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Gondwana's interlinked peripheral orogens

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ABSTRACT

After its Ediacaran-Early Cambrian assembly, Gondwana was flanked by a system of peripheral orogens, Terra Australis, Avalonian-Cadomian and newly defined North Indo-Australie, which display broad temporal correlations of their lithotectonic records. Prior to assembly, their initial histories were primarily controlled by the early Neoproterozoic breakup of Rodinia with second order variances reflecting the differing relationships of their basement continental blocks to that supercontinent. The Terra Australis Orogen developed on basement blocks that previously occupied interior locations within Rodinia and initial successions record development of a passive continental margin. The North Indo-Australie orogen records a similar history of passive margin development, but at least its Indian portion was likely separate from Rodinia. The basement blocks of the Avalonian-Cadomian Orogen previously occupied exterior locations around Rodinia with initial successions indicating the development of a convergent plate margin. As Gondwana assembled, Avalonian-Cadomian convergence terminated at about the same time as convergence commenced in the Terra Australis and North Indo-Australie orogens. The absence of a complete long-lived contemporaneous subduction girdle around Gondwana likely prevented its breakup, in contrast to Rodinia and Pangea, in which the presence of subduction girdles corresponds with lithospheric extension across the supercontinents as a precursor to their ultimate breakup.

1. Introduction

The opening and closing of oceans (Wilson cycle) result in the formation of orogenic belts along the margins of pre-existing continental blocks, and these belts provide a record of block assembly and dispersal. The linked nature of the global plate boundary network implies that the record of divergence and convergence preserved within an orogen continually adjusts to changes in the network. Thus, the history of an orogen is a complex multi-signal record that includes not only a first-order signal related to direct interactions along the boundary between an inboard continental block and an outboard oceanic plate, but also a second-order "far-field" signal(s) related to the evolving position of the global plates about shifting Euler poles. This paper explores how an orogenic belt not only records the first-order signal in its immediate environs but also contains a second-order record related to kinematic interactions with other temporally equivalent orogenic systems. By way of example, we focus on the spatial and temporal evolution of the peripheral orogens that developed along the margins of Gondwana during and after its assembly, and speculate on implications for the coherency of the supercontinent.

Orogens are distinctive belts of tectonothermal activity with quasi-linear distributions of sedimentary facies, deformation, metamorphism, and magmatism that are active over tens to hundreds of millions of years. Orogens originate at sites of lithospheric extension (rift/passive margin and intracontinental) and compression (subduction zones). They are stabilized and preserved in the geological archive by orogenic events that are typically the culmination of repeated episodes of magmatism, compressional deformation and associated metamorphism, and uplift and erosion. Orogenesis typically occurs along convergent plate boundaries driven by subduction of oceanic lithosphere into the mantle, at the termination of subduction during final ocean closure, and in intracontinental settings distant from active plate boundaries. These varying settings for orogenesis lead to a broad tripartite classification of orogens into accretionary, collisional and intra-continental (Cawood et al., 2009). Younger orogens are sites for new crustal generation and growth (in sense of Cawood et al., 2013a) and also inherit features from spatially overlapping older belts, in part by reworking

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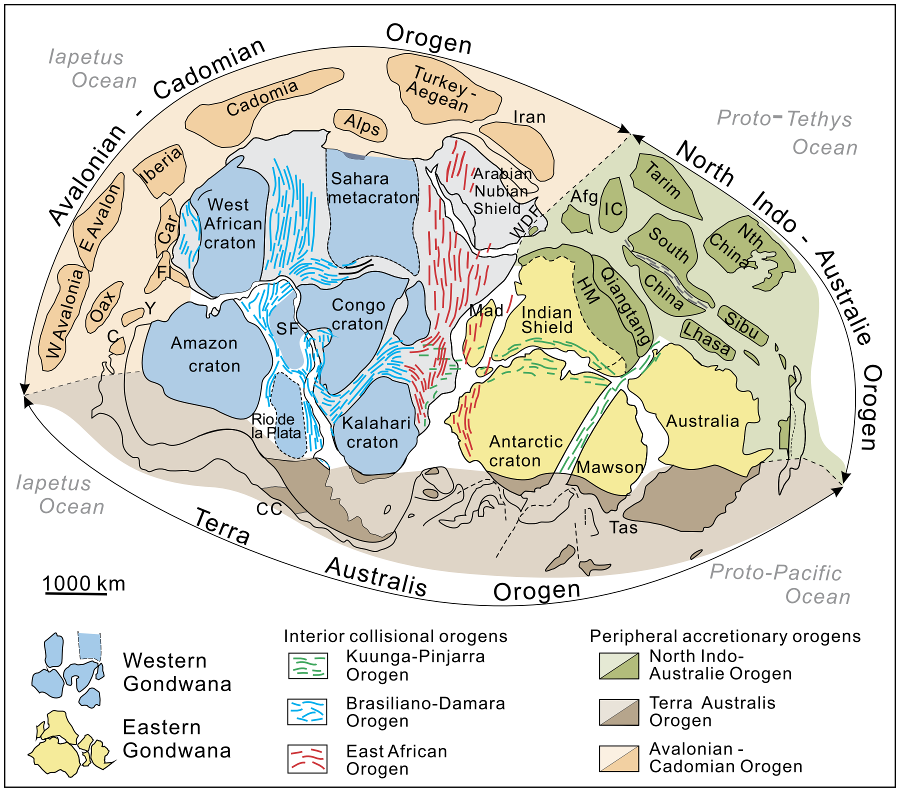

Fig. 1. Map of Gondwana at ca. 500 Ma showing cratonic blocks and interior and peripheral orogens. The absolute and relative positions of the majority of blocks within the peripheral orogens are poorly constrained and positions depicted on this diagram are indicative only. Abbreviations: Afg – Afghanistan; C – Cortis; Car – Carolina; CC – Cuyania and Chilenia; Fl – Florida; IC – Indochina; HM – Himalayas; Mad – Madagascar; Oax – Oaxaquia; SF – San Francisco; Tas – Tasmania; WDF – Western Deformational Front; Y – Yucatan.

of older rock assemblages, which commonly form a basement for the carapace of unconformably overlying syn-orogenic rock units. Accretionary orogens lie along the periphery of older continental blocks whereas collisional orogens form in the interior of a continent between colliding blocks (Murphy and Nance, 1991). These contrasting orogenic types are highlighted by those developed within and around Gondwana.

To consolidate the significant body of work investigating the tectonothermal and kinematic evolution of the discrete fragments of Gondwana's peripheral orogens (i.e., the Terra Australis, Cadomian and Indo-Australie orogens), we focus on the first-order elements of the orogens and their broader inter-orogen relationships, especially on the interval between 800 Ma and 400 Ma. We argue that the timing of major events within each orogen not only displays temporal and kinematic linkages to events in adjoining orogens, but also is linked to far-field events associated with Rodinia breakup and Gondwana assembly. Furthermore, we speculate that the failure of core continental blocks of Gondwana to breakup, contrasting with the breakup of the preceding Rodinia and succeeding Pangea, relates to the absence of a long-lived subduction girdle around its periphery.

2. Gondwana's interior and peripheral orogens

Gondwana consists of a series of Archean to Proterozoic continental blocks that collided in the late Neoproterozoic through closure of intervening oceanic tracts forming the Kuunga-Pinjarra, Brasiliano-Damara, and East African interior orogens (Fig. 1). Convergence between Gondwana's constituent blocks commenced in the mid-Neoproterozoic (ca. 760 Ma; e.g., Stern, 1994), and is coeval with the separation and sea-floor spreading between the continental blocks of Rodinia and closing of the encompassing Mirovoi Ocean. The main phases of Gondwana assembly through collisional orogenesis are between ca. 620 and 520 Ma (Collins and Pisarevsky, 2005; Cawood and Buchan, 2007).

Temporally overlapping with the convergence and collisional assembly of Gondwana's continental blocks, a series of peripheral orogens, termed the Terra Australis, Avalonian-Cadomian and North Indo-Australie orogens, formed around the margins of Gondwana (Cawood and Buchan, 2007) and lay inboard of the Proto-Pacific, Iapetus and Proto-Tethys oceans, respectively (Figs. 1, 2). Each peripheral orogen preserves a unique protracted history with the oldest elements in each orogen predating Gondwana assembly. These peripheral orogens are now preserved as dispersed continental blocks that are incorporated in, and variably reworked by, younger orogenic activity (e.g., Appalachian-Caledonian, Central Asian, Tethyan, circum-Pacific orogens).

3. Peripheral orogens

The extent of Gondwana's peripheral orogens and their constituent continental blocks are outlined in Fig. 1. The inboard (foreland) boundary of each orogen is located along its deformational front, the position of which is not always well constrained due to poor exposure and/or reworking. For example, the Florida Block of the Avalonian-Cadomian orogen is recovered only in subsurface wells (in southern Laurentia) and lack of data makes it uncertain if it underwent Cadomian-related orogenesis or lay in the foreland to the orogen (Nance et al., 2008). In addition, the various blocks of the North Indo-Australie Orogen rifted from Gondwana, starting in the mid-Paleozoic but were variably reworked when they accreted to Asia (Metcalfe, 2021), obscuring delineation of the extent and character of their earlier histories. The lateral boundaries of each peripheral orogen correspond with regions of poor exposure

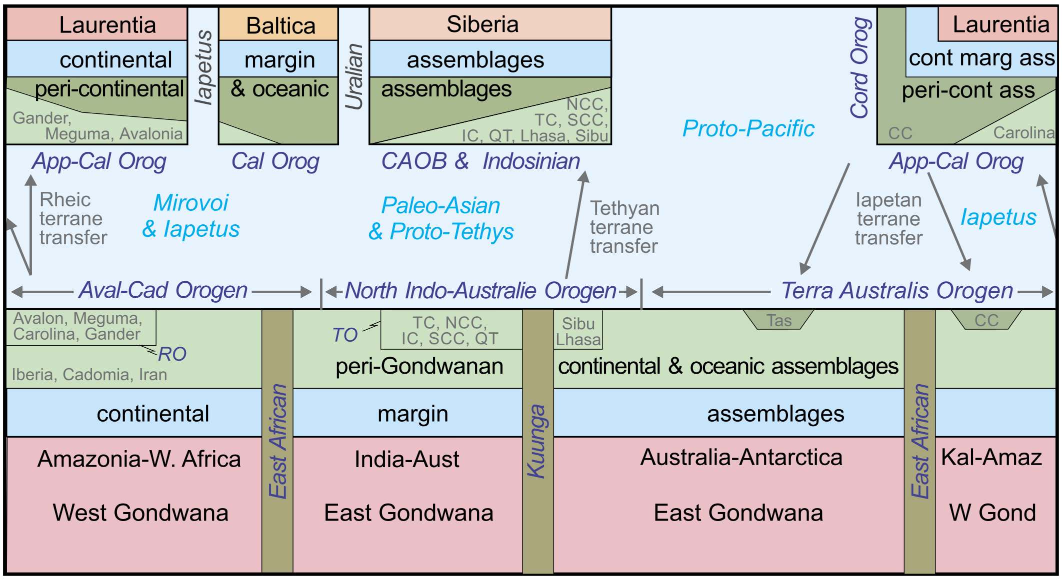

Fig. 2. Schematic representation of Gondwana's peripheral orogens with respect to interior cratonic bocks and orogens, outboard oceans, and continents on conjugate margins to these oceans and across which blocks are inferred to have migrated. Gondwana is unwound into a continuous strip forming the lower part of diagram. The peripheral Cadomian, North Indo-Australie and Terra Australis orogens separating the various blocks of East and West Gondwana from the outboard oceanic realm represented by the Mirovoi/Iapetus, Proto-Tethyan/PaleoAsian and Proto-Pacific oceans, respectively. The various continents and bounding orogens that lay across the oceans extend across the top o the diagram. The diagram covers a broad age range from the late Neoproterozoic to early Paleozoic rather than a specific time interval and as such it is inherently schematic. Abbreviations: Amaz – Amazonia; App – Appalachian; Aust – Australia; Aval-Cad – Avalonian-Cadomian; Cal – Caledonian; CAOB – Central Asian Orogenic Belt; Cord – Cordillera; IC – Indochina; K – Kalahari; NCC – North China Craton; CC – Cuyania & Chilenia; Orog – Orogen; QT – Qiangtang; RO – Rheic Ocean; SCC – South China Craton; Sibu – Sibumasu; Tas – Tasmania; TC – Trim Craton; TO – Tethyan Oceans; W Afr – West Africa.

(Fig. 1) but are herein drawn at the inferred limit of the spatial distribution of terminal tectonothermal events that stabilized each orogen. Thus, the lateral boundaries for the Avalonia-Cadomian orogen are located at the known lateral extent of ca. 630-530 Ma subduction-related tectonothermal activity, whereas for the Terra Australis Orogen it is the distribution of the ca. 300-230 Ma Gondwanide Orogeny, and for the North Indo-Australie Orogen it is the recognized extent of the ca. 500-420 Ma Bhimphedian Orogeny. Only the boundary between the Avalonian-Cadomian and North Indo-Australie orogens has sufficient data to relate to a specific geological feature; the Western Deformation Front in southeast Oman (Blades et al., 2020). This largely subsurface thrust zone was active around the early Cambrian and is inferred to mark the eastern lateral extent of the Arabian Nubian Shield and Western Gondwana. The non-synchronous timing of terminal events within the peripheral orogens makes it probable that younger events (e.g., Gondwanide Orogeny) reworked components along the margins of the laterally adjoining orogens (e.g., Cadomian and North Indo-Australie), although documentation is lacking.

These peripheral orogens not only vary in the timing of their onset and termination; they also vary significantly in duration. The Terra Australis ranges from ca. 830 Ma to 230 Ma, the Avalonian-Cadomian from ca. 800 Ma to ca. 530 Ma, and the Indo-Australie Orogen from ca. 800 Ma to ca. 420 Ma (see below). These variations reflect: a) differences in the kinematic framework that controlled the duration of each orogen including the timing of separation of their constituent basement blocks from Rodinia and their assembly into Gondwana; b) controls on the interaction between the basement blocks of each orogen with outboard oceanic realms (including the age of oceanic lithosphere and duration of subduction); c) the presence and accretion of outboard blocks; and, d) the inter-connected global kinematic framework in which regional events such as continental rifting and ocean basin formation occurred in non-Gondwanan terrane.

4. Terra Australis Orogen

The Terra Australis Orogen (Cawood, 2005) occurs in a belt from northeastern Australia to northwest South America (present-day coordinates) and transects the suture zones between East and West Gondwana (Fig. 1). Crustal components of the Terra Australis Orogen include basement blocks, overlain by continental margin successions, followed by convergent plate margin igneous rocks and coeval arc-related sedimentary successions (Figs. 2, 3; see Cawood, 2005 for detailed discussion of these constituent rock associations). Exotic accreted continental blocks are few, and limited to the Chilenia and Cuyania terranes in South America (e.g., Ramos, 2000; Martin et al., 2020a), and possibly Tasmania in southeast Australia (Mulder et al., 2020). Prior to the closure of the Mozambique Ocean, which led to the amalgamation of East and West Gondwana (East African Orogen), fragments of the Terra Australis Orogen displayed along-strike-variations in the character and timing of tectono-thermal events. For example, subduction initiated earlier in East Gondwana than in the South American fragments of the West Gondwana segment of the orogen (e.g., Cawood, 2005; Rapela et al., 1998).

The oldest elements of the Terra Australis Orogen are preserved along the East Gondwana segment and record ca. 830 Ma extension and rift-related magmatism that are associated with early stages of Rodinia breakup, involving the separation of the Australian-Mawson-Antarctica blocks (Fig. 1) from western Laurentia (Wingate et al., 1998). Timing of ocean floor spreading associated with opening of the proto-Pacific is not well constrained along either the Gondwanan or western Laurentian margins but, on the basis of rift-related magmatism and thermal subsidence histories, probably ranges from ca. 760-680 Ma and possibly younger (Colpron et al., 2002; Cawood, 2005). For the Terra Australis Orogen, this protracted breakup is interpreted to reflect a complex alternation of lithospheric extension and thermal subsidence, perhaps associated with the drift of continental ribbons and/or formation

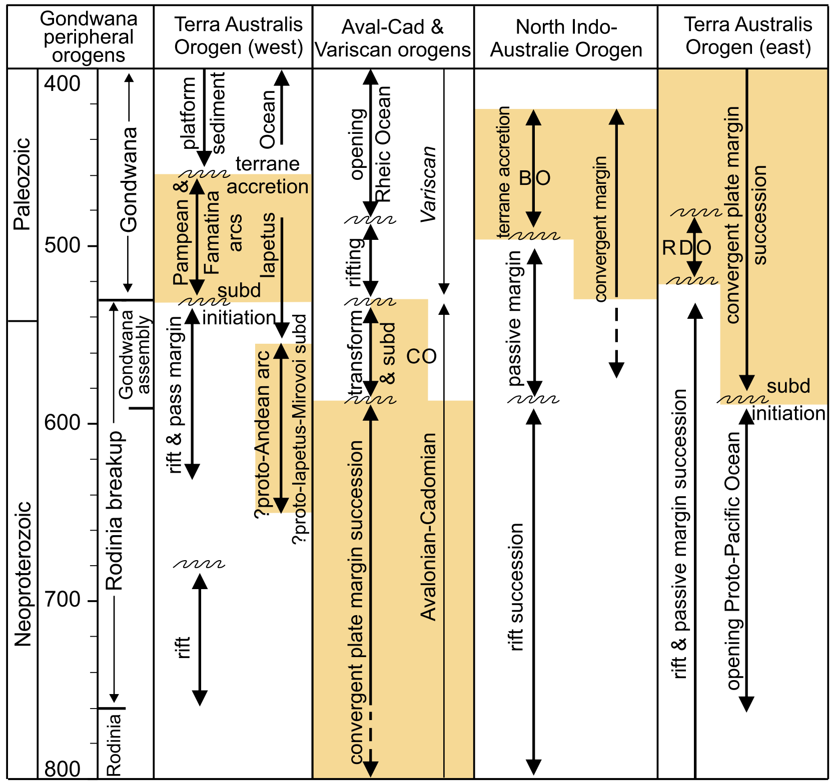

Fig. 3. Simplified time-space plot for the Terra Australis, Cadomian and North Indo-Australie orogens, displaying the timing of major lithotectonic events with respect to the Rodinia and Gondwana supercontinent cycles. Terra Australis Orogen presented in two columns related to development the development of the orogen on both West and East Gondwana basement terranes and resultant differences in tectonostratigraphic history, both prior to and after Gondwana assembly. For each column the left-hand side refers to more inboard components of the orogenic history and the right-hand side more outboard components. Coloured regions highlight main periods of subduction within each orogen. Abbreviations: BO – Bhimphedian orogeny; CO – Cadomian orogeny; RDO – Ross-Delamerian orogeny; marg – margin; pass – passive; subd – subduction. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

of hyper-extended margins prior to the development of the main East Australia-Antarctica passive margin succession (Li et al., 2008; Goodge, 2020). These structurally extended continental ribbons were subsequently re-accreted and formed basement blocks within the orogen (Cawood, 2005). West Gondwana, which abutted eastern Laurentia (Fig. 2) in Rodinia (Dalziel, 1991), displays evidence for at least a localized failed rift stage of lithospheric extension around 760-680 Ma (e.g., Appalachian Blue Ridge), prior to a second rifting event, which led to final breakup of Baltica and Amazonia from Laurentia between 630-550 Ma and the formation of the Iapetus Ocean (Cawood, 2005; Merdith et al., 2021). However, Chew et al. (2008) proposed that the initial, mid-Neoproterozoic, phase of rifting did not fail but led to ocean formation (proto-Iapetus, Fig. 3). This interpretation is based on the presence of detrital zircons with ages between 650-550 Ma recovered from clastic rocks that accumulated along the South American margin of West Gondwana, which are inferred to require derivation from a contemporaneous magmatic arc (Figs. 2, 3). The paleomagnetic analysis of Robert et al. (2020) provides further support for this concept. Hence, Chew et al. (2008) argued for an episode of subduction along the proto-Andean margin in West Gondwana spanning this time range, which in turn requires the southern segment of the Iapetus Ocean to have opened prior to 650 Ma.

Subduction of Proto-Pacific oceanic lithosphere beneath the East Gondwana segment commenced around 590 Ma based on the ages of the oldest calc-alkaline magmatism and derived arc detritus (Cawood, 2005; Goodge, 2020). However, the main phase of subduction did not commence until around 530 Ma, which is coeval with the onset of subduction along the South American margin of West Gondwana (e.g., Rapela et al., 1998), following closure of the Mozambique Ocean.

In East Gondwana, convergent margin arc magmatism occurred within an overall retreating accretionary orogen, periodically stabilized by tectonic switching (cf., Collins, 2002). This process resulted in the growth of the continental crust represented by the eastern third of Australia and by outboard terranes (e.g., New Zealand), which prior to opening of the Tasman Sea had an across-strike width of ca. 2000 km (and even wider if the effects of deformation are restored; Cawood et al., 2009). In contrast, arc magmatism along the West Gondwana margin was more intermittent occurring within a largely advancing accretionary orogen with major pulses in the early (ca. 530-460 Ma) and late (ca. 360-300 Ma) Paleozoic (Rapela et al., 1998; Ramos, 2000). The region remained relatively fixed in its position within the overriding Western Gondwana plate with little outboard continental growth (Martin et al., 2020b and references therein), which possibly resulted in loss of parts of the convergent plate margin record by tectonic erosion. At 300-230 Ma, in association with the assembly of Pangea, the Terra Australis Orogen was stabilized with the non-collisional Pan-Pacific Gondwanide Orogeny and succeeded by the Gondwanide Orogen (Cawood, 2005).

5. Avalonian-Cadomian Orogen

The Avalonian-Cadomian Orogen comprises a series of crustal blocks containing basement, continental margin and arc assemblages (Fig. 1) that was located along the Gondwanan margin, from northern South America to Arabia and Iran. Many of its constituent crustal blocks were dispersed by Paleozoic orogenesis and are suspect terranes in the Appalachian (West Avalonia, Ganderia, Carolinia, Meguma), Caledonian (Ganderia, East Avalonia) and Variscan (Armorica, Iberia, East Avalonia) orogens. Variations in the isotopic characteristics of these blocks indicate some were para-autochthonous whereas others were allochthonous with respect to Gondwana (Murphy et al., 2000). The early magmatic record of Avalonia is characterized by a juvenile Sm-Nd signature (1.2-1.0 Ga) suggesting it was oceanic until about 650 Ma. Most of Cadomia, on the other hand, has an evolved Sm-Nd signature with a model age of around 2.1 Ga, corresponding to the Eburnian, West African, basement (Murphy et al., 2000, 2008), suggesting it evolved along that continental margin. Taken together Avalonia and Cadomia may not have been contiguous until 650 Ma, when Avalonia accreted to Gondwana, with its contiguous nature further dependent on when West Africa and Amazonia amalgamated. Furthermore, the Iranian Block may not have been incorporated into the orogen until the late Neoproterozoic. Magmatism in the Iranian Block occurs between 600-520 Ma, with the bulk between 570-530 Ma (Moghadam et al., 2021), and appears to lack an earlier magmatic record. The block lies outboard of the East African Orogen and thus, was likely only incorporated into the Avalonian-Cadomian Orogen during final assembly of West and East Gondwana, consistent with its record of Ediacaran to Early Cambrian Cadomian related magmatism.

Subduction along (e.g., Iberia) or outboard (e.g., Avalonia) of cratonic blocks of West Gondwana commenced at least locally (e.g., West Africa) in the early Neoproterozoic, and the Avalonian-Cadomian Orogen is characterized by extensive convergent plate magmatic arc-related igneous and sedimentary successions that range in age from ca. 800-530 Ma, but with major episodes of magmatism between 760-590 Ma (Fig. 2; e.g., Nance et al., 2010; Murphy et al., 2013; Linnemann et al., 2014). Arc activity continued in some regions until ca. 540-530 Ma (e.g., Carolina, Iran) but its termination was diachronous and is inferred to be related to increasingly oblique subduction, which led ultimately to the development of a transform margin (e.g., Cadomia and Avalonia; Nance et al., 2010). By the early Cambrian, the cessation of subduction, associated with the changing kinematic environment, led to a transpressive regime and widespread deformation and metamorphism (Linnemann et al., 2014, and references therein). Subsequent lithospheric extension, from ca. 530-490 Ma, was marked by rift-related bimodal magmatism and sedimentation (e.g., García-Arias et al., 2018, and references therein). Rifting culminated in the opening of the Rheic Ocean and the development of passive margin successions on both the inboard blocks that remained joined to Gondwana (e.g., Iberia and Cadomia) as well as outboard blocks (e.g., Ganderia, Avalonia, Carolina and Meguma) that rifted from the margin and ultimately collided with Laurentia in the Silurian-Devonian as the Iapetus Ocean closed (Nance et al., 2010; Murphy et al., 2013; Linnemann et al., 2014). Successions post-dating the Avalonian-Cadomian Orogen and opening of the Rheic Ocean are part of the Late Paleozoic Hercynian-Variscan-Alleghenian orogenic cycle (Fig. 2).

6. North Indo-Australie Orogen

The North Indo-Australie Orogen is introduced herein as the orogenic tract lying along and outboard of northern India and Australia. The history of the orogen spans from the mid-Neoproterozoic to the mid-Paleozoic. It corresponds in part to the North India Orogen of Cawood et al. (2007), which records the evolution from a rift-to-drift succession to a convergent plate margin association of rock units preserved in northern India and Nepal that was stabilized by the beginning of the Ordovician. Subsequent work (Cawood et al., 2013b; Han et al., 2016; Zhao et al., 2018; Metcalfe, 2021) has shown that the northern Gondwana margin included a series of continental blocks with bounding suture zones that were located outboard of both India and Australia, and these are herein included within the orogen (Fig. 1). The history of the orogen is fragmentary and is preserved in the various blocks now located in Asia, with the early history of the blocks covered and overprinted by younger rock units and events associated with their migration from Gondwana to Asia (Metcalfe, 2021).

The Himalayas in Pakistan, India, Nepal and Bhutan preserve Neoproterozoic to early Paleozoic siliciclastic and carbonate successions with volumetrically minor igneous rocks that collectively record a long-lived (ca. 800-500 Ma) rift and passive margin setting (Myrow et al., 2016, and references therein). Margin development is related to opening of the Proto-Tethys Ocean and is inferred to record the separation of several continental ribbons from north Gondwana, whereas other blocks, which were not connected to Gondwana, lay further outboard in the Paleo-Asian Ocean (Fig. 2; Jiang et al., 2003; Zhao et al., 2018). The cessation of passive margin sedimentation in the Cambrian is marked by the development of a regional unconformity with overlying Ordovician strata (Myrow et al., 2016). The stratigraphic break also corresponds with Barrovian metamorphism, crustal melting and emplacement of both S- and I-type granites (Gehrels et al., 2006; Palin et al., 2018), an event termed the Bhimphedian orogeny (Cawood et al., 2007). Associated tectonothermal events produced regional unconformities, deformation and metamorphism that are now located in and around the margins of the Asian continental fragments (e.g., Tarim, North China, South China, Qiangtang, Lhasa and Sibumasu and Indochina; Cawood et al., 2007; Zhu et al., 2012; Han et al., 2016; Myrow et al., 2016; Palin et al., 2018; Hu et al., 2021; Wang et al., 2021c). These events are attributed to the initiation of subduction and the subsequent accretion of these blocks to the northern Gondwana margin, thereby closing the Proto-Tethys ocean (Zhao et al., 2018, and references therein). Magmatic activity at 560-530 Ma occurs in parts of the Himalayan succession but the bulk of the ages range between 500 Ma and 460 Ma, and are related to oceanic subduction along, and outboard of, the northern Gondwana margin (Gehrels et al., 2006; Cawood et al., 2007; Zhu et al., 2012; Wang et al., 2021c). Thus, the North Indo-Australie Orogen is characterized by various continental blocks that rifted away from the Indian and Australian margin of Gondwana, or already lay outboard of the margin and were accreted to Gondwana in the early Paleozoic along a series of suture zones. Dating of deformation and metamorphism in these belts mostly yield ages between 510-460 Ma (e.g. Himalayas, Altyn-Tagh) but for continental blocks further outboard, orogenesis continued to ca. 420 Ma, reflecting later accretion to Gondwana (Fig. 3, Qiadam and Qilian orogenic belts and South China Block; Han et al., 2016; Zhao et al., 2018).

There is general agreement on which blocks lay outboard of India and Australia (Fig. 1) but their relative positions both with respect to Gondwana and to each other are not resolved. For example, South China is argued by some to have lain outboard of India since at least the early Neoproterozoic, whereas others argue it was accreted to the margin of India at the beginning of the Paleozoic (Cawood et al., 2013b). Lhasa is variously interpreted to have been located off northwest India (Hu et al., 2021) or northwest Australia in the early Paleozoic (Zhu et al., 2012). Similar uncertainties concern the positions of Tarim, North China and Sibumasu (Han et al., 2016; Metcalfe, 2021). Furthermore, the relative position of blocks may have changed over time along the Gondwana margin. Thus, the Neoproterozoic rift-to-drift succession in northern India and its correlation with South China continental margin strata (Jiang et al., 2003) indicates at least their partial separation, with South China (and presumably adjoining blocks) inferred to have subsequently moved dextrally with respect to the northern Gondwana margin (Wang et al., 2021b). Knowledge of the Afghan Block and its position with respect to Gondwana is limited. We place it at the western end of the North Indo-Australie Orogen on the basis of recent dating near Kabul (Faryad et al., 2016), which indicates the presence of Neoarchean (2.8-2.5 Ga) basement and late Paleoproterozoic (1.85-1.80) and early Neoproterozoic (0.90-0.85 Ga) tectonothermal events, consistent with the timing of events in South China and/or Tarim.

7. Discussion

The peripheral orogens of Gondwana display histories reflecting their development prior to, during, and after Gondwana collisional assembly. Prior to assembly, the early histories of the different fragments of Terra Australis, Avalonian-Cadomian and North Indo-Australie orogens are linked to the continental basement blocks upon which they developed and the position of those blocks within, or with respect to, Rodinia (e.g., Merdith et al., 2021 and references therein). This connection is exemplified by a series of continental margin successions with variable timing of rift initiation and the onset of passive margin sedimentation along those continental fragments that occupied internal locations with Rodinia. These continental margin successions are exposed in the eastern Terra Australis Orogen and opposing western Laurentia as they separated to form the Proto-Pacific, and in the western Terra Australis Orogen, whose basement separated from East Laurentia to form the Iapetus Ocean (Fig. 2). In contrast, the Avalonian-Cadomian Orogen developed on the basement blocks of northern South America and Africa (i.e., Amazonia, West Africa and Sahara cratons) that were located either within (Avalonia) or faced (Cadomia) the circum-Rodinia Mirovoi Ocean. With the breakup of Rodinia, a subduction zone formed outboard of northern South America and along the margin of West Africa resulting in intra-oceanic (early Avalonia) and Andean (early Cadomian) arcs respectively (Murphy et al., 2000; Cawood et al., 2016). The Avalonian-Cadomian orogenic belt may not have been contiguous until Avalonia accreted to Gondwana at ca. 650 Ma. The initiation of the continental margin to the North Indo-Australie Orogen, or at least the component outboard of the Indian craton, is less well established with paleogeographic models suggesting India was either part of Rodinia (Li et al., 2008) or a geographically separate block that was never incorporated into the supercontinent (Merdith et al., 2017, and discussion therein; Merdith et al., 2021).

The progressive collisional assembly of Gondwana's cratonic blocks by the end of the Neoproterozoic led to the lateral juxtaposition of the developing components of the Terra Australis, Avalonian-Cadomian and North Indo-Australie orogens in their peripheral location encircling the supercontinent (Figs. 1, 2). After Gondwanan assembly, these belts became kinematically connected and so their respective evolutions became susceptible to far-field stresses from adjoining orogens. This connection is evidenced by the temporal similarity for step-changes in the evolution of these orogens. The initiation of subduction along the eastern part of Terra Australis Orogen at around 590 Ma followed by its propagation along the entire orogen by 530 Ma, corresponds with the diachronous termination of subduction in the Avalonian-Cadomian Orogen and the likely transition from rift to passive margin succession in the North Indo-Australie Orogen (Fig. 3). In the North Indo-Australie Orogen, subduction recorded in the continental fragments outboard of its northern Gondwana margin started in the early Paleozoic (ca. 530 Ma), although further outboard in the Proto-Tethyan and Paleo-Asian Oceans it may have started by the mid-Neoproterozoic (e.g., Qaidam, Qilian and Qinling blocks; Zhao et al., 2018). Consumption of oceanic lithosphere between these blocks and along the northern Gondwana margin resulted in sequential accretion of Asian terranes to the margin in the early to mid-Paleozoic (510-420 Ma). The timing of the main pulse of Bhimphedian orogenesis (500-470 Ma), related to closure of the Proto-Tethys Ocean, corresponds with progressive opening of the Rheic Ocean and commensurate closure of the Iapetus Ocean (Fig. 3; van Staal et al., 2012).

8. Speculations on geodynamic links of orogenic systems to mantle convection

The character and evolutionary patterns of Gondwana's three peripheral orogens are fundamentally different. The Terra Australis Orogen records a long term history of convergent plate interaction, the evolution of the Cadomian-Avalonian Orogen is that of a series of Wilson cycles of oceans opening and closing (Iapetus, Rheic), whereas the North Indo-Australie Orogen archives a complex history of terrane accretion, overprinted in part by their subsequent dispersal from Gondwana and accretion into Asia. Part of their respective distinctive characters derives from differences in the origins of basement blocks within Rodinia but we speculate that perhaps discrete evolutionary patterns, although kinematically linked, could be related to global-scale mantle convection at the time of Rodinia breakup and the subsequent assembly of Gondwana. There is a suggestion that at the time of Rodinia breakup the mantle was dominated by degree-2 planform convection, i.e. two antipodal regions of mantle upwelling that straddled the equator, bisected by a N-S great circle of mantle downwelling corresponding broadly to a subduction girdle, encircling the supercontinent (Zhong et al., 2007). The equatorial locations of the mantle upwellings reflect the optimal moment of inertia on a spinning Earth (Niu, 2018). As one upwelling would have formed beneath the supercontinent Rodinia, the antipodal upwelling would have been predominantly oceanic (Fig. 4). Progressive breakup of Rodinia from 0.8 to 0.6 Ga creates new oceanic lithosphere between its dispersing blocks that requires compensation by subduction within the peri-Rodinian (Mirovoi) ocean (cf., Cawood and Buchan, 2007). Subduction systems forming within that ocean (the subduction girdle) would tend to retreat towards the mantle downwelling zone forming oceanic island arcs (e.g., Spencer et al., 2019) whose ages match those of Rodinia rift-drift successions (Fig. 4).

The oldest example of arc magmatism in the Avalonian portion (proto-Avalonia) of the Avalonian-Cadomian orogenic belt (the 760 Ma Burin Group exposed in SE Newfoundland, the type region of Avalonia) may be an example of oceanic subduction linked to Rodinia breakup. Its supra-subduction zone geochemistry with Sm-Nd model ages between 0.8 and 1.0 Ga are interpreted to reflect the development of primitive oceanic island arcs (Murphy et al., 2008). These relationships imply that the oceanic lithosphere upon which proto-Avalonia was built formed in the Mirovoi Ocean over the time interval of Rodinia breakup. Such arc systems would tend to retreat until they stabilize when they reach the downwelling zone (Spencer et al., 2019), whereupon subsequent arc magmatism would begin to recycle the earlier arc substrate, generating a succession of arc magmas with similar (0.8 to 1.0 Ga) Nd model ages (Murphy et al., 2008).

As Rodinia broke up, its dispersed blocks would have migrated towards the subduction girdle (and mantle downwelling zone) (Fig. 4). The leading edges of these migrating blocks would have undergone Andean-type subduction, in a manner analogous to the leading (western) edges of North America and South America since the breakup of Pangea. The early history of the Cadomian portion of the Avalonian-Cadomian orogenic belt in which magmatism recycled West African (Eburnian) basement, may be an example of this process. The accretion of Avalonia to the Amazonian margin of Gondwana at ca. 650 Ma may reflect when the Amazonian margin reached the subduction girdle at the downwelling zone. At this stage, it is uncertain whether Avalonia and Cadomia were kinematically linked and this linkage depends on when West Africa and Amazonia amalgamated (Wen et al., 2020; Merdith et al., 2021). After accretion, subduction commenced outboard of the accreted

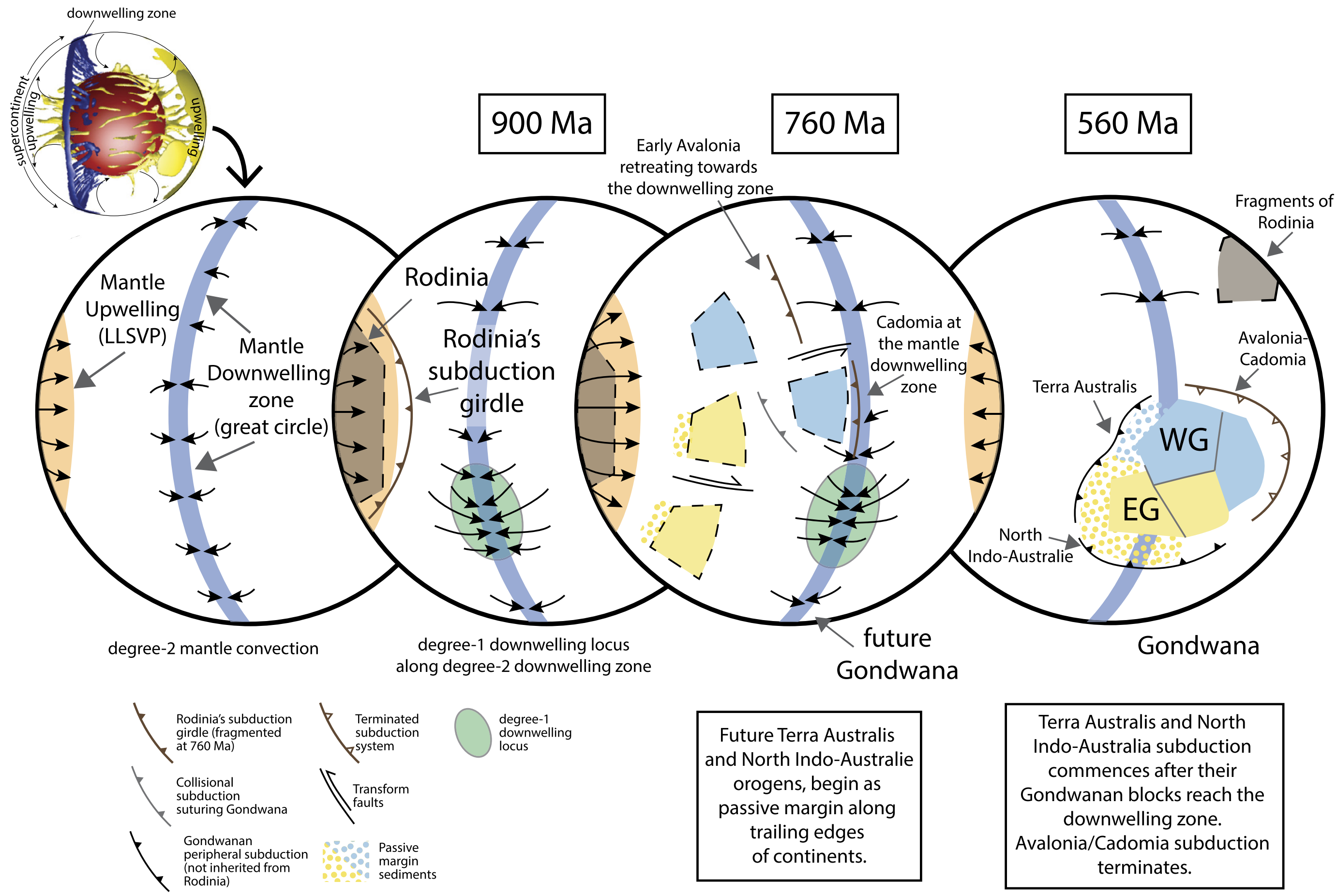

Fig. 4. Schematic model of peripheral orogen dynamics during Gondwana assembly (modified from Wang et al., 2021a). Upper left inset shows degree-2 mantle convection, with two sub-equatorial mantle upwellings bisected by a great circle of downwelling after Zhong et al. (2007). At 900 Ma, the mantle is dominated by degree-2 convection. The supercontinent Rodinia is located over one mantle upwelling and breaks up. During breakup, the Rodinian subduction girdle expands to align with the great circle of mantle downwelling. Blocks dispersing from Rodinia converge towards the downwelling zone. At 760 Ma, early magmatism in Avalonia and Cadomia is initiated along the downwelling zone, Avalonia in an oceanic setting, Cadomia along the margin of West Africa. Gondwana amalgamates piecemeal as continental blocks migrate towards the focused degree-1 mantle downwelling (green zone). The early passive margin sequences of Terra-Australis and the North Indo-Australie orogens (dots) reflect their locations along the trailing edge of the continents rifting from Rodinia. After these continents collide with the Gondwanan blocks that had previously arrived at the downwelling zone, their trailing edges are converted into subduction zones, thereby initiating subduction-related magmatism and accretionary tectonics that dominates their Paleozoic geological records. EG: East Gondwana; WG: West Gondwana.

margin producing the main phase of Avalonian-Cadomian magmatism.

Gondwana amalgamated progressively as the dispersing blocks of Rodinia converged towards the mantle downwelling zone. The trailing edges of these dispersed blocks would have developed coeval passive margin assemblages, as represented by the sedimentary rocks of the early history of the Terra Australis orogen. As the outermost blocks of Rodinia likely reached the downwelling zone first, the passive margin along their trailing edges would have been converted into active margins as blocks dispersed from the interior collided, forming the constituents of Gondwana, providing a mechanism for the onset of subduction in the Terra Australis and the North Indo-Australie orogens (Fig. 4).

As the peripheral orogens are oblique to the interior Gondwanan sutures, they were initially separated by tracts of oceanic lithosphere and so responded individually to Rodinia breakup. As the Gondwanan blocks progressively collided, intervening oceanic lithosphere was eliminated and they became kinematically linked.

Gondwana is a stepping stone on the path from Rodinia breakup to Pangea assembly. In the context of a mantle convection model, the orogens that form along the periphery of Gondwana are influenced both by the Rodinian history of their constituent peripheral blocks and the future evolution of Gondwana's margins with respect to Pangea. When the leading edges of margins of the north-south trending Terra Australis Orogen arrived at the downwelling girdle (Fig. 4) during Gondwana assembly, the orogen was parallel to the downwelling great circle. The subsequent blocks that collided to form Pangea do not interact with this margin, and the Terra Australis Orogen, as well as the subsequent Gondwanide Orogen, are inherited from Gondwana as orogens along the periphery of Pangea, thereby facilitating their continued development as peripheral accretionary orogens on the edge of he Pacific through the Paleozoic and Mesozoic. The Avalonian-Cadomian Orogen was in part oblique to this trend, and the subsequent collisional orogens that overprint the orogen developed as Gondwana migrated along the great circle of mantle downwelling to collide with Laurussia and form Pangea (e.g., Appalachian-Caledonian system and closure of Rheic ocean; Wang et al., 2021a). The formation of Pangea isolated the east-west trending North Indo-Australie Orogen to the margin of the interior and evolving Tethyian oceans of Pangea (e.g., Paleo-Tethys, Neo-Tethys), rather than a peripheral exterior ocean (cf., Murphy and Nance, 1991) such as the proto-Pacific for the Terra Australis Orogen. Formation and subsequent closure of the Tethyan oceans resulted in rifting, drifting and collision of the continental fragments in the North Indo-Australie Orogen and their incorporation into the collisional orogenic system that developed along the Eurasian margin of Pangea. Thus, kinematic reorganisation related to the assembly of Pangea resulted in varied evolution of each of Gondwana's peripheral orogens, following Gondwana assembly.

9. Conclusions and geodynamic considerations

The assembly of Gondwana through collisional orogenesis resulted in kinematic connections of previously discrete fragments of peripheral orogens, the Terra Australis, Avalonian-Cadomian and North Indo-Australie orogens around the margins of Gondwana. Prior to assembly, these had been fragmented orogenic systems that were each initiated by Rodinia breakup, but with Gondwana assembly their evolution became kinematically linked (Fig. 3). Each peripheral orogen has an early history of continental margin sedimentation followed by convergent plate margin activity (Terra Australis, North Indo Australie) or commenced with convergent plate margin activity (Avalonian-Cadomian). The Avalonian-Cadomian and North Indo-Australie orogens contain a number of continental blocks, some of which were accreted to Gondwana during their evolution (e.g., Avalonia, North China), but which were rifted and removed during subsequent orogenic cycles (Appalachian-Caledonian, Variscan, Alpine-Himalayan). Although there are broad temporal correlations of the lithotectonic records of the peripheral orogens, the history of each is distinct and preserves fundamental, first-order differences in their character and evolution. The Terra Australis Orogen was active from Neoproterozoic Rodinia breakup to end Paleozoic Pangea assembly. It displays a history of both retreating (eastern segment) and advancing (western segment) Paleozoic convergent plate margin processes (Cawood, 2005), and there was no widespread accretion, or rifting off, of continental fragments (apart from Chilenia, Cuyania, and possibly Tasmania, Figs. 1, 2). The various blocks of the North Indo-Australie Orogen record a protracted history of accretion and rifting, and the Avalonian-Cadomian Orogen formed through repeated Wilson cycles (Figs. 2, 3).

Phases of subduction were associated with each of the peripheral orogens. Convergent plate interaction characterizes much of the history of the Avalonian-Cadomian orogen but terminates at the end of the Neoproterozoic just as subduction commenced in the Terra Australis and North Indo-Australie orogens. Thus, although there were pulses of subduction around the Gondwana margin during various phases of its history, the absence of a long-lived contemporaneous subduction girdle likely hindered its breakup. In contrast, subduction girdles developed around the margins of Rodinia and Pangea, and are inferred to have facilitated supercontinent breakup by placing them under regional extension (Cawood et al., 2016). Within the context of global-scale mantle convection, Gondwana assembly occurred along the subduction girdle that encircled Rodinia and then migrated along the mantle downwelling zone to collide with Laurussia to form Pangea. Thus, the formation of Gondwana is a necessary precursor to the assembly of Pangea and earlier supercontinent cycles may display similar relationships (cf., Wang et al., 2021a).

CRediT authorship contribution statement

Peter Cawood: Conceptualization, data assembly and analysis, figure drafting, writing original draft; Erin Martin and Brendan Murphy: Critical assessment of concepts and validation, Writing - review and editing; additional drafting of figure. Sergei Pisarevsky - further assessment and validation, Writing - review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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