–210.
- Li, Z.X., Li, X.H., Kinny, P.D., Wang, J., Zhang, S., Zhou, H., 2003. Geochronology of Neoproterozoic syn-rift magmatism in the Yangtze Craton, South China and correlations with other continents: evidence for a mantle superplume that broke up Rodinia. *Precambrian Res.* 122, 85–109.
- Likhonov, I.I., Reverdatto, V.V., Kozlov, P.S., Khiller, V.V., Sukhorukov, V.P., 2015a. $P-T-t$ constraints on polymetamorphic complexes of the Yenisey Ridge, East Siberia: implications for Neoproterozoic paleocontinental reconstructions. *J. Asian Earth Sci.* 113, 391–410.
- Likhonov, I.I., Reverdatto, V.V., Kozlov, P.S., Zinoviev, S.V., Khiller, V.V., 2015b. Evidence for the Valhalla tectonic events at the western margin of the Siberian Craton. *Dokl. Earth Sci.* 462, 458–462.
- Lowman, J.P., Jarvis, G.T., 1995. Mantle convection models of continental collision and breakup incorporating finite thickness plates. *Phys. Earth Planet. Inter.* 88, 53–68.
- Malone, S.J., McClelland, W.C., von Werner, G., Piepjohn, K., 2014. Proterozoic evolution of the North Atlantic–Arctic caledonides: insights from detrital zircon analysis of metasedimentary rocks from the Pearya Terrane, Canadian High Arctic. *J. Geol.* 122, 623–647.
- Metelkin, D.V., Vernikovsky, V.A., Matushkin, N.Y., 2015. Arctida between Rodinia and Pangea. *Precambrian Res.* 259, 114–129.
- Miller, E.L., Kuznetsov, N., Soboleva, A., Udaratina, O., Grove, M.J., Gehrels, G., 2011. Baltica in the Cordillera? *Geology* 39, 791–794.
- Murphy, J.B., Nance, R.D., 1991. Supercontinent model for the contrasting character of Late Proterozoic orogenic belts. *Geology* 19, 469–472.
- Murphy, J.B., Nance, R.D., 2003. Do supercontinents introvert or extrovert?: Sm-Nd isotope evidence. *Geology* 31, 873–876.
- Murphy, J.B., Nance, R.D., 2005. Do supercontinents turn inside-in or inside-out? *Int. Geol. Rev.* 47, 591–619.
- Murphy, J.B., Nance, R.D., 2013. Speculations on the mechanisms for the formation and breakup of supercontinents. *Geosci. Front.* 4, 185–194.
- Murphy, J.B., Nance, R.D., Cawood, P.A., 2009. Contrasting modes of supercontinent formation and the conundrum of Pangea. *Gondwana Res.* 15, 408–420.
- Murphy, J.B., Pisarevsky, S., Nance, R.D., 2013. Potential geodynamic relationships between the development of peripheral orogens along the northern margin of Gondwana and the amalgamation of West Gondwana. *Mineral. Petrol.* 107, 635–650.
- Murphy, J.B., Pisarevsky, S.A., Nance, R.D., Keppie, J.D., 2004. Neoproterozoic–Early Paleozoic evolution of peri-Gondwana terranes: implications for Laurentia–Gondwana connections. *Int. J. Earth Sci. (Geol. Rundsch.)* 93, 659–692.
- Nance, R.D., Murphy, J.B., Santosh, M., 2014. The supercontinent cycle: a retrospective essay. *Gondwana Res.* 25, 4–29.
- Nance, R.D., Murphy, J.B., Strachan, R.A., Keppie, J.D., Gutiérrez-Alonso, G., Fernández-Suárez, J., Quesada, C., Linnemann, U., D’lemos, R., Pisarevsky, S.A.,

2008. Neoproterozoic–early Palaeozoic tectonostratigraphy and palaeogeography of the peri-Gondwanan terranes: Amazonian v. West African connections. *Geol. Soc. (Lond.) Spec. Publ.* 297, 345–383.
- Nosova, A.A., Kuz'menkova, O.F., Veretennikov, N.V., Petrova, L.G., Levsky, L.K., 2011. Neoproterozoic Volhynia–Brest magmatic province in the western East European craton: within-plate magmatism in an ancient suture zone. *Petrology* 16, 105–135.
- Novak, S.W., Rankin, D.W., 2004. Compositional zoning of a Neoproterozoic ash-flow sheet of the Mount Rogers Formation, southwestern Virginia Blue Ridge, and the aborted rifting of Laurentia. In: Tollo, R.P., Corriveau, L., McLellan, J., Bartholomew, M.J. (Eds.), Proterozoic tectonic evolution of the Grenville orogen in North America. In: *Mem. Geol. Soc. Amer.*, vol. 197. Boulder, Colorado, pp. 571–600.
- Park, R.G., 1992. Plate kinematic history of Baltica during the Middle to Late Proterozoic: a model. *Geology* 20, 725–728.
- Pisarevsky, S.A., Bylund, G., 2010. Paleomagnetism of 1780–1770 Ma mafic and composite intrusions of Småland (Sweden): implications for the mesoproterozoic supercontinent. *Am. J. Sci.* 310, 1168–1186.
- Pisarevsky, S.A., Elming, S.-Å., Pesonen, L.J., Li, Z.-X., 2014. Mesoproterozoic paleogeography: supercontinent and beyond. *Precambrian Res.* 244, 207–225.
- Pisarevsky, S.A., Gladkochub, D.P., Konstantinov, K.M., Mazukabzov, A.M., Stanevich, A.M., Murphy, J.B., Tait, J.A., Donskaya, T.V., Konstantinov, I.K., 2013. Paleomagnetism of Cryogenian Kitoi mafic dykes in South Siberia: implications for Neoproterozoic paleogeography. *Precambrian Res.* 231, 372–382.
- Pisarevsky, S.A., Murphy, J.B., Cawood, P.A., Collins, A.S., 2008a. Late Neoproterozoic and Early Cambrian palaeogeography: models and problems. In: Pankhurst, R.J., Trouw, R.A.J., Brito Neves, B.B., de Wit, M.J. (Eds.), West Gondwana: Pre-Cenozoic Correlations Across the South Atlantic Region. *Geol. Soc. (Lond.) Spec. Publ.* 294, 9–31.
- Pisarevsky, S.A., Natapov, L.M., Donskaya, T.V., Gladkochub, D.P., Vernikovsky, V.A., 2008b. Proterozoic Siberia: a promontory of Rodinia. *Precambrian Res.* 160, 66–76.
- Prave, A.R., 1999. Two diamictites, two cap carbonates, two $\delta^{13}\text{C}$ excursions, two rifts: the Neoproterozoic Kingston Peak Formation, Death Valley, California. *Geology* 27, 339–342.
- Prave, A.R., Fallick, A.E., Thomas, C.W., Graham, C.M., 2009. A composite C-isotope profile for the Neoproterozoic Dalradian Supergroup of Scotland and Ireland. *J. Geol. Soc.* 166, 845–857.
- Puffer, J.H., 2002. A late Neoproterozoic eastern Laurentian superplume: location, size, chemical composition, and environmental impact. *Am. J. Sci.* 302, 1–27.
- Robinson, F.A., Foden, J.D., Collins, A.S., 2015. Zircon geochemical and geochronological constraints on contaminated and Enriched Mantle sources beneath the Arabian Shield, Saudi Arabia. *J. Geol.* 123, 463–489.
- Ross, G.M., 1991. Tectonic setting of the Windermere Supergroup revisited. *Geology* 19, 1125–1128.
- Smith, M., Robertson, S., Rollin, K.E., 1999. Rift basin architecture and stratigraphic implications for basement-cover relationships in the Neoproterozoic Grampian Group of the Scottish Caledonides. *J. Geol. Soc.* 156, 1163–1173.
- Sonderholm, M., Fredericksen, K.S., Smith, M.P., Tirsgaard, H., 2008. Neoproterozoic sedimentary basins with glaciogenic deposits of the East Greenland Caledonides. In: Higgins, A.K., Gilotti, J.A., Smith, M.P. (Eds.), The Greenland Caledonides – Evolution of the Northeast Margin of Laurentia. The Greenland Caledonides. In: *Mem. Geol. Soc. Amer.*, vol. 202, pp. 99–136.
- Soper, N.J., 1994. Neoproterozoic sedimentation on the northeast margin of Laurentia and the opening of Iapetus. *Geol. Mag.* 131, 291–299.
- Sovetov, J.K., Kulikova, A.E., Medvedev, M.N., 2007. Sedimentary basins in the southwestern Siberian craton: late Neoproterozoic–Early Cambrian rifting and collisional events. *Spec. Pap. Geol. Soc. Am.* 423, 549–578.
- Strauss, J.V., MacDonald, F.A., Halverson, G.P., Tosca, N.J., Schrag, D.P., Knoll, A.H., 2015. Stratigraphic evolution of the Neoproterozoic Collison Lake Formation: linking the break-up of Rodinia to the Islay carbon isotope excursion. *Am. J. Sci.* 315, 881–944.
- Thomas, W.A., 2011. The Iapetan rifted margin of southern Laurentia. *Geosphere* 7, 97–120.
- Thomas, W.A., Astini, R.A., 1996. The Argentine Precordillera: a traveller from the Ouachita Embayment of North American Laurentia. *Science* 273, 752–757.
- Tohver, E., van der Pluijm, B.A., Mezger, K., Essene, E.J., Scandolara, J.E., Rizzotto, G., 2004. Significance of the Nova Brasilândia metasedimentary belt in western Brazil: redefining the Mesoproterozoic boundary of the Amazon craton. *Tectonics* 23. <http://dx.doi.org/10.1029/2003TC001563>.
- Vernikovsky, V.A., Vernikovskaya, A.E., 2006. Tectonics and evolution of granitoid magmatism in the Yenisei Ridge. *Russ. Geol. Geophys.* 47, 35–52.
- Volkert, R.A., Feigenson, M.D., Mana, S., Bolge, L., 2015. Geochemical and Sr–Nd isotopic constraints on the mantle source of Neoproterozoic mafic dikes of the rifted eastern Laurentian margin, north-central Appalachians, USA. *Lithos* 212–215, 202–213.
- Worsley, T.R., Nance, R.D., Moody, J.B., 1986. Tectonic cycles and the history of the Earth's biogeochemical and paleoceanographic record. *Paleoceanography* 1, 233–263.
- Yonkee, W.A., Dehler, C.D., Link, P.K., Balgord, E.A., Keeley, J.A., Hayes, D.S., Wells, M.L., Fanning, C.M., Johnston, S.M., 2014. Tectono-stratigraphic framework of Neoproterozoic to Cambrian strata, west-central U.S.: protracted rifting, glaciation, and evolution of the North American Cordilleran margin. *Earth-Sci. Rev.* 136, 59–95.
- Zhang, S., Li, Z.-X., Evans, D.A.D., Wu, H., Li, H., Dong, J., 2012. Pre-Rodinia supercontinent Nuna shaping up: a global synthesis with new paleomagnetic results from North China. *Earth Planet. Sci. Lett.* 353–354, 145–155.
- Zhao, G., Cawood, P.A., Wilde, S.A., Sun, M., 2002. Review of global 2.1–1.8 Ga orogens: implications for a pre-Rodinia supercontinent. *Earth-Sci. Rev.* 59, 125–162.