# Kinematic constraints on the Rodinia-Gondwana transition

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**Abstract**

Earth's plate tectonic history during the breakup of the supercontinent Pangea is well constrained from the seafloor spreading record, but evolving plate configurations during older supercontinent cycles are much less well understood. A relative paucity of available paleomagnetic and geological data for deep time reconstructions necessitates geoscientists to find innovative approaches to help discriminate between competing plate configurations. Periods of supercontinent assembly may be better constrained where paleomagnetic and geological data from multiple continental blocks can be combined. More difficult is tracing the journeys of individual continents during the amalgamation and breakup of supercontinents. Typically deep-time reconstructions are built using absolute motions defined by paleomagnetic data, and do not consider the kinematics of relative motions between plates, even for occasions where they are thought to be 'plate-pairs', either rifting apart leading to the formation of conjugate passive margins separated by a new ocean basin, or brought together by collision and orogenesis. Here, we use open-source software tools (GPlates/pyGPlates) that allow geoscientists to easily access quantitative plate kinematics inherent within alternative reconstructions, such as rates of absolute and relative plate motion. We analyse the Rodinia-Gondwana transition during the Neoproterozoic, investigating the proposed Australia-Laurentia configurations during Rodinia, and the motion of India colliding with Gondwana. We find that earlier rifting times provide more optimal kinematic results. The AUSWUS and AUSMEX configurations with rifting at 800 Ma are the most kinematically supported configurations for Australia and Laurentia (average rates of 57 and 64 mm/yr respectively), and angular rotation of ~1.4°/Myr, compared to a SWEAT configuration (average spreading rate ~76 mm/yr) and Missing-Link configuration (~90 mm/yr). Later rifting, at 725 Ma necessitates unreasonably high spreading rates of >130 mm/yr for AUSWUS and AUSMEX and ~150 mm/yr for SWEAT and Missing-Link. Using motion paths and convergence rates, we create a kinematically reasonable (convergence below 70 mm/yr) tectonic model that is built upon a front-on collision of India into Gondwana, while also incorporating a sinistral strike-slip motion against Australia and East Antarctica. We use this simple tectonic model to refine a global model for the break-up of western Rodinia and the transition to eastern Gondwana. Our refined tectonic model for the Neoproterozoic, beginning with the breakup of the

supercontinent Rodinia, provides an improved paleogeographic basis for investigating the causes of major climate change and the subsequent evolution of complex life.

## Introduction

Our knowledge of plate tectonic configurations through Earth history is limited by the availability of geoscientific data through time and space. Geological, geophysical, paleomagnetic, geochemical, structural and tectonic (e.g. large scale orogenies, passive margins) information helps to constrain both the motions of plates, and the relative configurations of continents within past supercontinents. The fabric and geophysical signatures preserved within the ocean basins, in particular, magnetic anomalies and fracture zones (Matthews et al. 2011; Wessel and Müller, 2015), allow the construction of detailed, global relative plate models for Mesozoic and Cenozoic times (e.g. Müller et al. 2016; Seton et al. 2012). These features indicate the extent to which relative plate motions are stable or change over timescales of millions to tens-of-millions years. For example, spreading rates globally are typically in the range 10 to 70 mm/yr. In the Atlantic basins, spreading rates have remained within 20 and 40 mm/yr over the last ~200 Myr. Other ocean basins have witnessed much larger variations in spreading rates, and changes in direction of relative plate motion at spreading centres, witnessed by sharp fracture zone bends (Matthews et al, 2011; 2012), notably along spreading centres in the Indian ocean. Mechanisms to explain major changes in relative plate motion rate and direction are either grouped into 'top-down' tectonic mechanisms or 'bottom-up' mantle flow mechanisms. Tectonic mechanisms relate to changes in plate boundary forces such as subduction initiation (e.g. Whittaker et al. 2007), cessation (Austermann et al. 2011, Patriat and Achache, 1984), or changes in the subduction regime through subduction of ridges (Seton et al. 2015), thick oceanic crust (Knesel et al. 2008) or young buoyant oceanic crust (Matthews et al. 2012). Proposed mantle flow mechanisms include plume arrival (Cande and Stegman 2011; van Hinsbergen et al. 2011), decoupling due to lubrication from plume arrival (Ratcliff et al. 1998) and heat buildup around subducted slabs leading to a reduction of negative buoyancy (King et al. 2002; Lowman et al. 2003). Feedback mechanisms between orogenesis and changes in convergence rates have also been proposed (e.g. Iaffaldano et al. 2006).

The supercontinent cycle theory implies that over time continents disperse forming ocean basins, before re-amalgamating into a new supercontinent. Evidence for this is provided by a number of punctuated geological and geochemical secular trends, such as in zircons which act as a proxy for continental magmatism (Belousova et al. 2010), the formation of mineral deposits (Bierlein et al. 2009; Groves et al. 1998; Pehrsson et al. 2016), and large igneous provinces (Bradley 2011; Nance and Murphy 2013). The theory suggests that the formation and breakup of supercontinents are intricately linked to both deeper earth processes, as well as surface, ocean and atmospheric processes (Bradley 2011; Nance et al. 2014). While Pangea, the last supercontinent, is well known, Proterozoic supercontinents are less well established due to the absence of ocean basins and the paucity of fossil evidence. Rodinia is the hypothesised late Mesoproterozoic to early Neoproterozoic supercontinent, originally envisioned on the basis of global orogenies (the Grenvillian orogeny of Laurentia and coeval Stenian-Tonian orogenies worldwide) at ca.1.2-0.9 Ga (Dalziel 1991; Hoffman 1991; Moores 1991). However, not all Proterozoic cratons clearly exhibit Stenian-Tonian aged orogenies, even if they do, the orogenies are not synchronous (Fitzsimons 2000), and, as more data have become available, a proliferation of plate configurations for the Neoproterozoic have been developed, including models with a large, long-lived Rodinia (Johansson 2014; Li et al. 2008), paleomagnetically defined models (Evans 2009; Powell et al. 1993), and models that have a partially complete supercontinent, with one-two cratons separate (usually Congo-São Francisco and/or India, e.g. Collins and Pisarevsky 2005; Meert 2003). Generally, most models of Rodinia tend to have Laurentia as the heart of the supercontinent due to the presence of rifted margins on the perimeter of the continent. Australia–East-Antarctica are typically matched to the western coast of Laurentia; Siberia-North China off the northern margin; Amazonia, Baltica and West Africa on the eastern margin; and the Kalahari craton on the southern margin (e.g. Collins and Pisarevsky 2005; Dalziel 1991; Hoffman 1991; Johannson 2014; Li et al. 2008, 2013; Meert and Torsvik 2003; Moores 1991), though some variations exist (e.g. Sears and Price 2003).

For pre-Pangea times, where ocean basins are not preserved, it becomes more important to use other approaches to help discriminate between competing plate motions and continental configurations. Typically either geological or paleomagnetic data (or a combination of both) is used to build deep-time plate models.

For example Goodge et al. (2008) used isotopic data from granites to tie East-Antarctica and Laurentia together at ~1.4 Ga, Ganade et al. (2016) dated zircons to constrain the timing of western Gondwana collision, geochemical signatures of large igneous provinces were used to determine pre-rift matches of cratons for Kenorland, Nuna and Rodinia (e.g. Ernst et al. 2008; 2013; Ernst and Bleeker 2010) and detrital zircon analyses have been used to link provenances together (e.g. Li et al. 2015; Mulder et al. 2015; Wang and Zhou 2012,) and measure secular changes in volume of continental crust (e.g. Condie et al. 2009; Nance et al. 2014). Evans (2009) constructed a (completely) paleomagnetically derived model of Rodinia, and Meert (2002) built a paleomagnetically constrained model of Nuna. Recent models that integrate both geological and paleomagnetic data for the globe have also been developed for Nuna (Pisarevsky et al. 2014) and Rodinia (Li et al. 2008, 2013). These models anchor relative plate configurations and motions suggested by geology with absolute position as determined through paleomagnetic data, as approaches to determining absolute plate motions for recent times (e.g. hot spot chains (Morgan, 1971; Müller et al. 1993; Steinberger et al. 2004) and tomographic imaging of slabs (Butterworth et al. 2014; van der Meer et al. 2010) are not applicable to deep time reconstructions.

Absolute plate motion models constructed for the Paleozoic (Domeier 2015; Domeier and Torsvik 2014;) use a combination of paleomagnetic data and large low-shear-velocity provinces (LLSVPs) to constrain paleolatitude and paleolongitude (Torsvik et al. 2008). These models are also supplemented with geological and paleontological data (e.g. Cocks and Torsvik 2002; Torsvik and Cocks 2013) to help with constraining the timing of events, paleolatitude and plate configurations. For all but the latest Neoproterozoic reconstructions, paleontological data are unavailable as complex life had not yet evolved; therefore the focus shifts to either paleomagnetic and/or geological information to reconstruct plate motions. During supercontinent assembly times, paleomagnetic data are especially useful, as a small number of reliable poles from different blocks can be pooled together to constrain the motion of a large number of cratons, leading to models that are grounded with absolute plate motions; however, during times of supercontinent dispersal and amalgamation it becomes more difficult to infer absolute plate motions due to fragmented apparent polar wander paths (APWPs). Two consequences of this are the development of tectonic models that cluster around paleomagnetic 'pierce points' (i.e. times at which high quality paleomagnetic data exist) such that these models simply consist of a series of snapshots of the positions of continents at specified times without incorporating relative motions suggested by geology, and, secondly, tectonic models that are unable to distinguish between some competing configurations or motions due to missing or poor quality data.

The Neoproterozoic, in particular the transition to Gondwana from Rodinia, is a key stage in global plate reconstructions due to the (near-)global glaciation events that occurred at that time (e.g. Gernon et al. 2016; Hoffman and Li 2009; Schmidt and Williams 1995) and because many present-day continents were formed during this transition. Gondwana, consisting primarily of Africa, South America, Australia, India and Antarctica, was the precursor to Pangea, and the major landmass of the southern hemisphere for much of the Phanerozoic. It occupies a particularly important position for both geological and biological purposes, as it is the oldest proposed supercontinental amalgamation for which a variety of geological data are readily available (Cawood and Buchan, 2007; Collins and Pisarevsky, 2005; Li et al. 2008; Meert 2003), as well being integral to the evolution and dispersion of complex life (e.g. Brasier et al. 2001; Halverson et al. 2010; Maruyama and Santosh 2008; Meert and Lieberman 2003; Santosh 2010; Squire et al. 2006).

Here we present an alternative approach to discriminate between competing Proterozoic reconstructions, using kinematic data extracted from a continent-focussed plate reconstruction model (adapted from Li et al. 2008; 2013). We use relative plate motion kinematics to help make informed decisions for plate reconstructions during times of supercontinent dispersal and amalgamation, when large gaps in the coverage of paleomagnetic data limit our ability to constrain plate motions. From this, we generate a simple tectonic reconstruction of the breakup of western Rodinia and amalgamation of eastern Gondwana. We demonstrate this during dispersal times by comparing the four competing Neoproterozoic configurations of Laurentia and Australia–East-Antarctica; SWEAT, AUSWUS, AUSMEX and South China as a 'Missing-Link' (Fig. 1a-d), reconstructing them from a common end point (650 Ma) back to the possible rifting times permitted by both paleomagnetic and geological data, and then in times of amalgamation, by tracing and constraining the relative motions of India with respect to Australia, and with respect to the Congo-São Francisco continent.

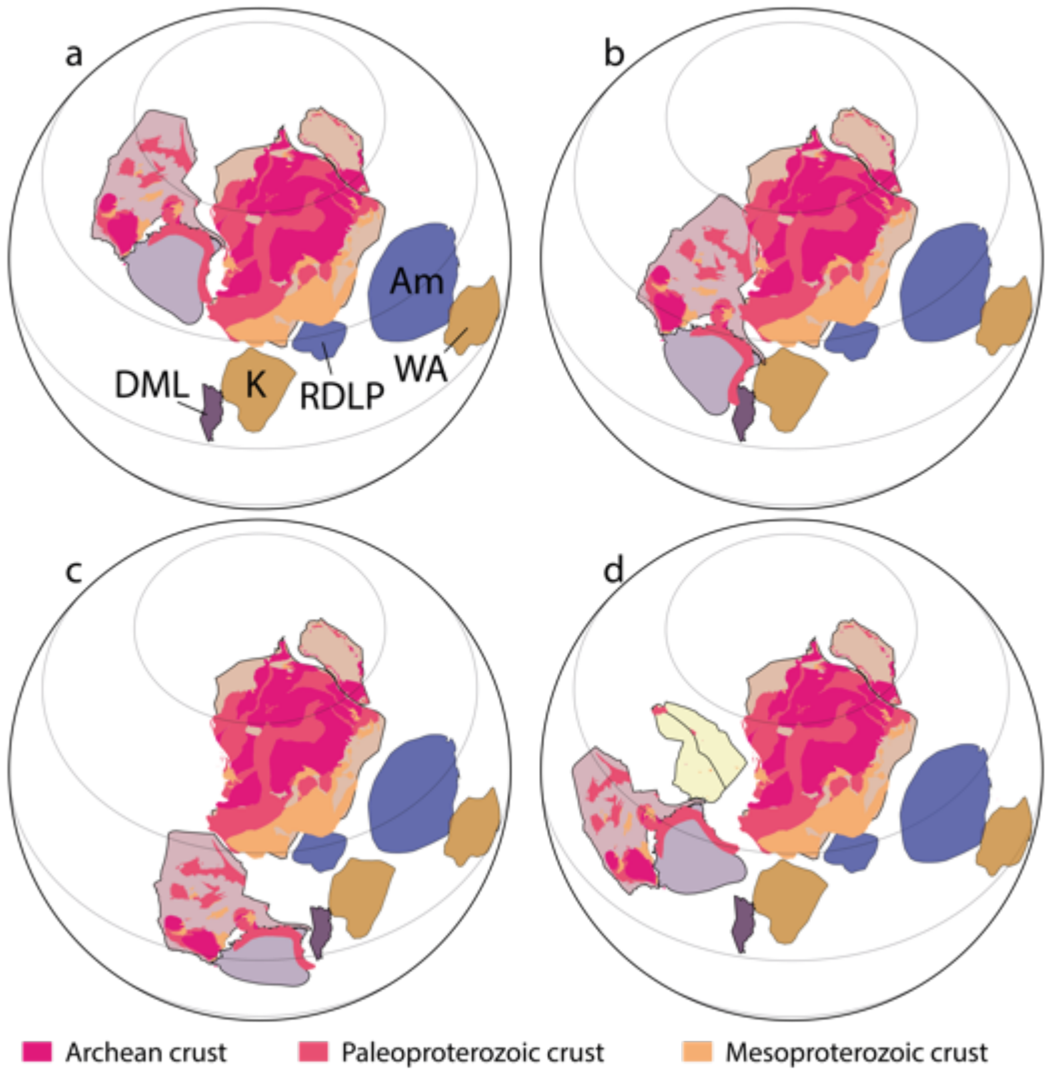


Figure 1: The different configurations of Laurentia with Australia-Eastern Antarctica and South China with pre-Neoproterozoic geology overlain. Laurentia is fixed in its present day position. (a) SWEAT fit, eastern Antarctica is pushed against the southwest US, while Australia lies further north near the US-Canadian border (Dalziel, 1991; Hoffman, 1991; Moores, 1991); (b) AUSWUS fit, eastern Australia is matched against the southwest United States of America (Karlstrom et al. 1999); (c) AUSMEX, Australia has only a small connection with Laurentia, where the north tip of Queensland fits against Mexico (Wingate et al. 2002), Kalahari Craton is shifted further south to accommodate Mawson; (d) Missing-Link model, which fits South China as a continental slither between Australia and Laurentia (Li et al. 1995). Laurentia is rotated to its 800 Ma position (after Li et al. 2008; 2013). Geology is taken from the Geodynamic map of

Rodinia after Li et al. (2008). Am, Amazonia; DML, Dronning Maud Land; K, Kalahari; RDLP, Rio de la Plata; WA, West Africa.

**Methodology**

We investigate the relative motion for two specific geological episodes: firstly, rifting between Australia—East-Antarctica and Laurentia during Rodinia breakup and subsequent continued divergence; and secondly, convergence between India and Australia, and India and Congo, during Gondwana amalgamation. The rifting time and alternative configurations of Australia—East-Antarctica and Laurentia were analysed to determine which timings and configurations are more kinematically feasible (i.e. at least compared to present-day kinematics) as well as to determine the possible range of relative paleolongitudinal distance between Australia—East-Antarctica and Laurentia for times postdating their interpreted connection. For the amalgamation of eastern Gondwana, known geological and paleomagnetic constraints of India, Congo and Australia were used to build a kinematically feasible, relative plate convergence model. The different scenarios, based on alternative Rodinian configurations, for Australia–East-Antarctica - Laurentia rifting, as well as the geological and paleomagnetic data pertinent to India's convergence into Gondwana are outlined below.

**Previous Analysis**

Four configurations of the Australia–East-Antarctica – Laurentia connection have been proposed in the last twenty years based on geological and paleomagnetic grounds, though both sets of data are insufficient to fully discriminate between them. SWEAT, juxtaposing the south-west USA with eastern Antarctica (Australia lies further north near Wyoming and the Canadian border) (Dalziel 1991; Hoffman 1991; Moores 1991) (Fig. 1a); AUSWUS, which matches the east coast of Australia with the west coast of the USA (Karlstrom et al. 1999) (Fig. 1b); AUSMEX, which pushes Australia–East-Antarctica further south, such that Queensland is against

Mexico (Wingate et al. 2002) (Fig. 1c); and the Missing-Link model, which fits South China as a continental slither between Laurentia and Australia (Li et al. 1995) (Fig. 1d).

Generally, the conjugate margins of both corresponding continents have thick sedimentary sequences intruded by magmatic dykes (e.g. Davidson 2008; Priess 2000; Rainbird et al. 1996; Walter et al. 1994; Young et al 1979) that suggest rifting somewhere between 825-700 Ma, though the transition from rift to drift is unconstrained partly due to difficulties in precisely dating many of the formations of the Adelaidian Rift Complex.

*SWEAT*

The original Rodinian connection proposed between Laurentia and Australia by Dalziel (1991), Hoffman (1991) and Moores (1991) was based on a number of similarities such as an extension of the Grenvillian Orogeny into Antarctica (and India) (Moores 1991) and similar tectonic histories and tectonostratigraphy of their margins (e.g. Bell and Jefferson 1987; Dalziel 1991; Eisbacher 1985). Both the west coast of Laurentia and the east coast of Australia are characterised by thick, broadly correlatable, sedimentary successions (e.g. Rainbird et al. 1996; Young et al. 1979; Young 1981) that are cut by dyke swarms (e.g. Ernst et al. 2008). These reconstructions placed the margin of eastern Antarctica against the southwest United States margin (called SWEAT), with the east coast of Australia aligning with the Wopmay Belt of north-eastern Canada (Moores et al. 1991) (Fig. 1a).

*AUSWUS*

The AUSWUS (Australia-Western United States, Fig. 1b) connection was originally proposed based on the structural relationship of the offsets from three transform faults between Laurentia and Australia, and then using them to more accurately align the margins (Brookfield 1993). Karlstrom et al. (1999; 2001) refined this connection (terming it 'AUSWUS') by connecting the Grenvillian orogeny in Laurentia with the Albany-Fraser and Musgrave orogenies in Australia and Burrett and Berry (2000; 2002) expanded on it further, matching the Broken Hill and Mt Isa Terranes in Australia with the Mojavia province and San Gabriel terrane in the western United States, suggesting a stronger affinity between eastern Australia and Western US, than Australia and Canada.

*AUSMEX*

AUSMEX (Australia-Mexico) was proposed by Wingate et al. (2002) in response to perceived poor reliability in paleomagnetic data during the latest Mesoproterozoic that made both SWEAT and AUSWUS models untenable (though this was later resolved by Schmidt et al., 2006). They proposed that if Australia–East-Antarctica was connected to Laurentia at all in the late Mesoproterozoic, then it could only be a marginal connection with northern Queensland with Mexico. This reconstruction was done using a new paleomagnetic pole from WA to constrain Australia's location at 1050 Ma (Fig. 1c). A paleomagnetic pole from the Officer Basin at 780 Ma provides a stronger argument for an AUSMEX-type configuration than either SWEAT or AUSWUS when compared to similar-aged Laurentian poles (Pisarevsky et al. 2007) though it doesn't completely disqualify the other configurations. A notable problem with the AUSMEX configuration is the absence of geological evidence that supports this configuration. Greene (2010) argued for an AUSMEX configuration (or Missing Link configuration) based on the mismatch strike of rifting basins within Australia and Laurentia.

*Missing-Link*

The Missing-Link model was originally proposed by Li et al. (1995) with the South China Cratons acting as a continental slither caught between the amalgamation of Australia–East-Antarctica and Laurentia in an otherwise typical SWEAT configuration (Fig. 1d). While the broad stratigraphy across eastern Australia-Laurentia is congruent, there are a number of mismatches such as geochemical discontinuities (Borg and DePaolo 1994) and the mantle plume record during the Neoproterozoic. Other issues exist such as mismatched stratigraphy (Li et al. 2008), but are either difficult to disprove or prove concisely due to ice cover in Antarctica, or they disallow a SWEAT connection for a late Mesoproterozoic but not necessarily the Neoproterozoic.

The Missing-Link model neatly accounts for these, as South China shares a similar stratigraphy with both Australia and Laurentia and has been used to explain the magmatic dyke record across all three cratons (Li et al. 1999). The offset provided by positioning this block between Australia and Laurentia also alleviated some of the problems fitting the timing of rifting within paleomagnetic constraints of Australia, though the 40° intraplate rotation suggested by Li and Evans (2011) offered a neat solution re-validating SWEAT-like configurations. A controversial component of the Missing-Link model is the presence of extensive magmatism in South China in the early Neoproterozoic (e.g. Du et al. 2014; Zhao et al. 2011). Li et al. (1999; 2008) ascribed these to rifting and intra-continental intrusions, though recent geochemistry suggests that they are from active subduction zones, suggesting that South China needs to face an open ocean and not occupy a central position of Rodinia (Du et al. 2014).

## Paleomagnetic constraints of Rodinia Breakup

### *Australian Constraints*

Paleomagnetic data from the Albany-Fraser Orogeny and the Gnowangerup–Fraser Dyke Suite during the Late Mesoproterozoic (~1.2 Ga) requires Australia to be situated at polar latitudes (Pisarevsky et al. 2003; 2014), while comparable data from Laurentia places it closer to the equator (Palmer et al. 1977). From 1070 Ma paleomagnetic data permit a connection between Australia and Laurentia (e.g. Schmidt et al. 2006; Wingate et al. 2002) in an AUSMEX type fit; with SWEAT, AUSWUS and Missing-Link type fits being permissible from 1050 Ma (Powell et al. 1993). There is little reliable Australian paleomagnetic data from the early Neoproterozoic (Table 1), which makes it difficult to discriminate between both the differing configurations and rifting time, though poorly dated results from the 830-720 Ma Buldya Group, constrain its position to low-latitudes (Pisarevsky et al. 2007) (Fig. 2-4). In particular, an 825 Ma pole from the Browne Formation (though there are uncertainties on the age of the sediments in the Browne Formation (cf. Schmidt

2014)) and a 780 Ma pole form the Hussar Formation suggests low latitudes, with the latter pole favouring an AUSMEX configuration *if* Australia-Laurentia had not separated yet (Fig. 2a, b) (Pisarevsky et al. 2007).

Two paleomagnetic 'grand-poles' (mean of two or more key-poles from separate laboratories) from Precambrian Australia were determined for the late Neoproterozoic by Schmidt (2014) in his recent review. The first, from the Mundine Dyke Swarms (MDS), combines a 755 Ma pole (Wingate and Giddings, 2000) with a 748 Ma pole (Embleton and Schmidt, 1985), and the second encompasses the Elatina Formation (EF), and is dated at ~635 Ma (Schmidt et al. 2009; Schmidt and Williams, 1995; Sohl et al. 1999). The former pole places Australia at low latitudes and was interpreted to constrain rifting to ~750 Ma at the latest (Wingate and Giddings, 2000) (Fig. 3b); however the 40° intraplate rotation of Li and Evans (2011) permits rifting to continue later (until ~700 Ma), by reconciling the MDS with the ~770-750 Ma Walsh Tillite Cap pole (Li 2000). A ~770 Ma pole from the Bitter Springs in central Australia by Swanson-Hysell et al. (2012) also supports this intraplate rotation, as the rotation reconciles this pole with the MDS pole (Schmidt 2014) (Fig. 3a).

Paleomagnetic data are available for the Ediacaran in Australia, with a series of poles from 650-580 Ma, including the EF grand pole (Schmidt et al. 2009; 2014) that constrain its position from equatorial to sub-equatorial (Schmidt et al. 2009, Schmidt and Williams 1996; 2010; Sohl et al. 1999), but having rotated counterclockwise relative to Laurentia, such that it is aligned NW-SE as opposed to NE/E-SW/W (depending on starting configuration) within Rodinia (Fig. 4a,b). The Yaltipena formation (Sohl et al. 1999) (Fig. 4a), taken here as ~650 Ma after Li et al. (2013), and on the basis that it must be older than the Elatina glaciation which has a maximum age of 640 Ma (Schmidt 2014; Williams et al. 2008) (Fig. 4b) is the start of the Australian Ediacaran polar wander path, which indicates that Australia drifted in low latitudes (Schmidt and Williams 2010). At some time in the Neoproterozoic prior to 650 Ma, Australia (together with East-Antarctica) must rift from Laurentia to reach this position, and we use this position as our common end point for all configurations.

We note that SWEAT, AUSWUS and AUSMEX are all problematic with younger rifting times (younger than ~770 Ma) on paleomagnetic grounds due to the mismatch between the MDS pole and equatorial position of Laurentia, which, given these fits, would have to sit N-S (similar to present day) rather than E-W (Wingate and Giddings 2000). Importantly, the position of Australia in the Missing-Link Model helps minimise the offset of the MDS pole (as it is situated more 'upright' relative to Laurentia).

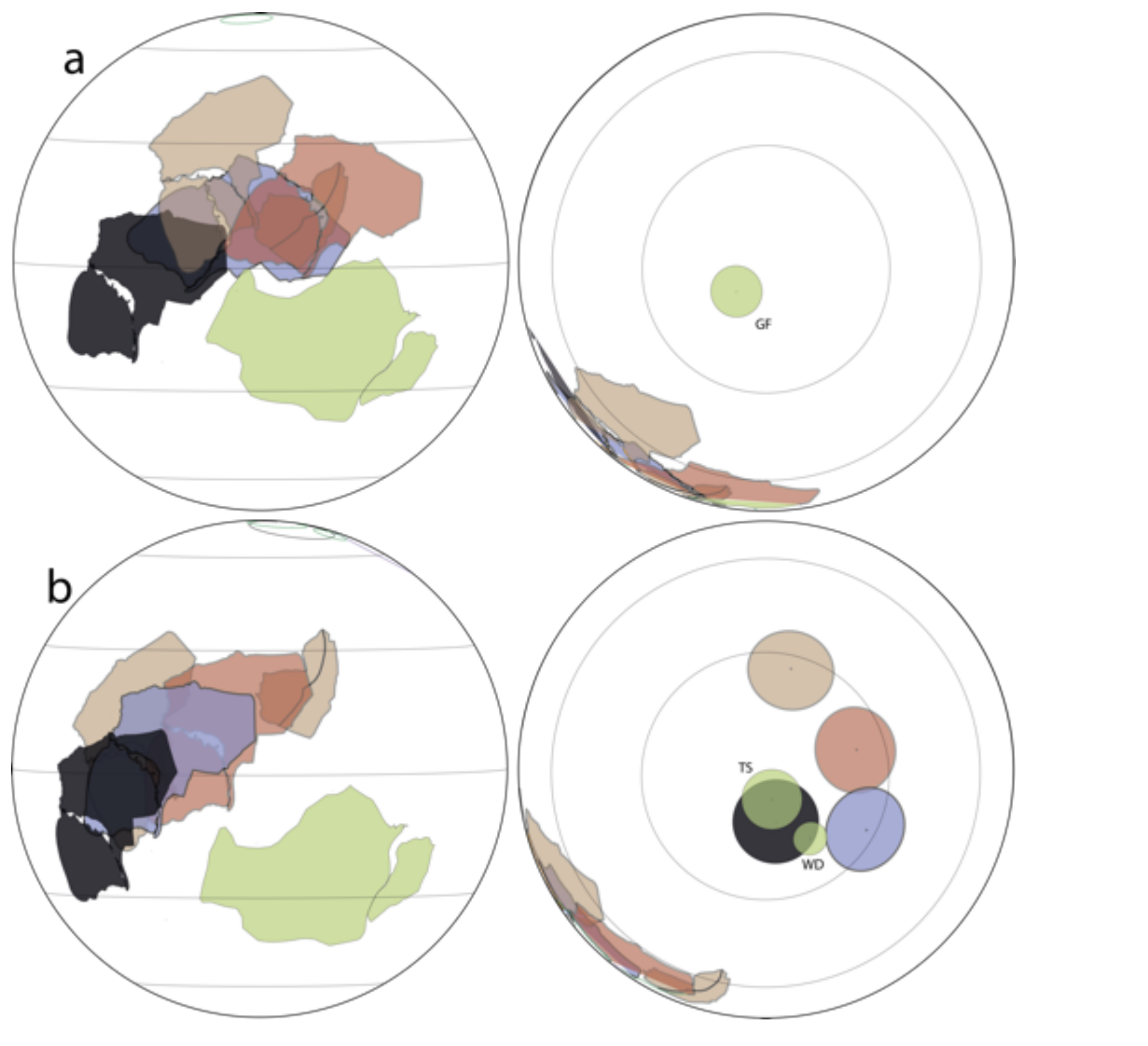


Figure 2: Paleomagnetic data for Australia and Laurentia at (a) 800 Ma, and (b) 780 Ma. Alternate Australia configurations are colour-coded; SWEAT, red; AUSWUS, blue; AUSMEX, black; Missing-Link, tan. Laurentia is in green. GF, Galeros Formation, TS, Tsezotene Sills, WD, Wyoming Dykes. Australian

pole in (b) is the Hussar Formation.

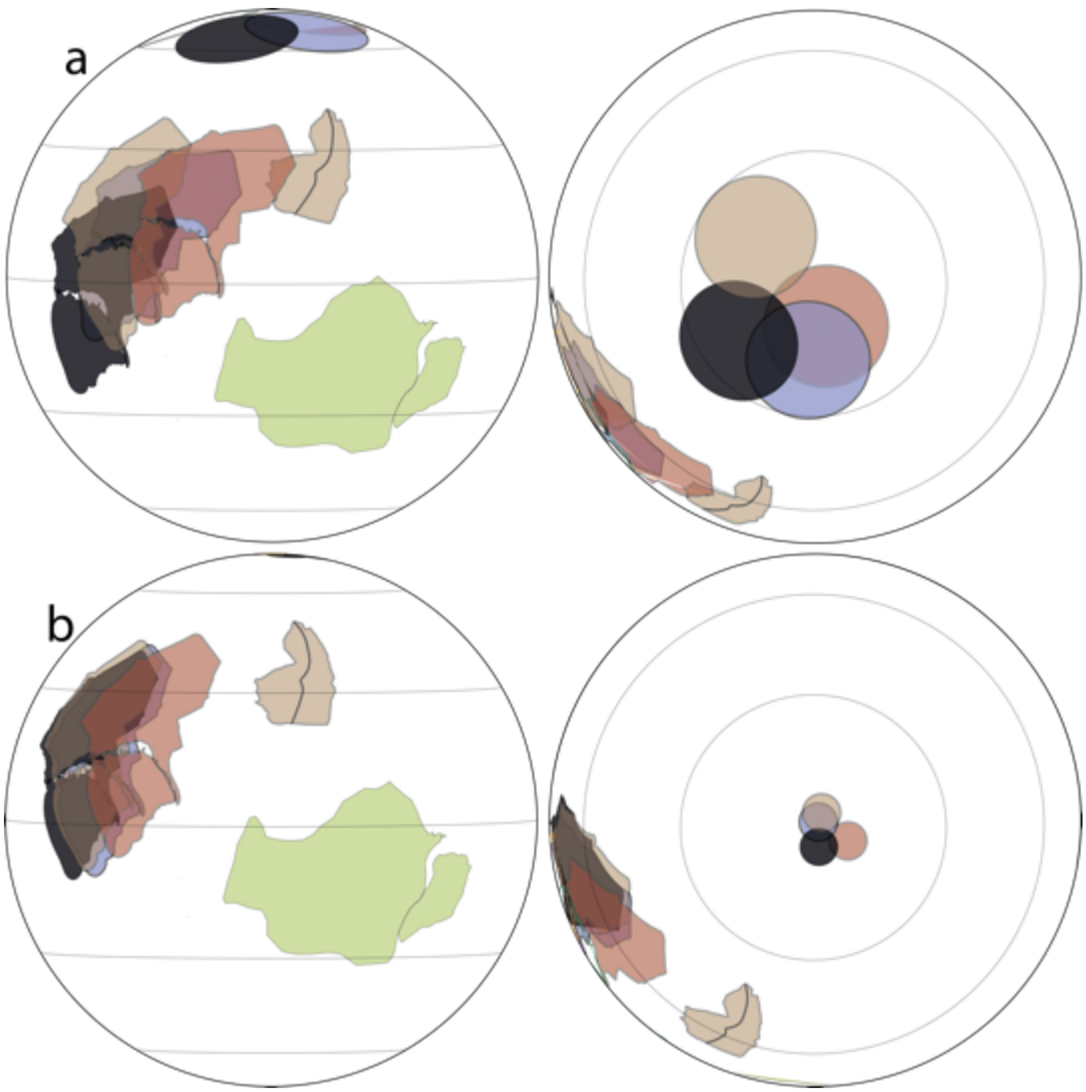


Figure 3. Paleomagnetic data for Australia and Laurentia at (a) 770 Ma (Johnny Creek Pole), and (b) 750 Ma ('grand-pole' from Mundine Dyke Swarms). Alternate Australia configurations are colour-coded; red, SWEAT; blue, AUSWUS; black, AUSMEX; orange, Missing-Link. Laurentia is in green.

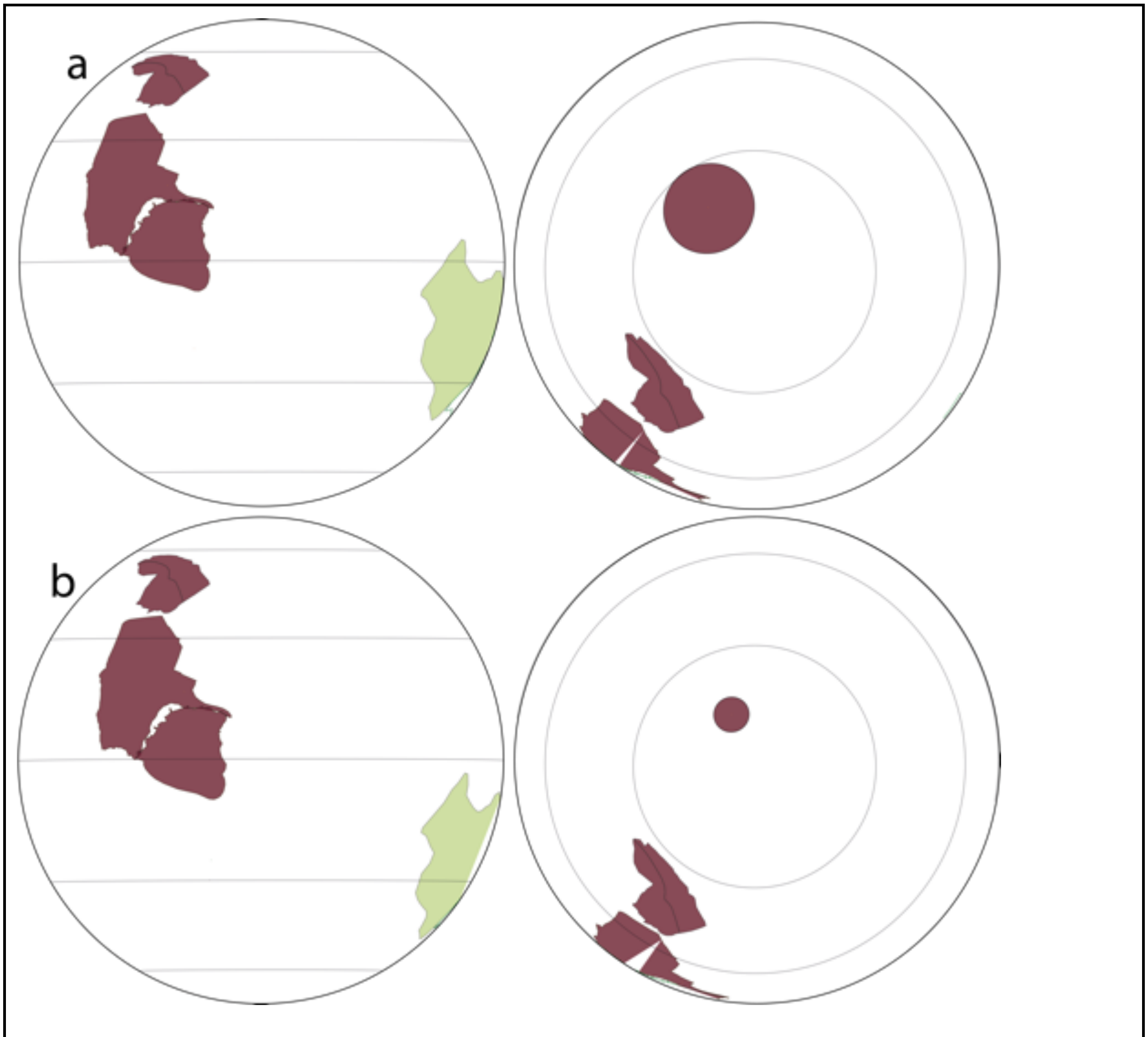


Figure 4. Paleomagnetic data for Australia and Laurentia at (a) 650 Ma, and (b) 640Ma. The alternate Rodinian configurations for Australia are now synonymous (red) and Laurentia is in green. Australian poles are Yaltipena Formation (a) and the 'grand-pole' of the Elatina Formation (b).

*Laurentia*

Only a few poles constrain Laurentia's position between 830-650 Ma. Two higher quality poles, the 782 Ma Wyoming Dykes (Harlan et al. 1997) and the 779 Ma Tsezotene sills and dykes (Park et al. 1989), both indicate Laurentia lying at low latitudes (Fig. 2b). A ca. 720 Ma pole from the Natkusiak volcanics in the Franklin magmatic event limits Laurentia to a low latitude (Denyszyn et al. 2009). Finally, two poorly-dated poles from the Galeros and Kwagunt Formations (800-740 Ma) (Fig. 2a) also suggest a low latitude Laurentia during this time (Weil et al. 2004), though the lack of a reliable age makes them difficult to use in reconstructions. No paleomagnetic data exists for Laurentia (or Baltica and Amazonia) at ~650 Ma with the closest reliable pole on the younger side from the Long Range Dykes (Murthy et al. 1992) placing Laurentia equatorially at 615 Ma. We follow Li et al. (2008; 2013) in assuming a simple interpolation between the two poles, leaving Laurentia at equatorial latitudes during this time.

## Assembly of Eastern Gondwana

### *Paleomagnetic Data*

Paleomagnetic data from India are incredibly sparse, hence the uncertainty attached to its position by nearly all global tectonic models of the Neoproterozoic (Table 1). Positions include having it attached to northwestern Australia (e.g. Li et al. 2008) attached to western Australia–East-Antarctica (similar to its Gondwana position) (e.g. Dalziel 1991; Hoffman 1991; Moores 1991), or not part of Rodinia at all (Powell and Pisarevskyb 2002; Torsvik et al. 2001a;b). Generally, it's relative position is always to the north-west/west of Australia, such that by ~650 Ma subduction of the ocean separating it from Australia leads towards Gondwana amalgamation. A ~770 Ma pole from the Malani Igneous Suite (Gregory et al. 2009, Torsik et a, 2001b) indicates a mid-latitude position for Neoproterozoic India at this time (Fig. 5a), and is supported by a ~750 Ma pole from the Seychelles that indicates a similar position (Torsvik et al. 2001a). Chronologically, the next Indian pole is that from the Bhander and Rewa Series at ~550 Ma, which constrains it to a sub-equatorial position, and is coeval with the final collision of India-Congo (Fig. 5b) (McElhinny et al. 1978). India's motion between these two poles is generally interpreted to be drifting south, which suggests that it wasn't part of a Rodinia through this time.

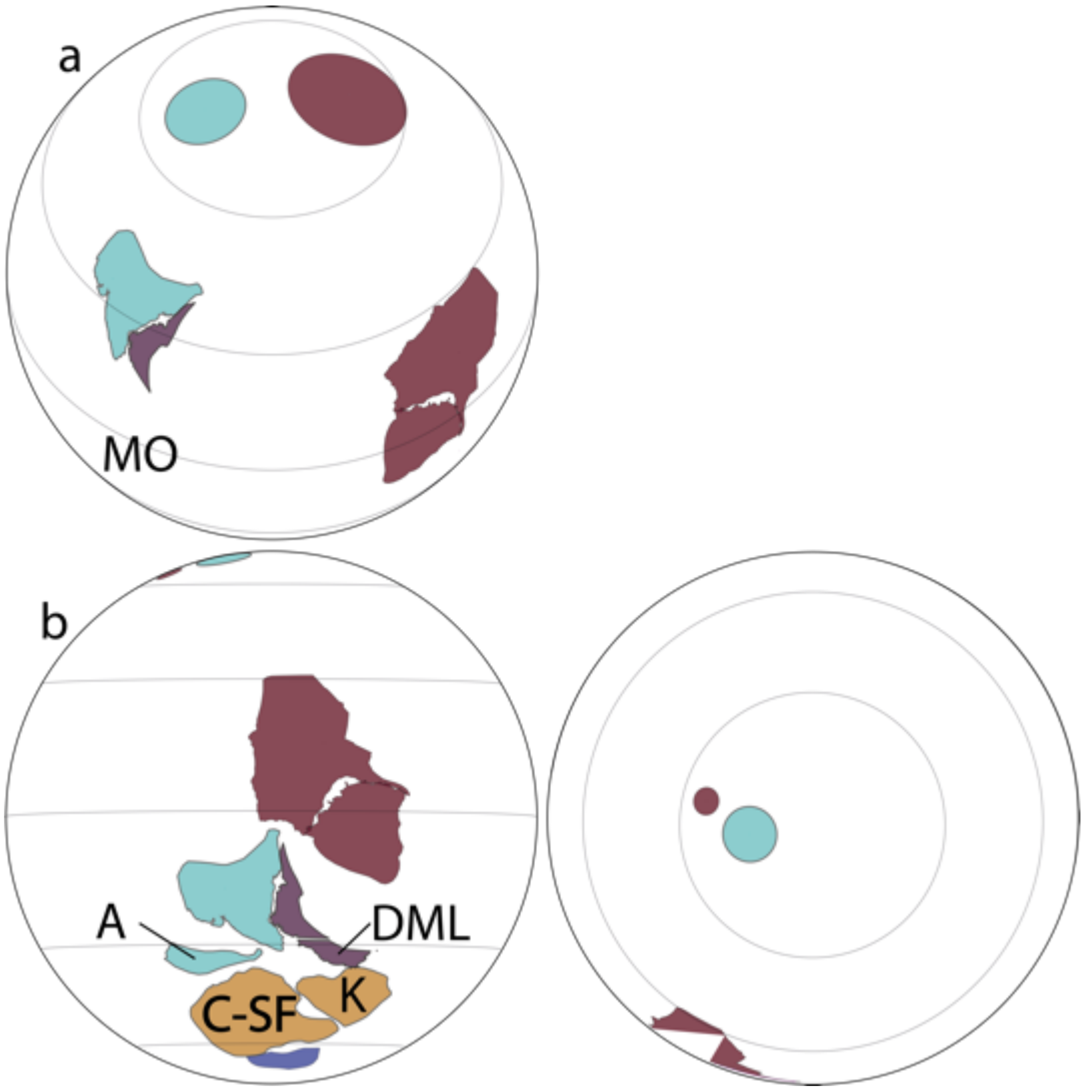


Figure 5. Paleomagnetic data for India at (a) 770 Ma (Malani Igneous Suite), and (b) 550 Ma (Bhander and Rewa Series). India in light blue; A, Azania; C-SF, Congo-Sao Francisco Craton; K, Kalahari craton; MO, Mozambique Ocean; Australia and Antarctica in purple,. Australian poles are the (a) Johnny Creek pole and (b) the 545 Ma Upper Arumbera Sandstone (Kirschvink 1978).

*Geological Data*

The assembly of eastern Gondwana was driven primarily by the subduction of the Mozambique Ocean forming two major orogenies, the East African Orogen (divided by Collins and Pisarevsky 2005 into the East African orogeny that was the collision of the Arabian Nubian Shield/Azania with Congo/Sahara, and the Malagasy orogeny, the collision of continental India with Congo based on distinct collisional ages) between India and Congo, and the Kuungan (or Pinjarra in Australia) Orogeny between India and Australia–East-Antarctica (Meert 2003). Detailed geological synopsis of this collision have been undertaken previously (e.g. Boger et al. 2015; Collins et al. 2014; Johnson et al. 2005), and we summarise below the pertinent geological observations available to constrain relative plate motion between India-Australia and India-Gondwana that links absolute positions constrained by paleomagnetic data.

Southward movement of India during the Cryogenian suggested by paleomagnetic data is broadly compatible with the geological record, where preserved ophiolites in the Manumedu Complex suggest not only supra-subduction zone roll-back between 800-700 Ma, but also that this formed the southern extent of Neoproterozoic Greater India (e.g. Collins et al. 2014; Yellappa et al. 2010). Southern India consists of a core of cratonised Archean-aged crust, the Dharwar Craton, and the Southern Granulite terrane, a series of Neoarchean and Proterozoic-aged terranes broadly younging southwards through; the Northern Madurai Block and Southern Madurai Block, which are separated from the Palaeoproterozoic Trivandrum Block and Nagercoil Blocks by the Achankovil Shear Zone (Collins et al. 2014). Collins et al. (2014) and Plavsa et al. (2014) show that these southern blocks of present-day India were likely to be part of Azania and the Malagasy arc (Archibald et al. 2015), outboard of the Congo craton, on the basis of detrital zircon signatures and similarities in metaigneous rocks, so that by the mid-Neoproterozoic a backarc basin (termed Neomozambique Ocean by Plavsa et al. 2014) separated Congo from Azania (and southern Indian blocks), and the larger Mozambique ocean separated Azania from India. Greater India entered a period of tectonic quiescence from ~700-625 Ma, though on the other side of the Mozambique ocean, Azania records convergence-related deformation and metamorphism from ~675-500 Ma (Ashwal et al. 1998; Buchwaldt et al. 2003; Collins 2006; Collins et al. 2014; Wit et al. 2001). The Malagasy orogeny is recorded in Azania (and the southern India blocks) from ~625-500 Ma (Collins et al. 2014), with an inferred collision between it and Greater India at ~550 Ma (e.g. Boger 2011; Collins and Pisarevsky 2005; Meert 2003).

The synthesis of paleomagnetic and geological data suggests a continuous southerly drift of India during the Cryogenian, with a subduction reversal, at ca. 700 Ma onto the southern margin of the Mozambique Ocean (i.e. north side of Azania), resulting in destruction of this ocean basin. Synchronously, subduction of the Neomozambique Ocean under Congo occurred, resulting in the closure of the basin between Congo-Azania. This created double-dipping subduction (Plavsa et al. 2014) and resulted in a perpendicular, 'head on' collision between India and Gondwana (Collins et al. 2014), the evidence for which, in part, is shown by the granulite facies metamorphism recorded in the Mozambique suture (e.g. Collins et al. 2007; Fitzsimons 2016).

The motion of India relative to Australia during the mid-late Neoproterozoic (i.e. ~750-550 Ma) was originally envisioned as relatively minor and intra-continental (Harris and Beeson 1993). This was largely due to an interpretation of the metamorphism and magmatism in the intervening region as being due to crustal thinning and strike-slip deformation rather than crustal thickening and plate convergence. This interpretation was revised during the 2000's with studies of the metamorphism, deformation and geochronology of SW Australia (Collins, 2003), the Prydz Bay area of Antarctica (Kelsey et al. 2007) and NE India (Yin et al. 2010) that concluded that the Neoproterozoic orogen between India and Australia in Gondwana represented periodic ocean subduction and crustal thickening – a true oceanic suture. To explain the (now necessary) relative motion of India to Australia during Gondwana assembly times, a sinistral strike-slip motion along the Darling Fault in Western Australia is used (e.g. Collins 2003; Fitzsimons 2003; Harris 1994; Powell and Pisarevsky 2002), suggesting that India was dragged south, past Australia, into a collision with Gondwana.

*Table 1 – Summary of paleomagnetic data discussed above. * indicate poles used to constrain position.*

| Location | Age (Ma) | Pole | | A95 | Reference |
| --- | --- | --- | --- | --- | --- |
| | | °N | °E | | |
| Australia | | | | | |
| Browne Formation | 830-800 Ma | 44.5 | 141.7 | 7.9 | Pisarevsky et al. 2007 |
| Hussar Formation | 800-760 Ma | 62 | 86 | 14.6 | Pisarevsky et al. 2007 |
| *Johnny's Creek | 780-760 | 15.8 | 83 | 13.5 | Swanson-Hysell et al. 2012 |
| *Mundine Dyke Swarms ('Grand Pole') | 750 | 45.3 | 135.4 | 5 | Embleton and Schmidt, 1985; Schmidt 2014; Wingate and Giddings, 2002 |
| *Yaltipena Formation | 650 | -44.2 | 352.7 | 11 | Sohl et al. 1999 |
| *Elatina Formation ("Grand Pole") | 635 | -43.7 | 359.3 | 4.2 | Schmidt 2014; Schmidt and Williams, 2010 |
| Laurentia | | | | | |
| Galeros Formation, | 800-780 | -2 | 163 | 6 | Weil et al. 2004 |
| *Wyoming Dykes | 785±8 | 13 | 131 | 4 | Harlan et al. 1997 |
| *Tsezotene Sills, | 779±2 | 2 | 138 | 5 | Park et al. 1989 |
| Kwagunt Fomration | 742±6 | 18 | 166 | 8.4 | Weil et al. 2004 |
| Franklin-Natkusiak Magmatic Event | 720 | 8 | 164 | 2.8 | Denyszyn et al. 2009 |
| India | | | | | |
| *Malani Igneous Suite | 770 | 68 | 73 | 9 | Gregory et al. 2009 |
| *Bhander and Rewa Series | 550 | 47 | 213 | 6 | McElhinny et al. 1978 |

**Formulation of Analysis**

For Australia—East-Antarctica and Laurentia rifting, we generated alternative scenarios as follows:

- Alternative starting configurations were based on published poles of rotation (Fig. 1)
- The Euler Pole describing Australia's position at 650 Ma is the same for all configurations, and defined by the beginning of the magnetostratigraphy of the South Australian sedimentary sequences (e.g. the Yaltipena, Elantina, Nuccaleena, Bunyeroo Formations)
- Variations of rifting time between Australia–East-Antarctica and Laurentia were generated in 25 Myr time steps from 800-725 Ma to examine how spreading rates change, with earlier rifting times adjusted by the insertion of a new Euler pole rotation at 750 Ma in order to satisfy the latitudinal position of the MDS pole

Though SWEAT, AUSWUS, AUSMEX configurations are paleomagnetically problematic with later rifting times (post ~770 Ma), we include their analyses to further highlight whether late rifting is likely or not. Consequently, this creates a 30° mismatch the MDS pole and the reconstructions for rifting at 750 and 725 Ma for these configurations. Additionally, we do not include the intraplate rotation of the North Australian Craton to the South Australian Craton of Li and Evans (2011) because both AUSMEX and AUSWUS were proposed before this rotation was introduced, and neither model has been tweaked to incorporate it.

Absolute constraints on paleolongitude have been explored for the Paleozoic (e.g. Torsvik et al. 2008), though there is yet to be a method for constraining longitude in the Precambrian. As we are looking at relative plate motions between times of absolute plate position (i.e. constrained by paleomagnetic data) the relative longitudinal constraints are bound by satisfaction of three criteria:

- Latitudinal positions as described by paleomagnetic data (i.e. we assume simple, continuous paths between the paleomagnetic end points)

- Geological data, specifically regarding major blocks colliding, sharing a connection, or separating from one another
- Kinematic criteria evidenced from present day ocean basins - reconstructions should be considered more likely where the spreading rates within oceans forming after continental rifting are reasonable

To deal with uncertainties in paleolongitude we calculate a range of possible widths for the Paleopacific Ocean (between Australia—East-Antarctica, Kalahari and Laurentia) at 650 Ma based on slow (20 mm/yr) and fast (120 mm/yr) spreading, while constraining the latitudinal position of each continent to remain consistent with paleomagnetic data.

For the Gondwana amalgamation we reconstructed India-Australia and India-Congo motions we used the following criteria:

- Start position of Australia–East Antarctica is from 650 Ma and follows the Australian Ediacaran APWP (Schmidt and Williams 2013, Schmidt et al. 2014)
- Congo at 550 Ma is situated mid-latitudes using a mean Gondwana pole (Torsvik et al. 2012)
- India is interpreted to have a southward motion based on the closure of the Neomozambique and Mozambique ocean under Congo and Azania respectively
- India collided head on with Congo
- A sinistral transform fault separated Australia–East Antarctica from India between 650-550 Ma this time

To assess the relative plate motions implied by Neoproterozoic plate models, we consider the post-Pangea evolution of the ocean basins. Figure 6a shows the fracture zones of the present day ocean basins (Matthews et al. 2011; Wessel et al. 2015) and indicates that rapid changes in the orientation and rate of seafloor spreading can occur *when* they coincide with changes in the global plate regime. For example, the change in the Indian Ocean is due to the onset of rifting between Australia and Antarctica at 40 Ma. Figure 6b shows the most recent compilation of seafloor spreading rates since Pangea breakup (Müller et al. 2016). The global mean spreading rates of currently preserved ocean crust is 37 mm/yr, with a standard deviation of 27 mm/yr (Fig. 6b). We take the optimal range of spreading rate to be 10-70 mm/yr, though we note that faster rates of spreading can be acceptable in certain circumstances, such as plates without cratonic lithospheric roots or plates comprised predominantly of oceanic crust (Zahirovic et al. 2015). We also note that as continental-continental collision occurs, the convergence rate of the moving plate slows, as suggested by India's collision with Eurasia (Cande and Patriat, 2015; van Hinsbergen et al. 2011). Finally, based on Bird (2003) and Argus et al. (2010; 2011) the angular rotation for cratonic landmasses in the present day is < 5 °/Myr though smaller plates without cratonic crust can exhibit faster (up to 20 °/Myr) rates of angular rotation.

Six sets of kinematic data were extracted; flowlines, position and angular rotation of Euler poles that describe the motion, relative spreading rates, and, mid-ocean ridge orientation, were extracted from the relative motions of Australia-Laurentia rifting and Kalahari-Laurentia rifting, and motion paths and convergence rates were extracted from the relative motion of India to Congo and Australia. Kinematic data were analysed at a regular time interval of 5 Myr, although, provided a full reconstruction is supplied, this can be altered to be of any temporal resolution. For the assembly of Gondwana, motion paths and convergence rates were extracted from the relative motion of India-Australia and India-Congo. The rotations of other continental plates, while not used for the analysis, were plotted to help with visual reference by placing Australia, India, Congo and Laurentia within a global context. The rotations of these continents were adapted from Li et al. (2008; 2013).

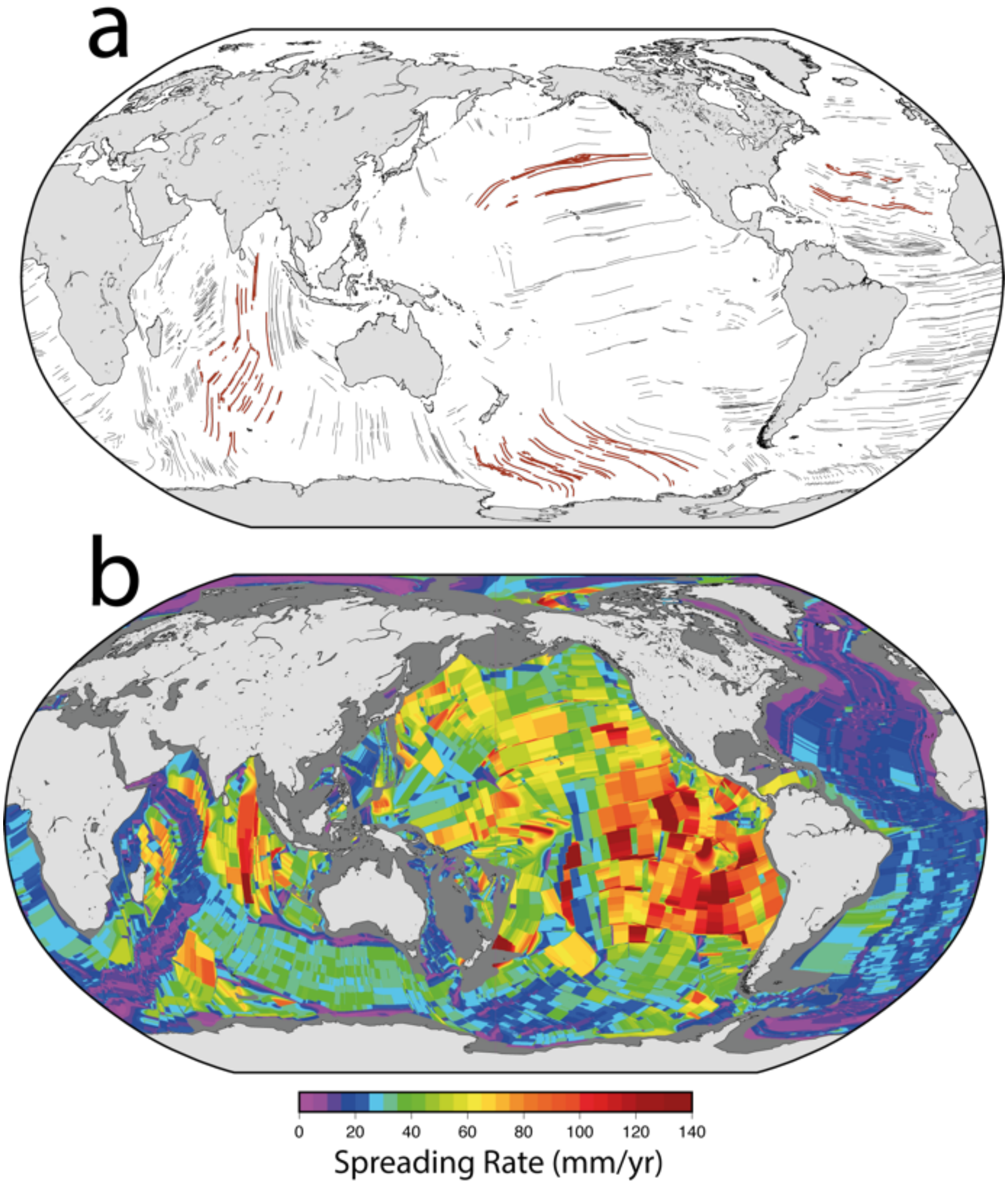


Figure 6: (a) Seafloor fabric map of the world after Matthews et al. (2011) showing the nature of present day fracture zones and spreading. In particular we highlight the rapid changes of spreading direction that occur regularly in the modern day ocean basins (visible along fracture zones highlighted red). (b) Seafloor spreading rate of the world's ocean basins based on Müller et al. (2016). The mean global spreading rate in

ocean floor preserved today is ~37 mm/yr, with a standard deviation of 27 mm/yr.

**Results**

Results are presented below in Figures 7, 8 and Table 1. SWEAT, AUSWUS and AUSMEX all have comparably simple rifting patterns and flowlines, while the Missing-Link model has a more convoluted spreading history. The present day range of spreading rates is plotted in black for each configuration for comparison. Average rates of motion refer to the average across all synthetic flowlines, while the maximum rate of motion refers to the single instance of maximum motion on any flowline for the specific configuration and rifting time.

**Rodinia breakup**

In SWEAT configurations the flowlines are simple, and the degrees of angular rotation are low for an 800 Ma rifting time, (~1 °/Myr) but higher for 750 Ma and 725 Ma rifting times (1.3 °/Myr and 1.7 °/Myr respectively), and divergence rates increase with later rifting times (average/maximum 76/94 mm/yr at 800 Ma and 149/170 mm/year at 725 Ma). Divergence direction changes from 210° at rifting time towards 290° at 650 Ma (Fig. 7a).

AUSWUS configurations show simple flowlines with the degrees of angular rotation increasing as the timing of rifting gets younger (from 1.5 °/Myr at 800 Ma to 1.8 °/Myr at 725 Ma) (Fig. 7b). The relative spreading of the plates away from each other is much lower with earlier rifting (average/maximum rates 56/73 mm/year for 800 Ma) and increases as rifting time decreases (average/maximum, 120/147 mm/year for 725 Ma) (Fig. 7b). For all rifting times the orientation of spreading changes from 220°, at rifting time, to 290° at 650 Ma (Fig. 7b).

The kinematics for AUSMEX configurations have similar results to AUSWUS configurations. Angular rotation is highest at 725 Ma where it reaches 1.6°/Myr. The divergence rates follow the same pattern as AUSWUS, increasing as rifting time decreases (average/maximum, 64/87 mm/yr with rifting at 800 Ma and 113/135 mm/yr at 725 Ma rifting, Fig. 7c) and rifting orientation increases stepwise from 220° at rifting time to 300° at 650 Ma (Fig. 7c).

The Missing Link configurations have the most complex flowlines of all configurations, depicting a series of reorganisations between rifting time and 650 Ma (Fig. 7d). All rifting times have periods of angular rotation at ~2 °/Myr), and the orientation of seafloor spreading changes more regularly than other configurations, with five different adjustments occurring between rifting time and 650 Ma for 800 and 775 Ma, four for 750 Ma, and three for 725 Ma. Average spreading rates mimic that of the other configurations, being slowest at earlier rifting times (90 mm/yr at 800 Ma) and higher at younger rifting times (150 mm/yr at 725 Ma), though all rifting times have similar maximum spreading rates of ~ 210 mm (Fig. 7d). In all cases the orientation of the spreading ridge varies between 60° and 270° /Myr (Fig. 7d).

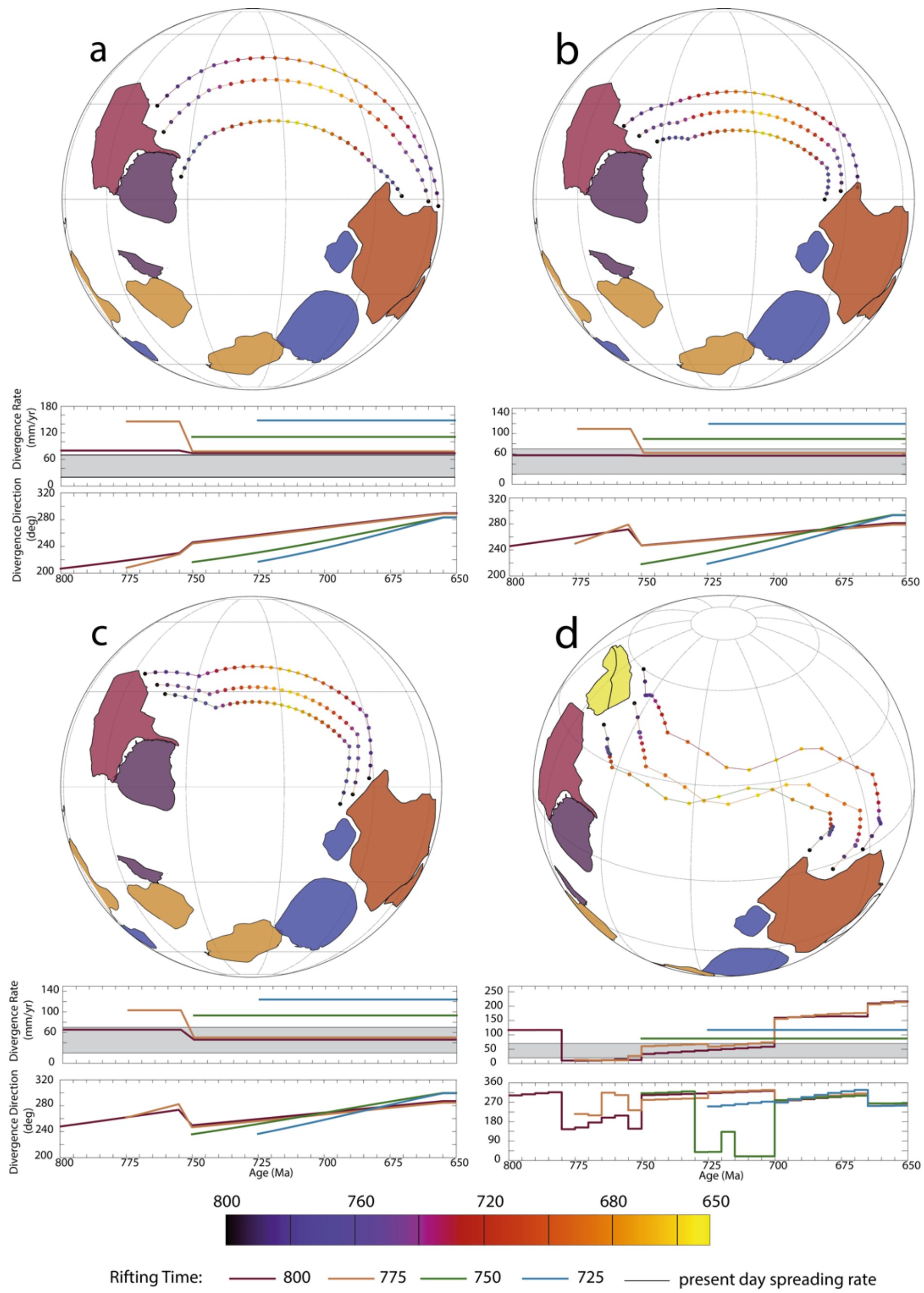


Figure 7: Kinematic results from Neoproterozoic Australia-Laurentia configurations, (a) SWEAT, (b) AUSWUS, (c) AUSMEX, (d) Missing-Link. Flowlines depicted are of rifting at 800 Ma, results for spreading rates and orientation of spreading are colour coded by rifting ages. South American cratons are dark blue; Africa, orange; India, light blue; Antarctica, purple; Australia, scarlet; Laurentia, red; and, South China, yellow.

## Longitudinal separation of Australia and Laurentia at 650 Ma

The two criteria governing Laurentia's (and West Africa and Amazonia that were attached to Laurentia) paleolongitudinal position are ensuring a reasonable rate of divergence from Australia, and ensuring that it drifts far enough to avoid early (i.e. before ~580 Ma) collision between the eastern and western Gondwanan constituents. Figure 8 shows a range of possible positions of Laurentia relative to Australia (with paleolatitudes consistent between all cases) given specific spreading rates at the different rifting times. To satisfy the paleolatitude constraints, at least ~3000 km of crust must be generated on both sides of the rift at a minimum (a total of 6000 km, Fig. 8, position of 'slow' Laurentia), this creates variations in the required minimum spreading rates depending on rifting time, with 800 Ma rifting able to satisfy this with a rate of 40 mm/yr, 775 Ma rifting at 48 mm/yr, 750 Ma rifting at 60 mm/yr and 725 Ma rifting at 80 mm/yr. Comparably, fast spreading rates, especially for the earlier rifting times (775 and 800 Ma) would place Laurentia ~15000-18000 km away respectively. Importantly, only these earlier rifting times can satisfy the constraints of modern day spreading rates, and for the later rifting times (750 and 725 Ma) the faster spreading rates (greater than 70 mm/yr) are required for moving Laurentia (with Amazonia and West Africa) far enough away to avoid collision with the Kalahari (Fig. 8c, d).

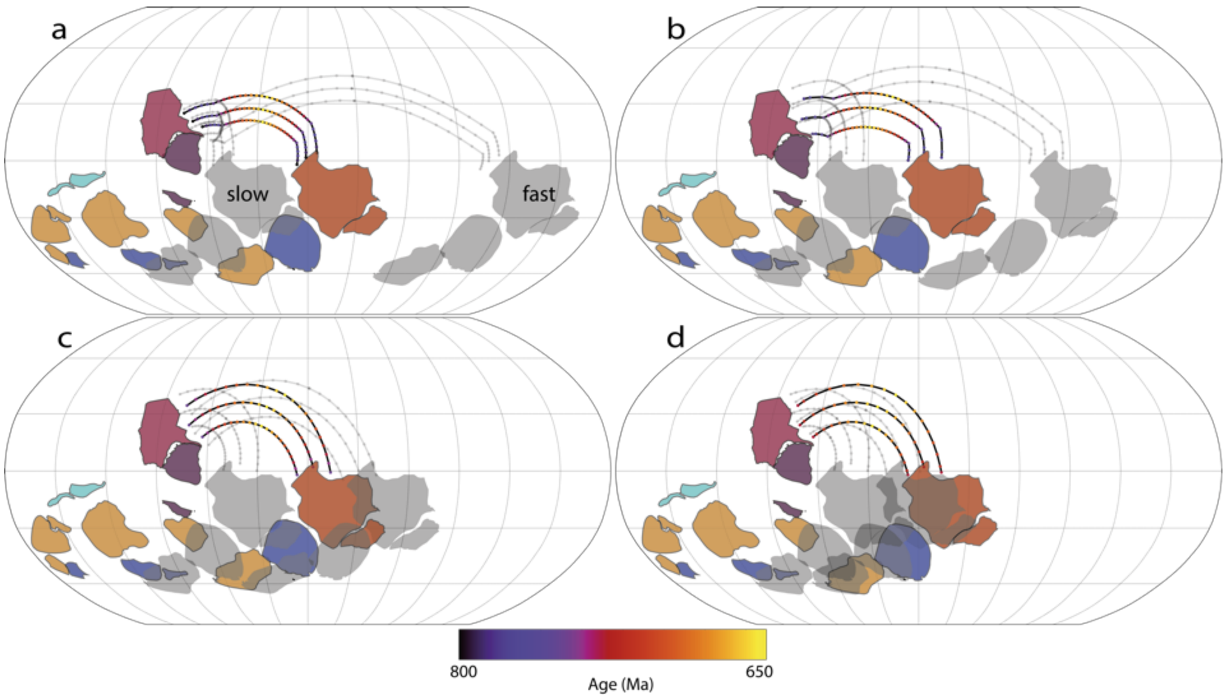


Figure 8: Laurentia and Gondwana constituents at 650 Ma with rifting at (a) 800 Ma, (b) 775 Ma, (c) 750 Ma, and (d) 725 Ma. Original configuration of Australia—East-Antarctica and Laurentia was the AUSWUS configuration, though all configurations have the same final position of Australia and Laurentia. Grey outlines are the position of Laurentia and the two major Gondwana cratons that remained attached to it, Amazonia and West Africa, but positioned if spreading rates were slow or fast (120 mm/yr). The shaded cratons are the results used in the analysis. The rate of slow spreading is determined by the minimum spreading distance between Laurentia and Australia (~6000 km) required to satisfy their paleolatiduninal position (see text).

**Eastern Gondwana Amalgamation**

The motion of India relative to Congo shows a front on collision of the southern tip of India with Congo, through to the north-west margin colliding with Azania and northern Madagascar. The rate of motion decreases from 60-75 mm/year between 700-650 Ma to 20-30 mm/year between 650-550 Ma (Fig. 9a).

Comparably, the movement of India relative to Australia (Fig. 9b) depicts a sinistral motion from 650-550 Ma between the two continents. From 550-520 Ma the motion becomes convergent as Australia–East-Antarctica collide with India forming the Kuungan orogeny. The rate of motion of India relative to Australia is 60 mm/year during the transform motion, before slowing to 20-30 mm/year at 550 Ma for convergence.

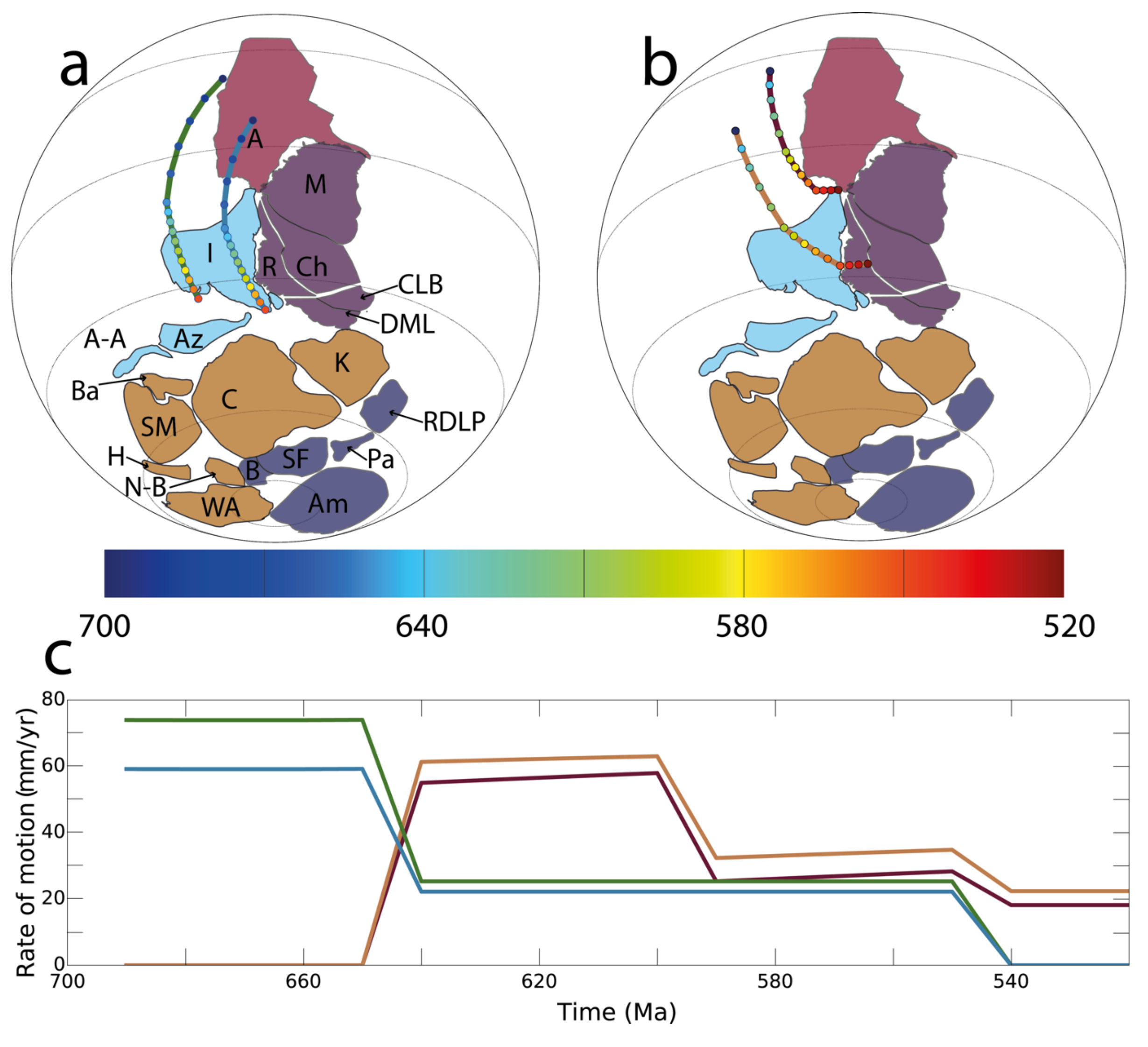


Figure 9: Kinematic results for India's motion relative to (a) Australia and (b) Congo. (c) Depicts the convergence rates of India. South American cratons are dark blue; Africa, orange; India, light blue;

Antarctica, purple; and, Australia scarlet. A, Australia; A-A, Afif-Abas; Am, Amazonia; Az, Azania; Ba, Bayuda; B, Borborema; C, Congo; Ch, Crohn Craton; CLB, Coats Land Block; DML, Dronning Maud Land; H, Hoggar; K, Kalahari; M, Mawson; N-B, Nigeria-Benin Block; Pa, Parana-Panema; R, Rayner Province; RDLP, Rio de la Plata; SF, Sao-Francisco; SM, Sahara Metacraton; WA, West Africa.

As India's position between 650-550 Ma is unconstrained, we determined possible positions of India relative to Congo (indicated by an arc, Fig. 10) assuming motion towards the Gondwana nucleus (as suggested by continuous southerly subduction) with alternative, uniform convergence rates. Slow convergence (~20 mm/yr) places India more southerly than Australia at 650 Ma, while convergence at 70 mm/yr places it slightly further north if the strike-slip boundary with Australia is preserved. A more westerly India that follows a similar convergence rate would remove this component. Fast convergence (140 mm/yr) places India ~14000 km away from the Gondwana nucleus and implies a vast area of ocean being subducted.

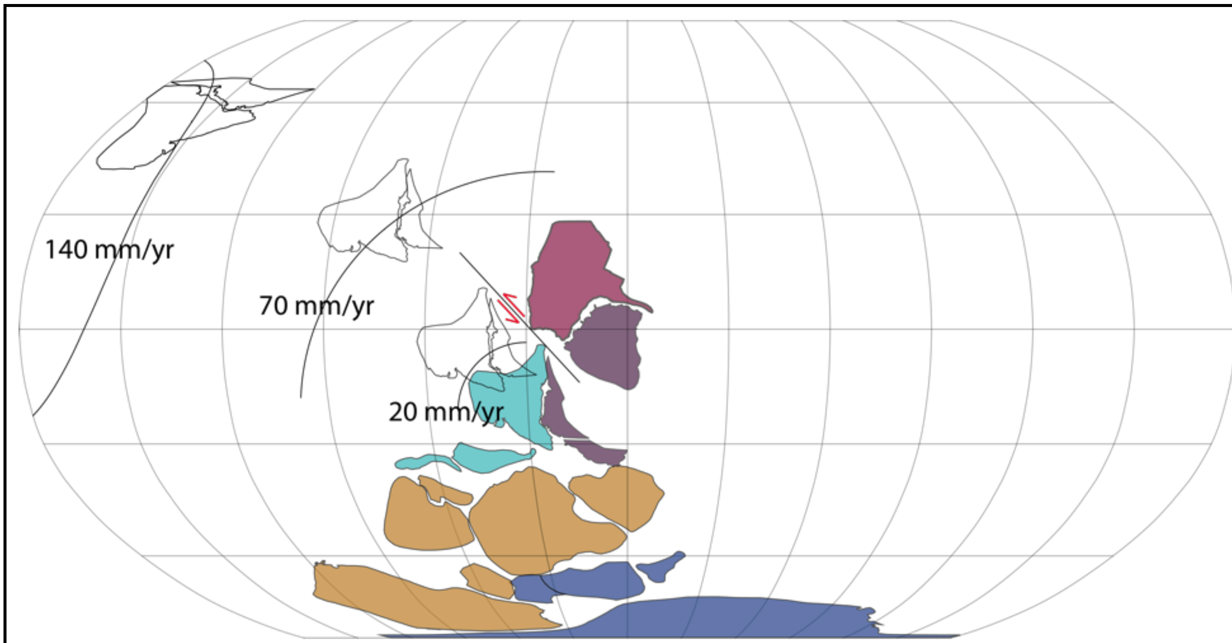


Figure 10: Possible positions of India relative to Gondwana constituents. Coloured polygons depict their

positions at 550 Ma (time of India-Congo collision). Three potential positions of India are shown based on convergence rates, they are depicted by the black arcs (i.e. India could sit anywhere along the arc and its convergence rate would be 20/70/140 mm/yr). The black shaded area is where India would be considered moving relative to Australia along a transform boundary.

## Discussion

### Spreading and convergence rates

As the final position of Australia at 650 Ma is the same for all configurations (defined latitudinally by paleomagnetic data), Australia *must* move a similar distance for each rifting time. Consequently, its angular rotation varies only by how the orientation of each configuration (i.e. ~040° for AUSMEX, 050° for AUSWUS, 080° for SWEAT and 010° for Missing Link) differs, and by how far north along the Laurentian coast Australia is attached. We find that maximum spreading rates for all configurations occur at 725 Ma, with spreading rate increasing as rifting time decreases due to Australia having to move the same distance, in a shorter time (i.e. 3500 km of spreading in 150 myr, or 75 myr). Similarly, the angular rotation rate is higher because of the shorter time between rifting and 650 Ma. Coupled with changes in rifting times, we can see that the reconstruction with the highest angular rotation is SWEAT at 725 Ma, while the reconstruction with the lowest angular rotation is AUSMEX at 800 Ma. Given modern day limits on spreading rates and angular rotation (e.g. Bird 2003; Zahirovic et al. 2015), either an AUSWUS or AUSMEX configuration with rifting at 800 Ma is, kinematically, the most optimal configuration, though SWEAT at 800 Ma could be permissible, though the spreading rate would be just over the upper limit of modern day acceptability. Later rifting times for all configurations must account for the higher spreading rate, and rifting at either 750 Ma or 725 Ma must also account for high rates of angular rotation. Later rifting times also create a limit on the size of the Paleo-pacific ocean, even permitting faster spreading rates (120-140 mm/yr), the maximum basin width is limited to ~3500 km (between Mawson and Laurentia, equivalent to 10000 km of seafloor spreading). A global reconstruction would necessitate having a wide enough ocean basin to allow for both Amazonia and West Africa to slip past southern Gondwana (along the Transbrasiliano lineament?). Earlier rifting times between Australia and Laurentia can accommodate larger basin sizes while maintaining reasonable rifting rates.

Convergence rates for India's motion into Gondwana are also within present day limits and bear similarity with the present day convergence rates of India and Eurasia. The slow down at 650 Ma of India relative to Congo is likely related to the tectonic configuration between it and Congo during this time, where, a series of terranes (e.g. Azania) were being accreted to the Congo margin prior to India's arrival. Closure of a backarc basin between Azania and Congo between 650-580 Ma (Collins and Pisarevsky 2005), or double dipping subduction of the Mozambique ocean under Azania, along with subduction under Congo closing the back-arc basin (Plavsa et al. 2014), are similar to tectonic models of India-Eurasia convergence today (Jagoutz et al. 2015; Van der Voo et al. 1999). Importantly, inferences of India kinematics between the times where its position is known from paleomagnetic data (the Malani Igneous Suite and Bhander and Rewa Series at 770 Ma and ~550 Ma respectively) are reasonable. Assuming a direct interpolation between both poles requires a convergence rate of ~50-70 mm/year. We have followed the idea that India slipped past Australia along a transform boundary, though a range of positions of India at 650 Ma are shown in Figure 9 that satisfy the geological data of its collision with Congo but not necessarily this transform boundary with Australia. If India converges too slowly it is further south than Australia, while high convergence rates create an incredibly large ocean basin that is consumed.

**Relative plate motion stability**

The orientation of spreading systems for AUSMEX, AUSWUS and SWEAT configurations is perhaps unrealistic, especially for the older times. Since Pangea breakup, every major ocean basin (Atlantic, Indian, Pacific) has experienced reorganisation events of varying magnitudes (Müller et al. 2016). Changes in plate kinematics are obviously not captured in the simpler reconstruction cases, which exhibit a first order pattern similar to an Atlantic-type basin opening. We would expect that post Australia-Laurentia rifting, other constituents of western Rodinia also begin to separate (e.g. Congo-São Francisco at ~750 Ma, Kalahari at

~700 Ma; Jacobs et al. 2008; Li et al. 2008) leading to new MOR complexes and the potential for reorganisation events that would impact the Australia-Laurentia MOR. Ideally, complete plate models (i.e. continents and plate boundaries) for the Neoproterozoic can be used to help constrain possible motions and configurations.

The more complex flowlines and series of Euler Poles for the Missing-Link Model, compared with the relatively smooth flowlines of the other three models, are a function for the motions of Australia and South China relative to Laurentia implemented in this model. They explain the motion of South China northwards from the Australia-Laurentia nexus, and then westwards over Australia, and then southwards down the west coast of Australia for Gondwana amalgamation, while Australia is also rifting westwards from Laurentia (Li et al. 2008; 2013). This more complex motion necessitates several major changes in angular rotation, mid-ocean ridge orientations and spreading rates. The movement of Australia relative to Laurentia is similar to that of SWEAT, as Australia is located in a similar position relative to the Laurentian coastline, though it is more upright (N-S orientated), which has the effect of reducing both its spreading rate and angular rotation (when compared to SWEAT), and would create an even more kinematically conservative rifting pattern than AUSWUS or AUSMEX.

A potential solution to account for the motion of South China in the Missing Link Model could follow the suggestion of Cawood et al. (2013), where the Yangtze Block of South China represents an early Neoproterozoic accretionary complex growing on the north side of the Cathaysia craton. This would suggest that South China was yet to be fully cratonised and potentially lack a deep cratonic root, allowing for more rapid and diverse motions than what we would expect using cratonic crust in the present day. Additionally, following the reasoning behind the Missing-Link model, the presence of a plume head (Li et al. 1999) could help facilitate more rapid and diverse motions as well through decoupling from the underlying mantle (e.g. Ratcliff et al. 1998). A similar exposition of plate motions could be found in the tectonic evolution of the Southeast Asia over the last ~150 Myr, where periodic rifting of small terranes and continental slithers during the Mesozoic from the northern Gondwanian margin to the southern Eurasian margin, has, in part, resulted in a complex melangé of terranes, seafloor spreading complexes, extinct ridges, subduction zones and changes in plate motion (e.g. Metcalfe 1996; 2011; Zahirovic et al. 2014).

**Integration of kinematic observations**

By integrating both sets of kinematic observations, along with the motion of two (poorly constrained) cratons, Congo-São Francisco (C-SF) and Kalahari, we can build a quantitative relative plate model bounded by absolute plate positions and constrained by geology. Following Li et al. (2008), but acknowledging the wide array of ideas about the Neoproterozoic journeys of C-SF and Kalahari (e.g. Evans 2009; Frimmel et al. 2011; Johnson et al. 2005; McGee et al. 2012; Wingate et al. 2010), we take the AUSWUS fit with rifting at 800 Ma (Fig. 10a), C-SF-Laurentia rifting at 750 Ma (McGee et. al. 2012) (Fig. 10b) and Kalahari-Laurentia rifting at 700 Ma (Fig. 10c,d). Based on the maximum expected spreading rate of Australia rifting from Laurentia at 800 Ma, we see a configuration with Australia and Kalahari with ~15° of latitude and longitude separation, but otherwise in a position favourable with what we expect for Gondwana amalgamation. Following the present day development of ocean basins (e.g. East Gondwana breakup), we interpret that the new spreading system between Laurentia-Kalahari at 700 Ma is most likely to be an extension of the existing one between Australia-Laurentia, either rifting in the same direction as Australia, or causing a reorganisation and altering the divergence direction such that while there is some minor relative motion between Australia-Kalahari (to accommodate the 650 Ma YF pole), they are otherwise moving on the same longitude. Given the lack of paleomagnetic data from the Kalahari Craton, it is impossible to constrain its position until ~550 Ma when it collides with Congo forming the Damara–Lufilian–Zambezi Orogen (Johnson et al. 2005), at which point it 'paleomagnetically reappears', using the Gondwana APWP, at mid-latitudes (Torsvik et al. 2012). This is more southerly than it's (inferred) rifting position from Laurentia, suggesting that it's relative motion can't be aligned with orientation of Australia-Laurentia spreading system (Fig. 10c), rather there is a reorganisation, changing the orientation of Australia-Laurentia rifting (Fig. 10d). We express this relative motion by a stage rotation of Australia relative to Congo around the Euler Pole *-5°S -98°W 57°*.

By 650 Ma, India is starting its (plotted) southward descent into Gondwana around the Euler Pole *11°N 59°E -72°* (Fig. 10e,f). The position of Australia can be constrained well now, due to paleomagnetic data, and we see that the conjunction of the absolute latitudinal position of Australia, along with geological data, fit well with the relative motions of the Indian plate to both Australia and Congo, with India moving past Australia along a transform fault (Fig. 10f). The rotation of Australia into Gondwana is more uncertain, primarily because of the lack of data from Antarctica, which forms the nucleus of eastern Gondwana amalgamation (e.g. An et al. 2015; Boger 2011). Both the Coats Land Block (colliding with Dronning Maud Land in Kalahari at 560 Ma after Boger (2011), and the hypothesized Crohn Craton (Boger 2011) act as an extension of the Mawson Craton (perhaps as series of accreted terranes?) and are the precursor to Australia–East-Antarctica's collision, which is likely to have occurred along a suture represented by the East-Antarctica Mountain Ranges (EAMOR) (An et al. 2015). The high quality poles from the Lower Arumbera and Upper Pertatataka Formations at ~540 Ma (Kirschvink, 1978) constrain Australia to a position where it's movement into Gondwana is head on into India along the Kuungan orogeny (Meert 2003; Meert and Van der Voo 1997), with a strike-slip motion along the Coats Land Block (Fig. 10g,h). This is perhaps somewhat supported by the granulite facies along the Kuungan orogeny suggesting a major collisional event (e.g. Kelsey et al. 2007; Grantham et al, 2013), though we note that future data from Antarctica may cause this to be revised. The motion of Australia–East-Antarctica relative to Congo is defined by the Euler Pole *-38°S -75°W 40°*.

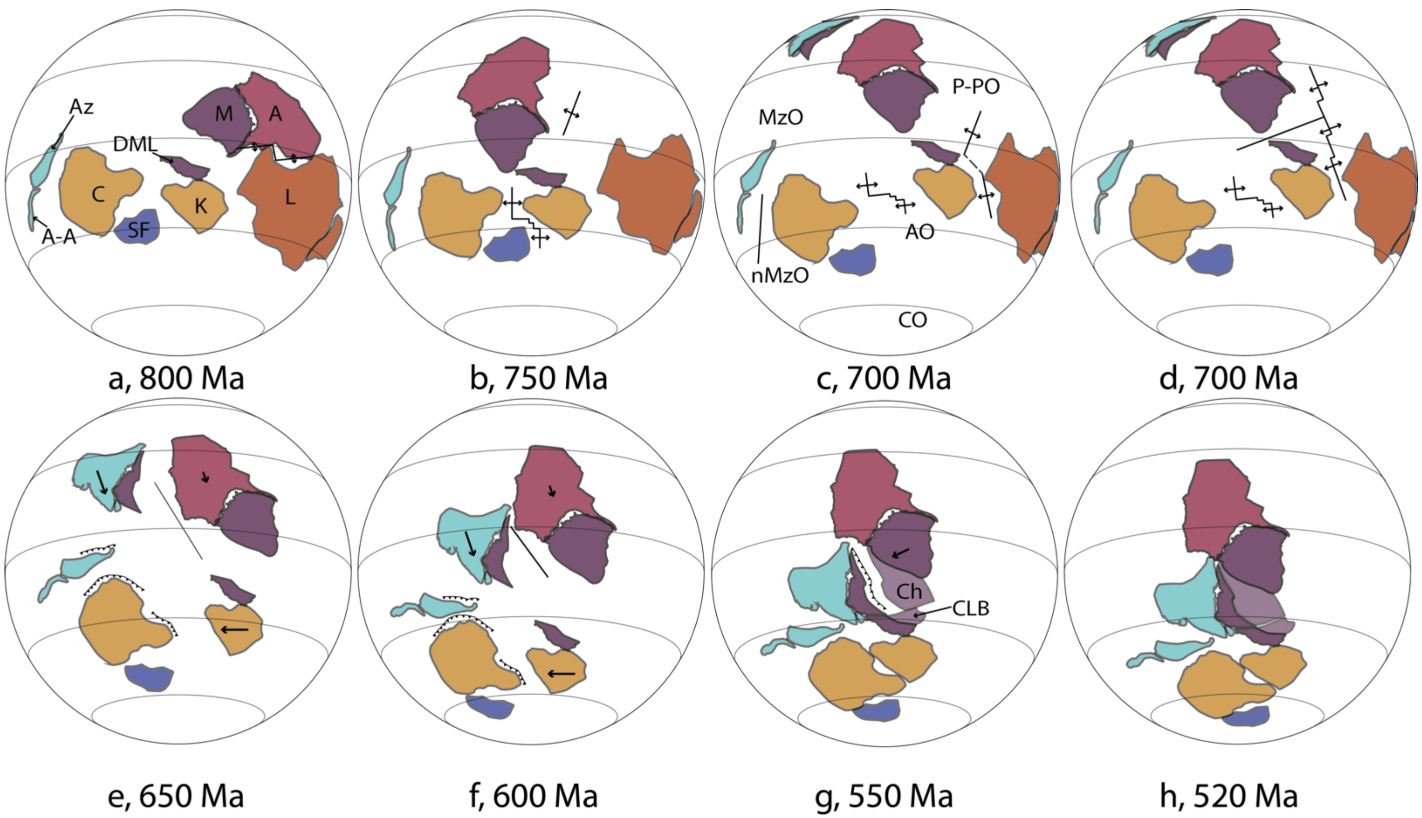


Figure 11: Reconstruction incorporating breakup of western Rodinia and amalgamation of Eastern Gondwana. Two possible options of spreading ridges at 700 Ma (when Kalahari rifts from Laurentia) either having divergence between Australia-Kalahari (c), or both moving along the same longitude (d). AO, Adamastor Ocean; CO, Clymene Ocean; MzO, Mozambique Ocean; nMzO, Neomozambique Ocean; P-PO, Paleo-Pacific Ocean. See Figure 9 for other label details.

**Non-unique solutions**

The (rudimentary) model described above is a non-unique solution of the Rodinia-Gondwana transition. Variations in Australia-Laurentia configurations can change interpretations about spreading systems in late-stage Rodinia breakup, particularly with respect to the position of South China. Changes in rifting time of this configuration will also strongly alter both the kinematics (if one desires Australia to be in the position described above) and development of spreading systems during late-stage Rodinia rifting when considering the other cratonic components (e.g. Kalahari, C-SF, Rio de la Plata). We also sidestep the problem of India's position (and inclusion) in Rodinia, noting that its 700 Ma position would be similar for models with India separate from Rodinia or as a product of early rifting, and that its final position in Gondwana is well established (e.g. Collins and Pisarevsky 2005; Meert et al. 2003). Rather, the emphasis here is on how kinematic tools and data can help users make educated, quantitative decisions about relative plate motions in deep time, especially when there is limited paleomagnetic data (e.g. either a begin or end position/time is well constrained, but the other is not). We also stress that decisions about the distances that plates move in a given model carry implications for mantle processes and geodynamics. For example, the maximum convergence rate of India-Congo from 700-550 Ma necessitates the closure of a ~14000 km wide ocean basin. The implication of a large slab burial ground (as compared to a slower convergence model which results in less subducted oceanic crust) is a strong drawdown effect of any overlaying portions of continental crust, potentially preserving a dynamic topography signature within sedimentary basins (e.g. Flowers et al. 2012).

**Conclusions**

Kinematic data suggest that a tectonic model where Rodinia splits up before 750 Ma is more consistent with Phanerozoic plate tectonics than competing models, in that an early split-up minimises both the speed and angular rotation of the Australian Plate, with rifting at ca. 800 Ma producing the only models that are within Phanerozoic spreading rate limits. SWEAT, AUSWUS and AUSMEX all have similar maximum rates of angular rotation (~1.9°/Myr at 725 Ma), though the SWEAT configuration has the highest average spreading rate for all rifting times (149 mm/yr at 725 Ma rifting). AUSWUS has the lowest average spreading rates (56 mm/yr at 800 Ma rifting), though AUSMEX is only slightly faster at 64 mm/yr. Kinematically, AUSWUS and AUSMEX at 800 Ma are the two preferred rifting configurations/times, though SWEAT at 800 Ma could be justifiable (76 mm/yr maximum spreading rate). As the onset of rifting becomes younger, the viability of configurations decreases due to the corresponding increase in subsequent spreading rates. For a rifting time of 725 Ma for any configuration, viable reasons for spreading rates of greater than 130 mm/yr would have to be provided. Similarly, for the Missing-Link Model, rifting at 800 Ma presents the most optimal spreading rates, though the flowlines and spikes in spreading rate and angular rotation for South China require a more complex explanation than that of the other configurations. We also demonstrate how kinematic tools can help constrain relative plate motions by creating a simple model that explicitly links together paleomagnetic, geological and kinematic data to explain the relative motions of India to Congo and Australia during its collision with Gondwana.

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**Supplementary Material**

Supplementary material is downloadable following this link:

https://cloudstor.aarnet.edu.au/plus/index.php/s/2kKJUB5GOpNhICK

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