

## Late Ediacaran inertial-interchange true polar wander (IITPW) event: a new road to reconcile the enigmatic paleogeography prior to the final assembly of Gondwana

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**Abstract:** The Ediacaran to Early Cambrian plate tectonics was dominated by a full dispersal of the supercontinent Rodinia and the subsequent amalgamation of Gondwana. There is a consensus that the final assembly of Gondwana was not completed until the Early Cambrian. Prior to the final assembly, however, one major uncertainty remains on the quantitative paleogeography: the mainland of Gondwana was plausibly positioned at either a high or low latitude at a single time instant to meet the dual-latitude ('high-latitude' and 'low-latitude') options of Laurentia and the requirement of <600 Ma Iapetus Ocean opening between Amazonia and Laurentia. This uncertainty mainly arises from the equivocal selections on the ca. 590–560 Ma paleopoles from Laurentia and very few paleomagnetic data from Gondwana continents. In this paper, we expanded the dataset of high-quality paleomagnetic poles on the basis of Robert et al. (2017, 2018) and Wen et al. (2020), and confirmed an inertial interchange true polar wander (IITPW) event from ca. 590–580 to 560 Ma. We then provide a continuously kinematic reconstruction in the TPW-based ('absolute') framework and thus reconcile the two enigmatic paleogeographic models in this interval. The occurrence of IITPW in late Ediacaran has important implications for understanding the coevolution of Earth's system, and multidisciplinary investigations of the IITPW associated processes are needed in future work.

**Key words:** Inertial-interchange true polar wander (IITPW), paleomagnetism, paleogeography, late Ediacaran

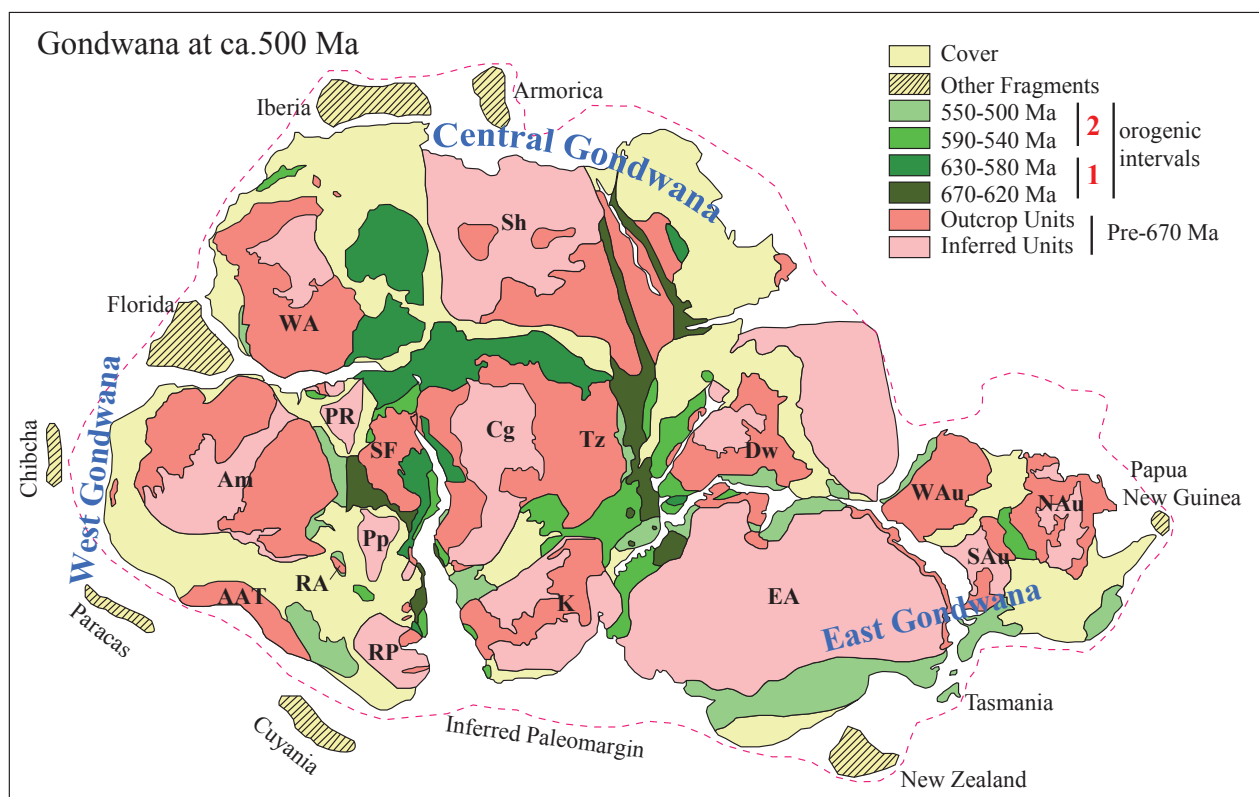
### 1. Introduction

Plate tectonics during most of the Ediacaran time was dominated by a full dispersal of the supercontinent Rodinia and subsequent amalgamation of Gondwana on the other side of the Earth (e.g., Hoffman, 1991; Li et al., 2008; Merdith et al., 2017, 2021; Wen et al., 2017). This process had been linked to the wholesale evolution of Earth's system involving the geosphere, atmosphere, and hydrosphere at that time (e.g., Nance et al., 2014; Li et al., 2019). For example, the weathering of voluminous basaltic rocks related to the breakup of Rodinia was regarded as the main trigger for the initiation of "Snowball Earth" (reviewed in Hoffman et al., 2017). Meanwhile, the buildup of Gondwana "semisupercontinent" or "megacontinent" (a geodynamical precursor to supercontinent amalgamation; Wang et al., 2021) may have played an important role in the supercontinental transition from Rodinia to Pangea (Wen et al., 2018; Wang et al., 2021). Regarding the amalgamation of this landmass, Meert et al. (1995) first recognized that the East Gondwana (Australia-Antarctica and associations) had not sutured with its neighboring continents of Central

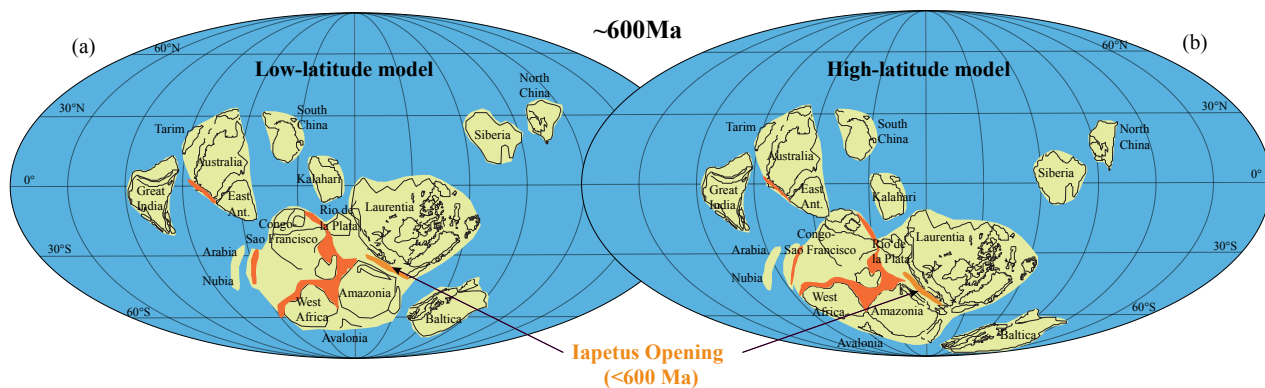
Gondwana by the late Ediacaran. Since then, a growing number of studies show that a coherent Gondwana was not welded together until the Early Cambrian (e.g., Meert, 2003; John et al., 2004; Tohver et al., 2010; Merdith et al., 2017, 2021; Robert et al., 2017; Schmitt et al., 2018; Wen et al., 2020). This consensus has recently been well summarized and at least two-stage orogenic activities were emphasized through approximately 650 to 500 Ma (Figure 1; Merdith et al., 2017, 2021; Schmitt et al., 2018). These achievements, together with the discussions on the evolution of East Asian blocks incorporated in the course of the Gondwana assembly (e.g., Zhao et al., 2018, 2021), comprise major progress in the late Precambrian paleogeographic research.

Prior to the final assembly of Gondwana, however, there is still an open question about the paleogeography in a quantitative reconstruction: the mainland of Gondwana was plausibly positioned at either a high or low latitude at a single time instant due to two equivocal paleomagnetic datasets for Laurentia (Figure 2; Li et al., 2008; Pisarevsky et al., 2008). Either way, one can ensure

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**Figure 1.** Configuration of the coherent Gondwana in the Early Cambrian time, showing pre-Gondwana continents and multiple-interval suturing belts (after Merdith et al., 2017, 2021; Schmitt et al., 2018). WA, West Africa; Am, Amazonia; PR, Parnaíba; SF, São Francisco; Pp, Paranapanema; RA, Rio Apa; AAT, Arequipa-Antofalla Terrane; RP, Río de La Plata; Sh, Sahara; Cg, Congo; Tz, Tanzannia; K, Kalahari; Dw, Dharwar; EA, East Antarctica; W (N, S) Au, West (North, South) Australia.



**Figure 2.** Two representative alternative models at one single time on a global reconstruction, showing the Iapetus opening (<600 Ma) between Gondwana (Amazonia) and Laurentia at low (a) and high (b) latitudes (after Cawood et al., 2001; Li et al., 2008).

the Iapetus Ocean opened between Amazonia (Gondwana side) and Laurentia in the subsequent (<600 Ma) process (Cawood et al., 2001; Li et al., 2008). But this ambiguity will hamper the understanding of the paleogeographic evolution because different models will lead to different interpretations, especially on the geometry and geodynamics of the Iapetus opening. In order to avoid this

problem, some researchers even favored one scenario by omitting the majority of Ediacaran palaeomagnetic data (e.g., Merdith et al., 2017, 2021). It may also account for the controversy on the evolution of East Asian blocks related to the Gondwana amalgamation during the transition from Rodinia to Pangea (e.g., Zhao et al., 1992, 2018; Yang et al., 2002; Huang et al., 2019; Xian et al., 2019). The dual-

latitude models largely arise from equivocal selections of the ca. 590–560 Ma paleomagnetic poles from Laurentia and the fact that there are very few reliable poles from the Gondwana side (reviewed in Li et al., 2008; Merdith et al., 2017). Recently, new high-quality paleopoles of Ediacaran strata/rocks have been reported from the Gondwana continents (Rapelini et al., 2015; Robert et al., 2017, 2018; Wen et al., 2020), providing an opportunity to quantitatively test the enigmatic paleogeography for this interval.

## 2. Methods and paleomagnetic data compilation

This study builds upon the work of Robert et al. (2017, 2018) and Wen et al. (2020). We expand the ca. 590–560 Ma high-quality paleomagnetic pole dataset by adding more paleopoles of supplement continents (such as the East Asian blocks) from the global *Precambrian database* (PALEOMAGIA; <https://h21.it.helsinki.fi/index.php>). The selection criteria are applied in this study: (i) paleopoles satisfy at least three or more reliability factors ( $R_f \geq 3$ ) of Meert et al. (2020) and with  $A_{95}$  less than  $16^\circ$ ; (ii) data are only selected from sedimentary and igneous rocks (including volcanics and dikes) of older cratons/continents, eliminating those from metamorphic rocks and active orogenic belts; and (iii) reliable (including U-Pb) ages are updated if available from new literature; (iv) Grand mean poles are used for the same rock units to avoid duplication. For convenience in the following discussion, all the quality-filtered poles are assigned with abbreviated names (Table). *GPlates* software (<https://www.gplates.org/>) was used for the reconstruction. Motions of the continents in our plate hierarchy of *GPlates* are given in Figure 3.

## 3. Paleogeography in an ‘absolute’ framework

### 3.1 An inertial-interchange true polar wander event from ca. 590–580 to 560 Ma

As mentioned earlier, the ca. 590–560 Ma ambiguous models are mainly caused by an equivocal use of the paleomagnetic poles from Laurentia. The apparent polar wander path (APWP) established from those poles displays large oscillations in this interval (Abrajevitch and Van der Voo, 2010). But most poles for the large oscillations are the two-component (steep and shallow) directions from the same rock unit (reviewed in Robert et al., 2017), and are not equally reliable as pointed out by other researchers (e.g., McCausland et al., 2007, 2011; Bono and Tarduno, 2015). So, only the most robust ca. 590–560 Ma paleopoles from Laurentia were selected using the methodology of Robert et al. (2017, 2018). Their selections are briefly described as follows: (i) the shallow component (L-Sla) of Sept-Iies intrusion (Tanczyk et al., 1987) is selected for its primary nature supported by a positive reversal

test (Bono and Tarduno, 2015); (ii) the “A” pole (L-Cat) of Catoctin Basalts (steep) is used after Meert et al. (1994) while the other one has been interpreted as a late Cambrian remagnetization by the authors; (iii) although no paleomagnetic stability test is available for the pair of poles from Baie des Moutons complex (McCausland et al., 2011), the shallow one is eliminated for its close to younger Ediacaran poles, including the pole of L-Sla (Tanczyk et al., 1987); (iv) for the approximately 590 Ma Grenville dike swarms, their steep components (referring to the poles L-GD2, L-GDe, and L-GDb) are primary origin strongly supported by field tests (reversal and contact tests), while their shallow ones are not (Murthy, 1971; Hyodo and Dunlop, 1993; Halls et al., 2015); and (v) the pole from the Johnnie Formation (Van Alstine and Gillett, 1979) is excluded from the compilation for its very loose age constraint and the lack of demagnetization details. Also, the 550 Ma pole from the Skinner Cove volcanics (McCausland and Hodych, 1998) is not included because its age is not in this IITPW interval.

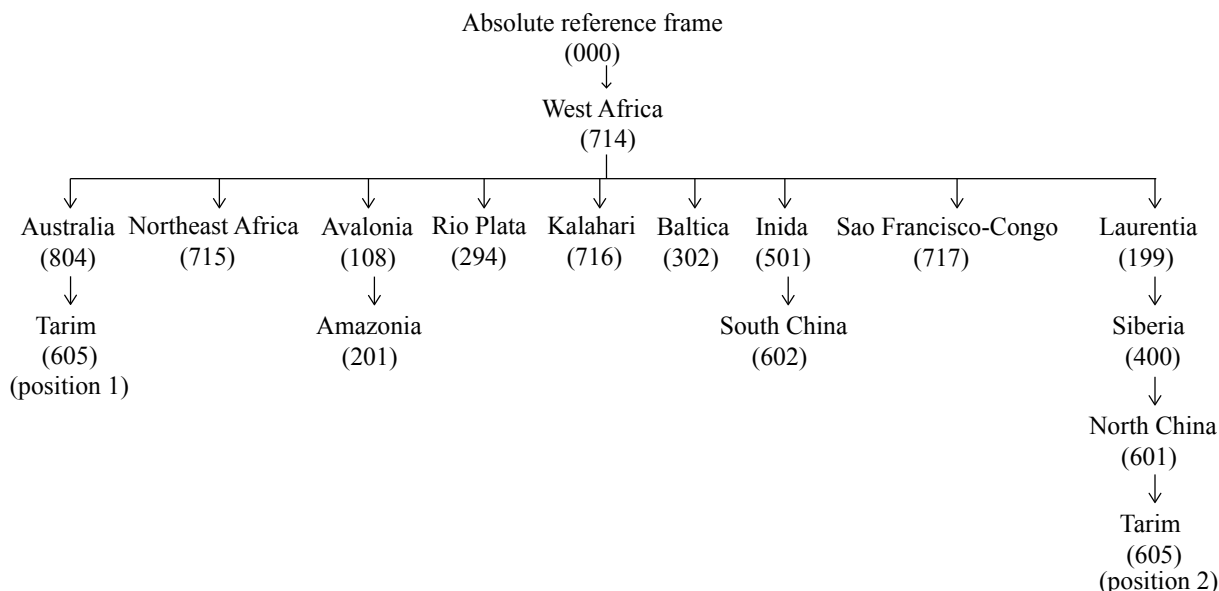
All the ca. 590–560 Ma poles from Laurentia are summarized in Table. Integrating those data with the coeval poles from West Africa and the Amazonia-proximal Avalonia terrane of Newfoundland, a similar trend of APWPs is defined and no oscillation occurred in this interval (Figure 4; Robert et al., 2017, 2018; Wen et al., 2020). The rate of this polar motion is calculated to be approximately  $2\text{--}9^\circ/\text{Myr}$ , which is consistent with a plausible speed of inertial-interchange true polar wander (IITPW; Tsai and Stevenson, 2007; Greff-Lefftz and Besse, 2014). IITPW involves a nearly  $90^\circ$  rotation of the whole solid Earth (lithosphere and mantle) in response to large and rapid changes in the moment of inertial (Kirschvink et al., 1997; Tsai and Stevenson, 2007). In a numerical model, this large magnitude of TPW process had been attributed to an inertial interchange associated with a girdle of subduction system at that time (Robert et al., 2018). Taking age errors of the poles into account, the initiation of the IITPW is around ca. 590–580 Ma. This IITPW event is also well compatible with the quasistatic Sutton plume under Laurentia while the latter showed a large APWP shift in this interval (Mitchell et al., 2011). At the same time, a rapid movement of continents towards low latitudes through IITPW will cause a transient sea-level rise (Mound and Mitrovica, 1998). The “Johnnie Oolite” within the Rainstorm Member in southwest Laurentia (Verdel et al., 2011) and C3 Formation of the Schisto-Calcaire Subgroup (Delpomdor et al., 2015) could represent a marine transgression and regression, respectively, when they switched their latitudes during that rotation. Obviously, current data weighs more towards TPW explanation rather than the alteration of geomagnetic fields between an axial and an equatorial

**Table.** Compilation of ca. 590–560 Ma paleomagnetic poles for the reconstruction in this study  
 Notes: P-lat/P-long, latitude/longitude of a paleomagnetic pole.  $A_{95}$ , radius of the pole 95% confidence cone.  $R_p$ , Reliability factor of Meert et al. (2020). Pole T-Zma with “\*” may also represent a Paleozoic remagnetization after Wang et al. (2019).

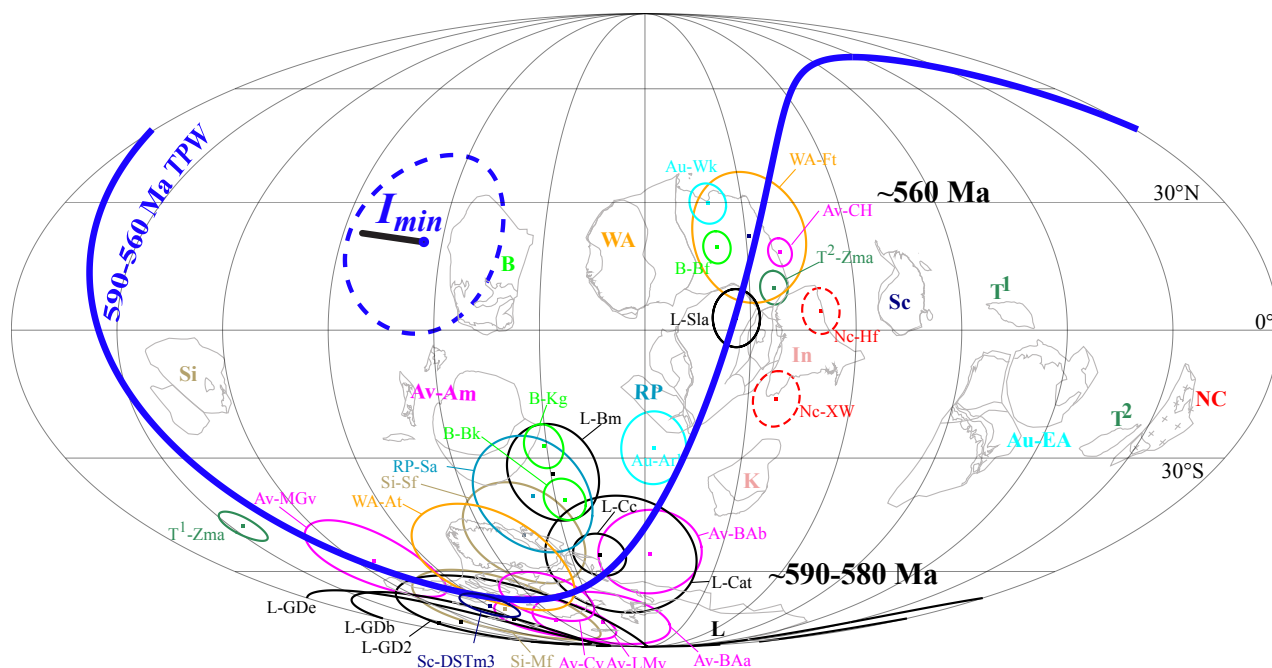
Pole ID	Rock unit (area)	Age (Ma)		P-lat (°N)	P-long (°E)	$A_{95}$ (°)	1	2	3	4	5	6	7	$R_p$	Reference
		Max	Min												
<b>Laurentia</b>															
L-Sla	Sept-Iles intrusion (Shallow)	565 ± 4	569	-20	321	6.7	1	1	1	1	1	0	0	5	Tanczyk et al., 1987
L-Cat	Catoctin Basalts (steep)	572 ± 5	577	42	297	17.0	1	1	1	1	1	1	1	7	Meert et al., 1994
L-Cc	Callander Alkaline Complex intrusive	577 ± 1	578	46	301	6.0	1	1	1	1	0	1	1	6	Symons and Chiasson, 1991
L-Bm	Baie des Moutons complex	583 ± 2	585	42.6	332.7	12.0	1	1	1	0	0	0	1	4	McCausland et al., 2011
L-GDb	Grenville Dikes (Steep)	587.3 ± 0.7	588	55.7	233.4	10.6	1	1	1	1	1	0	1	6	Halls et al., 2015
L-GDe	Grenville Dikes (Steep)	586 ± 4	590	51.5	231.2	11.6	1	1	1	1	1	0	1	6	Hyodo and Dunlop, 1993
L-GD2	Grenville Dikes (Steep)	590 ± 2	592	61.6	249.9	14.5	1	0	1	1	1	1	1	6	Murthy, 1971
<b>East and West Avalonia</b>															
Av-CH	Crown Hill Fm, Newfoundland, Canada	< 557+/-14; 566+/-13	570	-48.1	9.9	3.3	1	1	1	1	1	1	1	7	Wen et al., 2020
Av-BAb	Bonavista Bull Arm Fm, Newfoundland, Canada	592 ± 2.2; 591.3 ± 1.6	594	-15.5	278.2	11.9	1	1	1	1	1	1	1	7	Wen et al., 2020
Av-BAa	Argentia Bull Arm Formation, Newfoundland, Canada	< 600		-2.9	256.3	10.6	0	1	1	1	1	1	1	6	Pisarevsky et al., 2012; reference age of Mills et al., 2017
Av-MGv	Marystown Group volcanic-sedimentary sequence, Newfoundland, Canada	585 ± 2; 580 ± 3; 576.8 ± 2.6; 575 ± 2	587	26.6	239.6	11.1	1	1	1	1	1	1	1	7	McNamara et al., 2001; Sparkes and Dunning, 2014
Av-LMv	Lynn-Mattapan Volcanics, New England, USA	595.8 ± 1.2; 597.4 ± 1.5; 596.0 ± 1.4; 595.7 ± 1.6	599	60	206	8.4	1	1	1	1	1	1	1	7	Thompson et al., 2007
Av-Cv	Caldecote Volcanics, England (East Avalonia)	603 ± 2	605	-5	329.7	8.2	1	1	1	1	1	0	1	6	Vizan et al., 2003

Table. (Continued).

Pole ID	Rock unit (area)	Age	Age range (Ma)		P-lat (°N)	P-long (°E)	A <sub>95</sub> (°)	1	2	3	4	5	6	7	R <sub>i</sub>	Reference
			Max	Min												
<b>Baltica</b>		(Ma)														
B-Bf	Basu Formation	570–560	Fossils		-2	6	3.8	1	1	1	1	1	1	0	6	Levashova et al., 2015
B-Kg	Kurgashlya Formation	600–570?			50.9	314.5	5.3	0	1	1	1	1	1	1	6	Lubnina et al., 2014
B-Bk	Bakeevo Formation	600–570?			42.3	299.1	5.3	0	1	1	1	1	1	1	6	Lubnina et al., 2014
<b>West Africa</b>																
WA-Ft	Fajjoud and Tadoughast Volcanics, Morocco	566 ± 6; 564 ± 6; 567 ± 5; 565 ± 5; 556 ± 5	572	551	21.9	31	15.6	1	1	1	1	0	1	1	6	Robert et al., 2017, 2018
WA-At	Adrar-n-takoucht Volcanics	572 ± 5; 570 ± 6	577	564	-57.6	295.6	15.7	1	0	1	1	0	1	1	5	Robert et al., 2017, 2018
<b>Río de La Plata</b>																
RP-Sa	Sierra de las Ánimas Magmatic Complex (bimodal igneous suite)	578 ± 4	582	574	-12.2	258.9	14.9	1	1	1	1	1	1	1	7	Rapalini et al., 2015
<b>Australia</b>																
Au-Wk	Wonoka Formation, S. Australia	Approximately 565	Fossils		-5.2	30.5	4.9	0	1	0	1	1	1	1	5	Schmidt and Williams, 2010
Au-Arl	Lower Arumbera sandstone	Approximately 570	Strati		-53.9	348.1	8.8	0	0	1	1	1	1	1	5	Mitchell et al., 2010
<b>South China</b>																
Sc-DSTm3	Doushantuo Formation Member3	570–565			-28	4.4	3.8	1	1	1	1	1	1	1	7	Zhang et al., 2015; Jing et al., 2018; reference age of Li et al., 2022
<b>Tarim</b>																
*T-Zma	Zhamoketi Formation	<600?			4.9	326.7	3.9	0	1	1	0	0	0	1	3	Zhao et al., 2014
<b>Siberia</b>																
Si-Mf	Minya Formation	<590			33.7	217.2	12.7	0	0	1	0	1	1	0	3	Kravchinsky et al., 2001
Si-Sf	Shaman Formation	<590	Fossils		32	251.1	13.8	0	1	1	1	1	1	0	5	Kravchinsky et al., 2001



**Figure 3.** Schematic depiction of plate hierarchy used in this study (with ID numbers). Lower plate is rotated relative to the one above it: Tarim position 1 (‘T1’; 12.1°N, 95.7°E, 197.3°) relative to Australia and 2 (‘T2’; 14.9°N, 109.8°E, 332.5°) relative to North China, North China (17.9°S, 309°E, 172.9°) relative to Siberia, Siberia (54.6°N, 162.3°E, -302.6°) relative to Laurentia, and South China (33.2°N, 94.5°E, 82.2°) relative to India.



**Figure 4.** Ca. 590–560 Ma inertial-interchange true polar wander (IITPW) portion of the great circle fitted by a global composite apparent polar wander path (APWP), showing the orthogonal axis  $I_{min}$  with 95% confidence ellipse. All data are shown in West African coordinates. Laurentia, Baltica, and Avalonia–Amazonia are rotated to West Africa after Robert et al. (2017, 2018) and Wen et al. (2020). Parameters of rotations to West Africa for other major continents are: East Gondwana (Australia–East Antarctica and option ‘T1’ of Tarim; 13.1°S, 311.1°E, 32.3°), India (41.4°N, 24.2°E, 302.6°), Rio de La Plata (36.1°S, 140.8°E, -64.3°), Kalahari (30.1°S, 288.6°E, -11.4°). Please see Figure 3 and main text for more details. The pole list and abbreviations are in Table. Cambrian poles from the Xinji–Wudaotang Formation (referred to as Nc–XW; Huang et al., 1999) and Hsuehuang Formation (Nc–Hf; Zhao et al., 2021) of North China are dashed and shown as a reference. Continent names are abbreviated in Figure 5.

dipole (Abrajevitch and Van der Voo, 2010), although the latter is permissible during a polarity reversal (Halls et al., 2015). For example, the advocacy of high speed (>45 cm/year) back-and-forth polar/continent motions, for the hypothesis of coaxial fields switch (Abrajevitch and Van der Voo, 2010), is inconsistent with the newly reported paleomagnetic data from West Africa (Robert et al., 2017) and Newfoundland (Wen et al., 2020). On the contrary, these paleomagnetic data may support a high-frequency rate of polarity reversals in an axial-dipole regime with low field strengths (Bono et al., 2019), but without involving orthogonal field transitions (Gissinger et al., 2012). Moreover, a stable occupation at high latitudes for Gondwana (versus low latitude for Laurentia) during the Ediacaran in the equatorial dipole model (Abrajevitch and Van der Voo, 2010) is not consistent with the stratigraphic records in West Africa, where a approximately 1000 m thick succession of shallow-marine dominated carbonates deposited (Delpomdor et al., 2015). In addition, numerical simulations suggested that axial dipoles would be generated on a giant gas planet (such as Uranus) rather than on a terrestrial planet such as Earth for very different Raylei numbers of outer core (Aubert and Wicht, 2004).

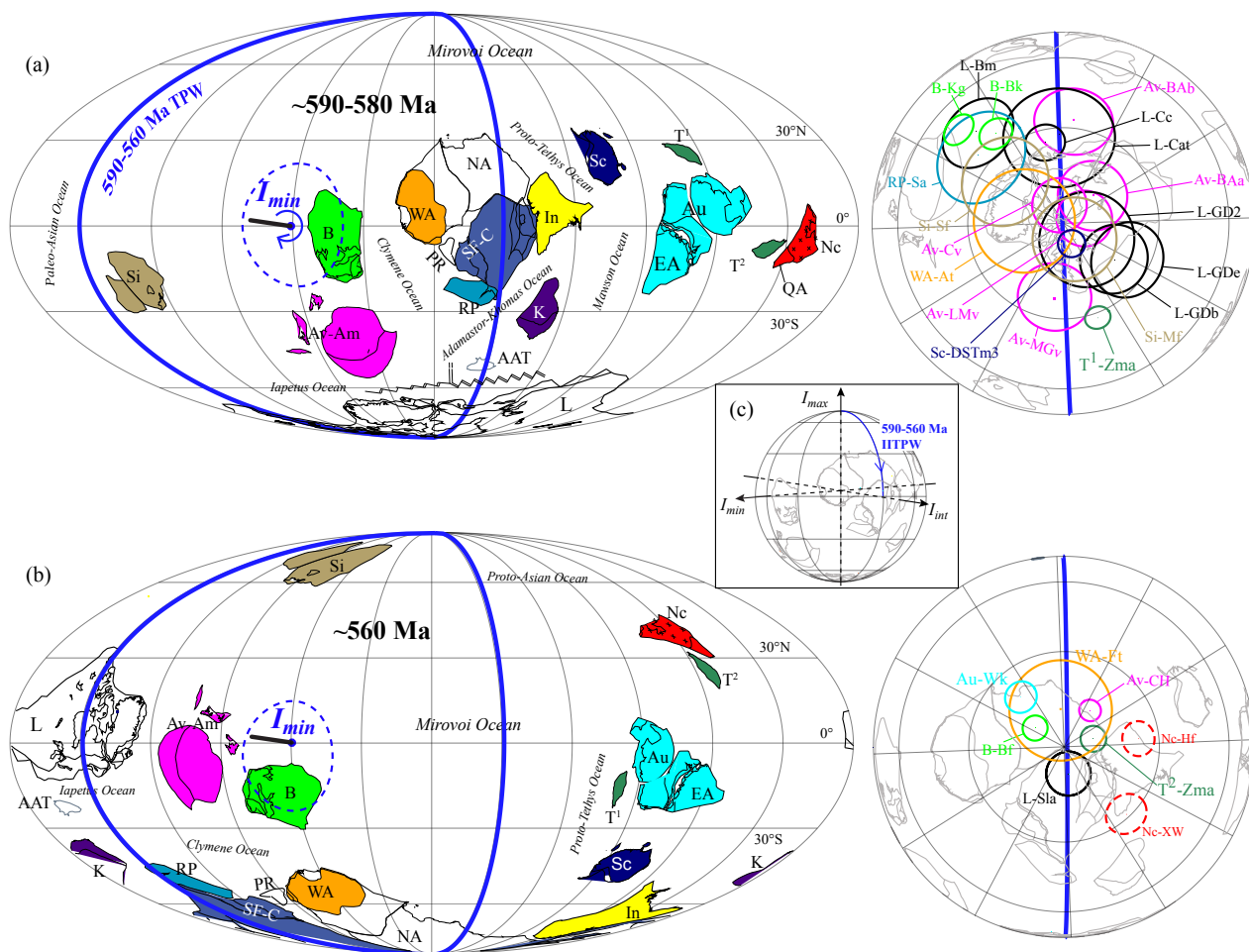
In summary, the Earth may have experienced an IITPW process during the late Ediacaran time. This process involves a wholesale rotation of the solid Earth about the liquid outer core to align Earth's maximum moment of inertia ( $I_{max}$ ) with the spin axis (Kirschvink et al., 1997), through which positive mass anomalies are quickly rotated to the equator around the minimum moment of inertia ( $I_{min}$ ) following the law of conservation of angular momentum (Evans, 2003). It commonly happened and magnified during supercontinental transitions in the Earth's history (Steinberger and O'Connell, 1997; Evans, 2003). Also, this kind of inertial interchange is not unique on Earth and also happened on other planets (known as planet reorientation), such as Mars (Perron et al., 2007). In principle, APWPs of different continents spanning an IITPW event will fit one great circle with the orthogonal axis approximating  $I_{min}$  ( $I_{max}$  and  $I_{min}$  are orthogonal; Evans, 2003). As shown in Figure 4, the great circle of the TPW event from ca. 590–580 to 560 Ma was defined by the global composite APWP in a West African reference frame and  $I_{min}$  was calculated at  $\lambda = 20.5^\circ\text{N}$ ,  $\varphi = 294.6^\circ\text{E}$ ,  $A_{95} = 21.4^\circ$  (error) in the West Africa reference frame. To sum up, the ca. 590–560 Ma paleopoles well-defined a single-robust APWP, eliminating two alternative solutions of paleogeography in this interval. Therefore, we will complete the reconstruction in a TPW framework.

### 3.2 Reconstruction

The foundation of this reconstruction is adopted from Wen et al. (2020) in which West Africa was selected as the reference frame because of its central position in Gondwana

(Figure 1; Schmitt et al., 2018). By fitting the complement paleopoles (Table) to those of the West Gondwana regime (West Africa, Avalonia-Amazonia, Laurentia, and Baltica), a TPW great circle of the global APWP and its orthogonal  $I_{min}$  are defined in the West Africa reference frame (Figure 4). Around the  $I_{min}$  axis, the entire solid Earth rotated from ca. 590–580 to 560 Ma. This is the basis for matching the coeval APWPs of individual continents during an IITPW process regardless of whether they were directly connected to each other or not. Moreover, their relative positions can be quantitatively constrained after matching their APWPs. For example, a big gap existed between Avalonia-Amazonia and the central part of Gondwana, indicating the Clymene Ocean (Figure 4; Tohver et al., 2010; McGee et al., 2015; Rapalini et al., 2015; Wen et al., 2020). Based on this principle, a continuously kinematic reconstruction in the TPW-based ('absolute') framework is achieved and two end-member segments of ca. 590–580 and ca. 560 Ma are given by coinciding the two different groups of paleopoles with the South Pole, respectively (Figure 5). Also, the locations of the  $I_{min}$  axes remaining at the equator meet the predictions in an IITPW model (Figure 5c; e.g., Kirschvink et al., 1997; Evans, 2003).

The configuration for the West Gondwana realm, including Avalonia-Amazonia, Laurentia, Baltica, and their relationships with the Central Gondwana, had been well established (discussed in Wen et al., 2020) and is used as the basic framework for the whole reconstruction in this study. For Central Gondwana, it is widely accepted that this part had been welded together by that time through two major orogenic belts: the ca. 650–620 Ma East African Orogen between Northeast Africa (Sahara), India and São Francisco-Congo (e.g., Meert, 2003; Schmitt et al., 2018) and the ca. 620–580 Ma Pan-African (Brasiliano) belt where West Africa and Río de La Plata accreted (e.g., Cordani et al., 2013; Ganade de Araujo et al., 2014; Schmitt et al., 2018). These characteristics are in good agreement with the composite APWP of three high-quality poles (WA-At, WA-Ft, and RP-Sa; Table) from both West Africa and Río de La Plata (Figure 4). To the south, although no reliable paleomagnetic data is available from Kalahari, its geological and geochronological evidence strongly supports an open ocean (Adamastor-Khomas Ocean) between Río de La Plata-Congo and Kalahari at around 580–550 Ma (e.g., John et al., 2004; Merdith et al., 2017; Schmitt et al., 2018). So, Kalahari is adjusted in an appropriate position, leaving some space for oceans around it (Figure 5). As for East Gondwana, paleomagnetic data from Australia are used to construct the whole connections of Australia-Antarctica because they shared a coherent evolution for more than 2.4 billion years until the late Cretaceous (Boger, 2011). After aligning the approximately 570–565 Ma poles (Au-Arl and Au-Wk) of Australia (Mitchell et



**Figure 5.** A kinematic paleogeography in a TPW-based (‘absolute’) framework from ca. 590–580 (a) to 560 Ma (b), showing the coincidences of paleopoles with the South Pole in different segments, respectively. The inset figure (c) illustrates the IITPW event for this interval in 3D view.  $I_{max}$ ,  $I_{int}$  and  $I_{min}$  represent the maximum, intermediate, and minimum moment of inertia, respectively. Poles and their corresponding continents are in the same color. Si, Siberia; B, Baltica; Av-Am, Avalonia-Amazonia; L, Laurentia; WA, West Africa; NA, Northeast Africa; PR, Parnaíba; SF-C, São Francisco-Congo; In, India; RP, Río de La Plata; K, Kalahari; AAT, Arequipa-Antofalla Terrane (after Escayola et al., 2011); Sc, South China; T, Tarim (with two options ‘T1’ and ‘T2’); Nc, North China; Au, Australia; EA, East Antarctica; QA, Qaidam/Qilian-Alxa block.

al., 2010; Schmidt and Williams, 2010; Robert et al., 2017) with the APWP segment of the TPW circle, a wide ocean is constrained to the Central Gondwana (Figures 4 and 5). This ocean represents the Mawson Ocean between the East and Central Gondwana, along which the East Gondwana amalgamated into the main landmass by Early Cambrian and the Pinjarra-Prydz-Denman (Kuunga) orogen formed (e.g., Meert et al., 1995; Li et al., 2008; Merdith et al., 2017; Schmitt et al., 2018; Axelsson et al., 2020).

Compared to the main Gondwana, none of the East Asian blocks (North China, South China and Tarim) have sufficient paleopoles to establish a segment of APWP (Table and Figure 4). Also, few records of the ca. 650–530 Ma multistage orogens corresponding to the assembly of Gondwana were recognized from these blocks (reviewed in

Zhao et al., 2018). Paleomagnetic data were supplemented to a composite context for a quasiquantitative constraint. Among the three blocks, only South China has a very reliable paleopole (Sc-DSTm3; Table), which was obtained from Doushantuo Formation Member 3 and represents a grand mean pole for the same rock unit across the whole block (Zhang et al., 2015; Jing et al., 2018). Its precise age (575–565 Ma) has been refined with an astrochronologic calibration and global correlation of the Shuram carbon isotope ( $\delta^{13}C$ ) excursions (Li et al., 2022). Coinciding the pole of Sc-DSTm3 with those of the ca. 590–580 Ma group, a paleolatitude of 20–30°N is indicated (Figure 5a). Then, its longitude is constrained around both India and northwestern Australia by geological evidence as most researchers proposed (Zhao et al., 2018 and references



wherein). As to the North China, it needs to move away from the northwestern margin of Laurentia in Rodinia (Li et al., 2008; Zhao et al., 2020; Ding et al., 2021) towards a position, where it acted as a biogeographic link (both *Redlichiids* and *Olenellids*) between East Gondwana (*Redlichiids*) and Laurentia (*Olenellids*) in the middle Cambrian (Zhao et al., 2021). To facilitate this migration, it should be situated somewhere in between (Figures 4 and 5), with the ca. 514–505 Ma poles (Huang et al., 1999; Zhao et al., 2021) not far from those of the ca. 560 Ma group for a reference because no Ediacaran data is available from this craton. This reconstruction is further reinforced by the geobiological data from Qaidam: (1) Both stratigraphic sequences (including the post-Gaskiers Hongtiegou glaciation) and newly discovered biotic assemblage (e.g., *Shaanxilithes*) in Qaidam suggest that this small block should stay together with North China in the late Ediacaran (Zhou et al., 2019; Pang et al., 2021); (2) The ca. 600–580 Ma plume-related magmatism in the northern margin of Qilian-Qaidam Block (Xu et al., 2015) could be a good match with the volcanic passive margin in southeastern Australia at that time (Crawford et al., 1992; Meffre et al., 2004).

For the Tarim Block, due to the lack of high-quality paleomagnetic data in this interval, its position and tectonic evolution are still controversial. Although Wang et al. (2019) reported a reliable pole from the Ediacaran strata of Sugetbrak Formation above the Marinoan-age cap carbonates in the northwestern margin of Tarim (Wen et al., 2015), its age has been well constrained at around 600 Ma or older by a series of geochronological studies (Xu et al., 2013; He et al., 2014). For an advanced solution, two ('T1' and 'T2'; Figures 4 and 5) options are discussed herein. In the conventional view, Tarim was on a periphery position during the most Neoproterozoic time: juxtaposed to somewhere in northwestern Australia or India (option 'T1') (e.g., Li et al., 2008; Merdith et al., 2017; Zhao et al., 2018). However, this position faces some challenges. First, the Tarim Block shows a more similar tectonic history and comparable stratigraphic/biological records with North China rather than with nearby South China during the late Ediacaran-early Paleozoic time. A new compilation of zircon U-Pb ages and Hf isotopic data indicated that Tarim and North China shared a similar tectonic pattern in the Early Cambrian (Han et al., 2016). Also, the deposits of late Ediacaran glaciations are well preserved in both the Tarim (Hankalchough Formation) and North China (Luoquan Formation), but not in South China (Zhou et al., 2019). Second, Tarim needs to experience complicated kinematics for its collision with the Qaidam Block and a similar tectonic pattern with North China in the subsequent evolution. In this configuration, the Tarim Block must have taken a circuitous path around northern Australia

to come together during the early to middle Paleozoic time (Han et al., 2016; Zhao et al., 2018). Third, a long connection between Tarim and northwestern Australia cannot be achieved by fitting their Neoproterozoic-early Paleozoic APWPs as pointed out by Wen et al. (2017), Huang et al. (2019), and Wang et al. (2019). As a result, an alternative position ('T2') is provided. This option could well solve the mismatches or problems above, particularly meet the requirement of comparable tectonic patterns in both the Tarim and North China (Han et al., 2016) within a large subduction-accretionary system along the margins of peri-Gondwana (Zhao et al., 2018). The detrital zircons from post-Rodinia (<720 Ma) sedimentary rocks in Tarim, showing comparable age populations with India (Wang et al., 2021), could be a result of the drainage along this vast system. More importantly, this reconstruction can facilitate Tarim's migration from its "missing-link" connection (between Australia and Laurentia) near the center of Rodinia (Wen et al., 2017, 2018; Ding et al., 2021). It is worth noting that the paleopole (T-Zma) from the ca. 615 Ma Zhamoketi andesites in northeastern Tarim (Zhao et al., 2014) is overlapped either with the ca. 590–580 Ma ('T1') or the 560 Ma ('T2') poles of other continents (Figure 5), and younger age is implied because no field test is available for its age. Of course, this uncertainty can be further constrained by getting more high-quality poles from the late Ediacaran strata of this craton. Siberia has the least controversial position relative to Laurentia. It was separated from Laurentia by ca. 600 Ma (Li et al., 2008) and situated in an isolated position until the final formation of the supercontinent Pangea (Merdith et al., 2017; Zhao et al., 2018). Using its <590 poles (Si-Sf and Si-Mf), a position is attained outside away from Laurentia (Figure 5).

#### 4. Implications and remarks on future work

As discussed above, a continuously kinematic reconstruction in a TPW-based ('absolute') framework is well illustrated (Figure 5). Through the ca. 590–560 Ma IITPW process, all the continents coherently (i.e. the entire solid Earth) underwent an amount of approximately 90° rotation around the  $I_{min}$  axis and maintained relatively stable paleogeography on the Earth's surface during the wholesale rotation, such as the Iapetus Ocean between Laurentia and Amazonia. Meanwhile, due to the same angular velocity during the rotation, Laurentia and the mainland of Gondwana along the TPW great circle (perpendicular to the  $I_{min}$  axis of rotation; Figure 5) switched their latitudes at a very high speed, while the cratons (such as Avalonia-Australia and Amazonia) close to the rotation axis only experienced a large amount of "vertical-like" rotations. As a result, the ca. 590–560 Ma IITPW event could well account for the rapid (>2°/Myr)

polar migration and a large approximately 90° latitudinal shift for Laurentia in this interval, reconciling the two alternatively 'high-latitude' and 'low-latitude' models in previous studies. Even extended back to 615 Ma, another earlier (615–590 Ma) IITPW event happened (e.g., Evans, 1998; Mitchell et al., 2011). The two IITPWs together constituted a single oscillation occurred (two back-and-forth TPW rotations) for Laurentia: low latitude at 615 Ma to high-latitude around 590–580 Ma and then back to low-latitude at 560 Ma (McCausland et al., 2007; Mitchell et al., 2011; Robert et al., 2017, 2018). Therefore, our model provides a simple mechanism to reconcile the enigmatic paleogeography in the late Ediacaran and bridges a continuous tectonic evolution prior to the final assembly of Gondwana.

Besides paleogeographic evolution, the IITPW in late Ediacaran may also provide new clues to understanding of the coevolution of Earth's system, including the internal

geodynamics and surface environment (e.g., Kirschvink et al., 1997; Steinberger and Torsvik, 2008; Mitchell et al., 2011). For example, a mid-to-high-latitude distribution spanning the IITPW process may have been the main cause of the prolonged (>20 Myr) Ediacaran glaciation from ca. 580 to 560 Ma (Wang et al., in review). Therefore, a comprehensive multi-disciplinary investigation for this interval is needed to further understand the Earth's evolution during the late Ediacaran when the metazoans sharply diversified (Xiao and Narbonne, 2020).

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