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The enduring Ediacaran paleomagnetic enigma

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ABSTRACT

The Ediacaran Period was an interval of significant global transformation, marked by major changes in the biosphere, cryosphere, hydrosphere and atmosphere, and possibly the solid Earth. A better understanding of this interval is thus important to an understanding of the diversification of complex life, the history of long-term climatic change and the evolution of global geochemical cycles. Increasingly detailed temporal records are being acquired from Ediacaran rocks to investigate these changes in time, but we still lack a robust paleogeographic framework to study them in space. Paleomagnetic data—which are used to quantitatively determine the ancient position of continents—appear unusually complex and often contradictory throughout this period. The nature of these complex data remains elusive and four distinct hypotheses have been forwarded to explain them: 1) the tectonic plates were moving especially fast, 2) many of the paleomagnetic data have been corrupted in some as-yet unrecognized way, 3) the solid Earth underwent rapid bouts of true polar wander, or 4) the magnetic field was behaving abnormally. Each of these hypotheses have far-reaching implications. Hypotheses 1, 3 and 4 reflect processes which differ dramatically from their present-day counterparts and defy prevailing paradigms of secular change, whereas hypothesis 2 raises questions about the reliability of existing paleomagnetic interpretations and their paleogeographic derivatives. Significant advances will be garnered through resolution of this enigma, but its endurance reflects its intricacy, and any solution is going to require a collective effort. With the aim to stimulate additional community efforts toward solving it, we probe these multiple working hypotheses, elaborate how they may be further tested and discuss the implications of their possible validation.

1. Introduction

The Ediacaran period (~635–539 Ma) was a particularly tumultuous time in our planet's evolutionary history. Major transformations or otherwise extreme events were observed in the biosphere, cryosphere, hydrosphere, and atmosphere (Fig. 1). With respect to the history of the biosphere, the Ediacaran is distinguished by the seemingly abrupt appearance and rapid diversification of metazoan life—i.e. the Ediacaran fauna, their extinction, and the subsequent Cambrian 'radiation' that marked the appearance of all major animal phyla in the fossil record (Conway Morris, 2006; Erwin et al., 2011; Marshall, 2006; Xiao and Laflamme, 2009). In the cryosphere, the Ediacaran marked the transition out of protracted and global-scale glaciations ('Snowball Earth') that had come to characterize Earth in the preceding Cryogenian Period (Hoffman and Schrag, 2002). Ediacaran geochemical records likewise reflect significant changes in the hydrosphere and atmosphere, including the most deeply negative carbon isotope excursion yet known in Earth history, and possibly the rise of atmospheric oxygen to present-day levels (Canfield et al., 2007; Grotzinger et al., 2011; Macdonald et al., 2013). An understanding of these Ediacaran events is thus critical to an understanding of the diversification of complex life, the history of climatic change and the evolution of global geochemical cycles. It is

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therefore important to place these records in a proper spatiotemporal context. However, while ever more detailed temporal records of those changes are being assembled, we still lack a first-order understanding of their absolute spatial framework. This is because Ediacaran paleomagnetic data, which would normally be used to establish global paleogeography, have consistently exhibited complex to contradictory behavior that remains enigmatic.

The use of paleomagnetism to identify past plate motions, based on the assumption that Earth's magnetic field can be approximated as a geocentric axial dipole (GAD), helped kick-start the plate tectonic revolution (Creer et al., 1957; Runcorn, 1962), and in the six subsequent decades has allowed mapping of the wanderings of the major continents through the Phanerozoic (Besse and Courtillot, 2002; Irving, 1977; Torsvik et al., 2012). One key observation that emerged from that effort is that paleomagnetic directional changes since the Cambrian are smoothly varying (accounting for polarity reversals) and, when converted to paleomagnetic poles, reflect plate motion rates of <20 cm a^{-1} (Fig. 1d) (Torsvik et al., 2012; Zahirovic et al., 2015). Such rates are consistent with the motions of plates since ~130 Ma, which are known from marine magnetic anomalies and hotspot tracks (Doubrovine et al., 2012; Müller et al., 1993).

In contrast to Phanerozoic paleomagnetic data, Ediacaran paleomagnetic results from multiple continents exhibit abrupt directional variations that seem to imply minimum rates of continental drift in excess of 35 cm a^{-1}, and possibly much higher (Fig. 1d) (Abrajevitch and Van der Voo, 2010; Halls et al., 2015; Evans, 1998; Meert, 2014; Robert et al., 2017). Such rates are nearly twice the fastest plate motion determined from the last 130 Ma and may exceed the ill-defined plate 'speed limit'. This has spurred the pursuit of other explanations for these data, to which there are at least three alternatives (Fig. 2): many of the paleomagnetic data have been corrupted in some way (Bono and Tarduno, 2015; Hodych et al., 2004), the planet experienced rapid bouts of true polar wander (TPW) (Evans, 1998; Robert et al., 2017), or the geomagnetic field was behaving anomalously (Abrajevitch and Van der Voo, 2010; Halls et al., 2015). Each of these alternative hypotheses has significant implications for geophysics and/or paleogeography. Critically, they also present differing predictions for how paleomagnetic changes should manifest through time and space and are thus testable and discriminable. Several earlier studies have enumerated ways in which some of these hypotheses could be tested or distinguished from one another (Abrajevitch and Van der Voo, 2010; Halls et al., 2015; Robert et al., 2017). However, given the persistence of this enigma despite more than a decade of scrutiny and new infusions of data, as well as the continued invocation of these different mechanisms to derive

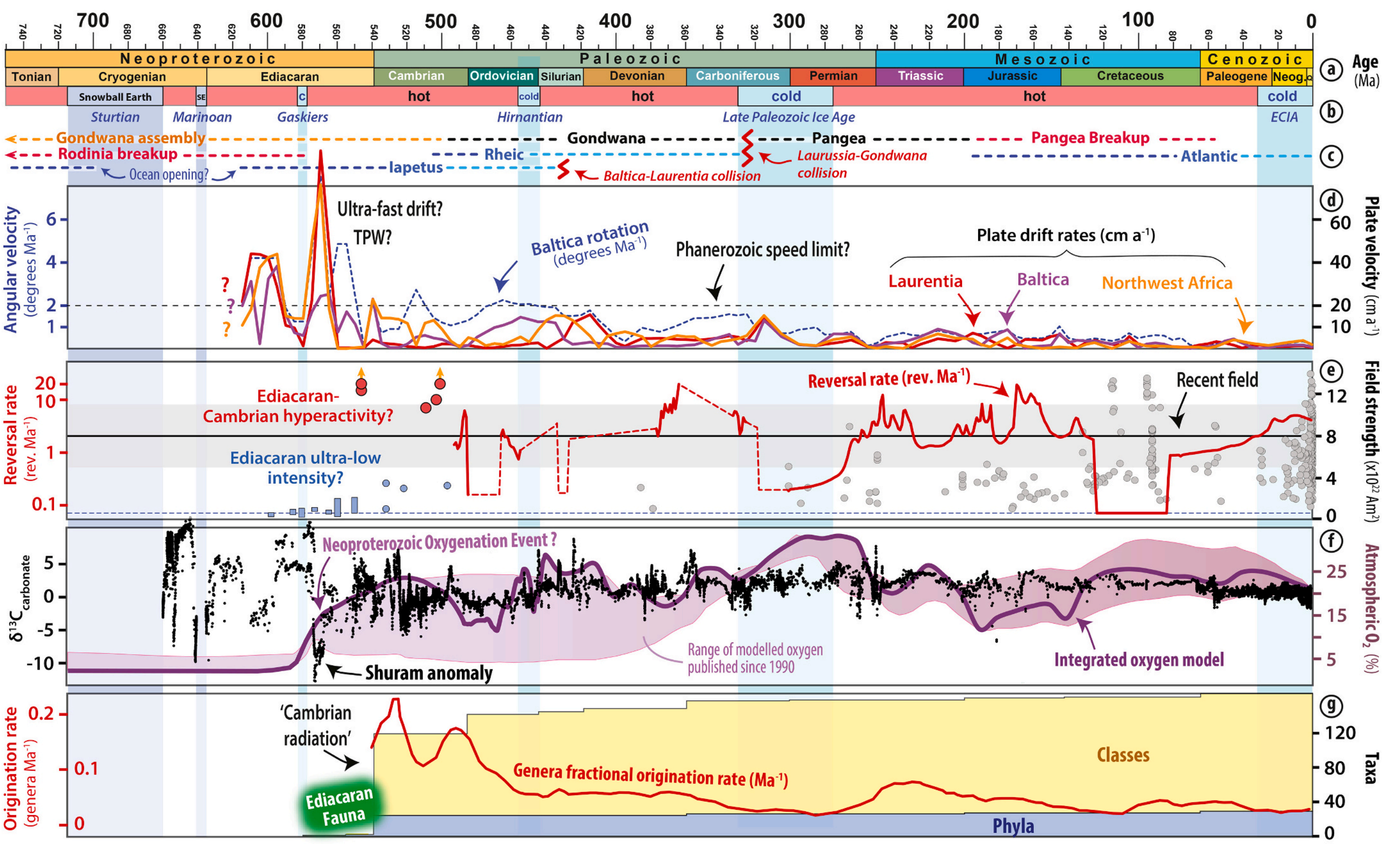

Fig. 1. Summary of some major climatic, tectonic, geomagnetic, geochemical and biologic changes since the Cryogenian. a) Geologic time. b) Climate modes and snowball Earth/Icehouse episodes (Hoffman and Schrag, 2002; Torsvik and Cocks, 2017). c) Major tectonic events (Torsvik and Cocks, 2017). d) Plate speeds and rotation rates for 3 major continents (Laurentia, Northwest Africa and Baltica) determined from the models of Torsvik et al. (2012) [0–540 Ma] and Robert et al. (2017) [540–620 Ma]. e) Reversal rates: red solid/dashed line = Phanerozoic observations/inferences (Hounslow et al., 2018), red circles = Ediacaran-Cambrian estimates (Bazhenov et al., 2016; Duan et al., 2018; Gallet et al., 2019; Kouchinsky et al., 2008; Meert et al., 2016; Shatsillo et al., 2015), and paleointensity estimates: solid black line with grey envelope = recent field intensity, grey circles = Phanerozoic estimates summarized by Bono et al. (2019), blue bars (circles) = Ediacaran (Cambrian) estimates summarized in Lloyd et al. (2022), Thallner et al. (2022) and Zhou et al. (2022). f) Carbon isotopic records from the Phanerozoic (Saltzman and Thomas, 2012; Shields et al., 2019), Ediacaran (Rooney et al., 2020) and Cryogenian (Park et al., 2020), and a range of modelled oxygen curves (since 1990). Also shown is an integrated oxygen model based on Lyons et al. (2014) for the Cryogenian and parts of the Ediacaran, and after 570 Ma calculated from GEOCARBSULF using the parameterization in Marcilly et al. (2021; model 12). This integrated curve is very similar to that reported in Royer et al. (2014). g) Diversity in the biosphere since the Ediacaran (Cornette et al., 2002; Erwin et al., 2011). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

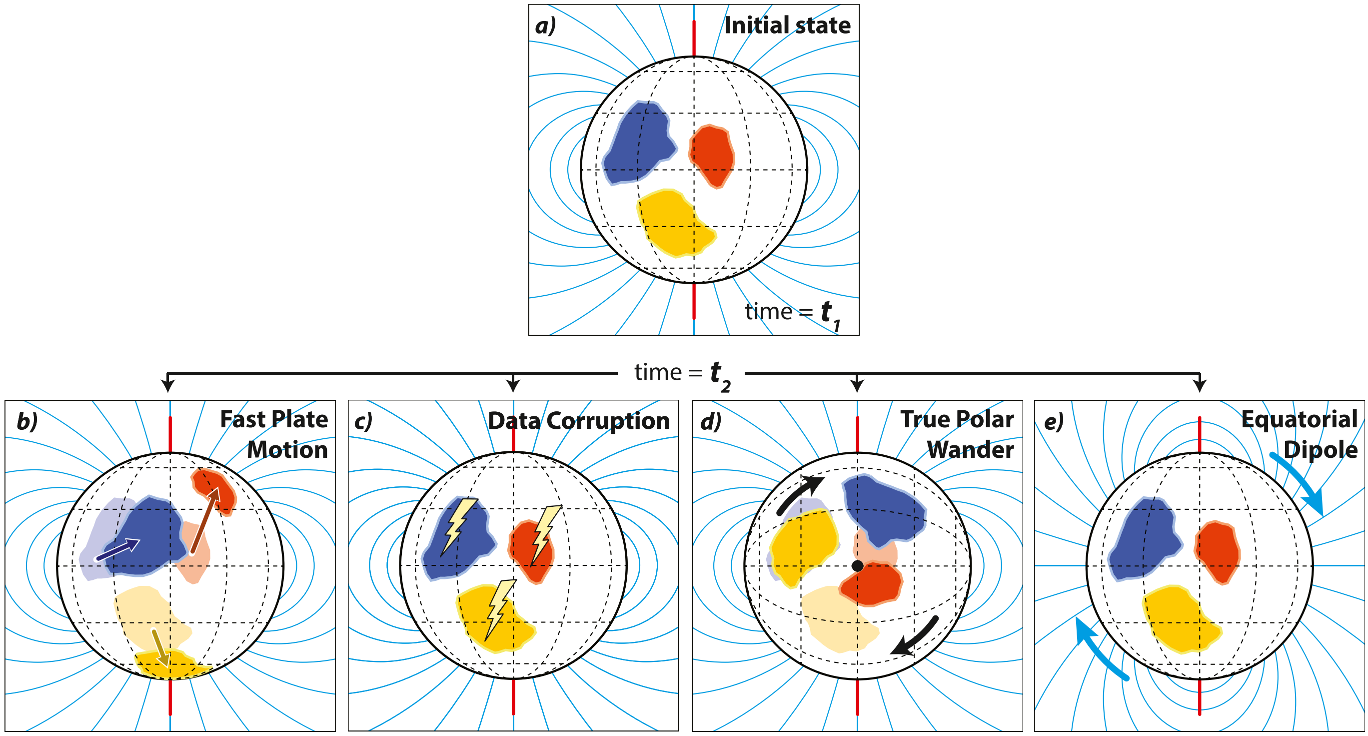

Fig. 2. Alternative hypotheses to explain complex Ediacaran paleomagnetic data. a) Initial geographic position (at time = t_1) of three continents (blue, red and yellow polygons). Light blue lines depict the magnetic dipole which is here aligned with the planetary spin-axis (red line). b-e) Alternative positions of the continents at some later time = t_2, according to different proposed mechanisms: b) Fast plate motion; c) Data-corruption (continents have not significantly moved but paleomagnetic records have been perturbed); d) True polar wander (black arrows show sense of rotation of the entire solid Earth about the true polar wander axis [black dot on equator]); e) Equatorial dipole (the continents have not significantly moved, but the blue arrows show that the axis of the dipole field has been repositioned to the equatorial plane). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

contrasting paleogeographic models, we consider it worthwhile to revisit and expand on these hypothesis tests.

2. Paleomagnetic observations

Our intention here is not to exhaustively detail the presently available Ediacaran paleomagnetic data, as have already been amply dissected by several other contributions (e.g. Abrajevitch and Van der Voo, 2010; McCausland et al., 2007; Meert, 2014; Robert et al., 2017), but rather to highlight specific constraints that characterize the problem and enable consideration of the alternative hypotheses. We focus on relatively rich datasets from Laurentia, Northwest Africa and Baltica (Table 1), but note that multiple Ediacaran paleomagnetic data are also available from several other continents, including Australia (e.g. Kirscher et al., 2021), Rio de la Plata (e.g. Rapalini et al., 2021) and Siberia (e.g. Vinogradov et al., 2023). A striking characteristic of the datasets from each of these continents is that their paleomagnetic poles (hereafter 'paleopoles') appear to form two or more populations that are disparate in space, but very close or even indistinct in age (Fig. 3). Note that there are also indications from the paleomagnetic records of some continents that this behavior may continue into the early Cambrian (e.g. Meert, 2014; Pavlov et al., 2018).

In Laurentia, these groups have conventionally been associated with observed 'steep' vs. 'shallow' paleomagnetic directions that are nearly orthogonal to one another, and in some instances these different directional populations have been reported to co-exist in the same lithologic units (Halls et al., 2015; McCausland et al., 2011; Meert et al., 1994; Murthy, 1971; Tanczyk et al., 1987). In the case of the Grenville dikes, Halls et al. (2015) reported steep directions from a dike dated to 587.3 ± 0.7 Ma (Key River dike; GDb in Fig. 3) and shallow directions from dikes dated to 585.2 ± 0.8 Ma (Sand Bay dike; GDd) and 584.8 ± 0.6 Ma (Augusta Lake dike; GDc). If primary, those records imply apparent polar wander (APW) at a rate of ~48° Ma^{-1}. However, the primary nature of the shallow magnetic directions has not been demonstrated by paleomagnetic field tests, so the possibility that they are younger remagnetizations cannot be excluded. It is moreover prudent to be cautious about the interpretation of data from individual cooling units that likely have not averaged paleosecular variation. Nevertheless, co-existing steep and shallow directions have also been observed in the 583 ± 2 Ma Baie des Moutons complex (BMa, BMb) (McCausland et al., 2011), 572 ± 5 Ma Catoctin volcanics (CTa, CTb) (Meert et al., 1994) and 565 ± 4 Ma Sept-Îles intrusion (SIa, SIb) (Tanczyk et al., 1987). Steep directions are also found in the 577 ± 1 Ma Callander complex (CC) (Symons and Chiasson, 1991), whereas unambiguously shallow directions are reported from the 550 ± 3 Ma Skinner Cove volcanics (SC) (McCausland and Hodych, 1998). Various interpretations of those multi-component units have been formulated and debated, but irrespective of which components are deemed primary (further discussed in section 3.2), the data imply late Ediacaran APW rates in excess of 4° Ma^{-1} (Fig. 3b). Although of poor precision, an early Ediacaran paleomagnetic result from the 615 ± 2 Ma Long Range dikes (LR) (Murthy et al., 1992) gives a pole position similar to that of Skinner Cove, such that Laurentia's Ediacaran apparent polar wander path (APWP) exhibits a sharp, 'hairpin' shape from 615 to 550 Ma (McCausland et al., 2007; Robert et al., 2017) (Fig. 3a).

The most reliable Ediacaran paleomagnetic data from Northwest Africa similarly appear to trace out an oscillatory APWP from ~615 to 565 Ma (Fig. 3c). A steep direction from the 613 ± 3 Ma Adma diorite (AD) is followed by shallow directions recorded in the 577–564 Ma Adrar-n-Takoucht volcanics (AT) and then steep directions in the 572–551 Ma Fajjoud and Tadoughast volcanics (FT) (Robert et al., 2017). When transformed to paleopoles, those results imply minimum rates of APW in excess of 4° Ma^{-1} (Fig. 3d). Note that while the polarity of pole AT is ambiguous, we prefer the option depicted in Fig. 3c because

Table 1
Ediacaran–Cambrian paleomagnetic poles from Laurentia, Northwest Africa and Baltica.

Unit	Comp.	Tag	Reference	Age	Error	N	Plat	Plon	K	A95	Notes
LAURENTIA											
APWP @ 500		500	Torsvik et al. (2012)	500	10	8	−3.8	344.5	80.2	6.2	
APWP @ 510		510	Torsvik et al. (2012)	510	10	4	−1.1	345.6	51.6	12.9	
Mont Rigaud & Chatham-Grenville intrusion		MR	McCausland et al. (2007)	532	2	15	12.4	4.6	43.24	5.9	Recalculated from site-level VGPs
Skinner Cove volcanics		SC	McCausland and Hodych (1998)	550	3	10	−14.8	337.1	31.1	8.8	Recalculated from site-level VGPs
Sept-Iles intrusion	A	SIa	Tanczyk et al. (1987)	565	4	10	−19.7	321.3	56.9	6.5	Recalculated from site-level VGPs
Sept-Iles intrusion	*B*	*SIb*	Tanczyk et al. (1987)	*565*	*4*	*16*	*59.4*	*295.8*	*15.9*	*9.5*	Recalculated from site-level VGPs
Catoctin volcanics	A	CTa	Meert et al. (1994)	575	5	8	41.6	291.4	16.2	14.2	Recalculated from site-level VGPs
Catoctin volcanics	*B*	*CTb*	Meert et al. *(1994)*	*575*	*5*	*9*	*3.8*	*3.5*	*27.9*	*9.9*	Recalculated from site-level VGPs
Callander complex		CC	Symons and Chiasson (1991)	577	1	26	46.5	300.9	24.8	5.8	Recalculated from site-level VGPs
Baie des Moutons complex	A	BMa	McCausland et al. (2011)	583	3	8	42.9	331.9	24	11.5	Recalculated from site-level VGPs
Baie des Moutons complex	*B*	*BMb*	McCausland et al. *(2011)*	*583*	*3*	*6*	*−33.9*	*321.9*	*19.2*	*15.7*	Recalculated from site-level VGPs
Grenville dikes (Augusta Lake dike)	*C*	*GDc*	Halls et al. *(2015)*	*584.8*	*0.6*	*2*	*−13.4*	*330.1*	*58.9*	*33.1*	Recalculated from site-level VGPs
Grenville dikes (Sand Bay dike)	*D*	*GDd*	Halls et al. *(2015)*	*585.2*	*0.8*	*3*	*0.1*	*338.4*	*86.3*	*13.4*	Recalculated from site-level VGPs
Grenville dikes (Mattawa dike)	E	GDe	Hyodo and Dunlop (1993)	586	4	28	48.3	237.2	7.7	10.5	Recalculated from sample-level VGPs
Grenville dikes (Key River dike)	B	GDb	Halls et al. (2015)	587.3	0.7	5	59.6	226.1	20.5	17.3	Recalculated from site-level VGPs
Grenville dikes	1 (A)	*GD1*	Murthy *(1971)*	*590*	*2*	*11*	*3.1*	*331*	*14.8*	*12.3*	Recalculated from site-level VGPs
Grenville dikes	2 (B)	GD2	Murthy (1971)	590	2	12	61.8	248.9	7.7	16.7	Recalculated from site-level VGPs
Long Range dikes		LR	Murthy et al. (1992)	615	2	5	29.1	354.5	6.9	31.5	Recalculated from site-level VGPs
NORTHWEST AFRICA											
APWP @ 500 [NW Afr coords*]		500	Torsvik et al. (2012)	500	10	10	25.8	6.1	21.38	10.7	*restored by Euler pole: [33.6, 26.0], −2.3
APWP @ 510 [NW Afr coords*]		510	Torsvik et al. (2012)	510	10	9	17.6	3.7	44.46	7.8	*restored by Euler pole: [33.6, 26.0], −2.3
APWP @ 520 [NW Afr coords*]		520	Torsvik et al. (2012)	520	10	11	14.5	−3	25.38	9.2	*restored by Euler pole: [33.6, 26.0], −2.3
Djebel Boho volcanics		DB	Robert et al. (2017)	536.5	10.5	16	27.3	27.1	7.12	14.9	Recalculated from site-level VGPs
Fajjoud & Tadoughast volcanics		FT	Robert et al. (2017)	561.5	10.5	20	21.9	31	5.34	15.6	Recalculated from site-level VGPs
Adrar-n-takoucht volcanics		AT	Robert et al. (2017)	570.5	6.5	9	−57.6	295.6	11.74	15.7	Recalculated from site-level VGPs
Adma diorite		AD	Morel (1981)	613	3	13	32.6	344.8	7.83	15.8	Recalculated from site-level VGPs
BALTICA											
APWP @ 480		480	Torsvik et al. (2012)	480	10	7	23.4	52.9	109.9	5.8	
Narva sediments	C	NS	Khramov and Iosifidi (2009)	500	15	14	22	87	46.7	5.5	K estimated from A95 (from dp/dm) and N.
Zigan Fm. (clastic rocks)	C	ZN	Levashova et al. (2013)	547.6	3.8	36	15.8	318.7	34.6	4.1	Recalculated from site-level VGPs
Zolotica sediments	B	Z1	Iglesia Llanos et al. (2005)	550	5.3	57	28.3	290	23.8	3.8	K estimated from A95 and N.
Zolotica sediments	Z	Z2	Popov et al. (2005)	550	5.3	234	31.7	292.9	19.4	2.1	K estimated from A95 (from dp/dm) and N.
Verkhotina sediments	Z	VS	Popov et al. (2005)	550	5.3	322	32.2	287.1	15.6	2.0	K estimated from A95 (from dp/dm) and N.
Winter Coast sediments	Z	WC	Popov et al. (2002)	555	0.3	94	25.3	312.2	24.5	2.9	K estimated from A95 (from dp/dm) and N.
Chernokamenskay Gr.	C	CH	Fedorova et al. (2014)	557	13	19	17.6	306.7	36.0	5.7	Recalculated from site-level VGPs
Podolia	P2	PO	Iosifidi et al. (2005)	557.5	12.5	7	41.2	274.4	144.6	5	Recalculated from site-level VGPs
Basu Fm.		BA	Levashova et al. (2015)	573	2.3	24	−1.7	6.1	62.4	3.8	Recalculated from site-level VGPs; age from Razumovskiy et al. (2020)
Kurgashlya Fm.		KF	Lubnina et al. (2014)	585	15	44	50.9	314.5	15.8	5.3	K estimated from A95 (from dp/dm) and N.
Bakeevo Fm.		BK	Lubnina et al. (2014)	585	15	48	42.3	299.1	14.8	5.3	K estimated from A95 (from dp/dm) and N.
Egersund dikes		ED	Walderhaug et al. (2007)	616	3	9	34.2	42.7	12.3	15.2	Recalculated from site-level VGPs

Comp: component label assigned by original authors; Tag: label assigned to pole in Fig. 3; Age: mean age (in Ma); Error: 2σ error associated with mean age (normally distributed). Underlined entries are uniformlly distributed and give the uniform range from the mean age. N: number of contributing observations (sites or samples). Plat/Plon: paleolatitude/paleolongitude of paleopole. K/A95: precision parameter/cone of 95% confidence of paleopole. Italicized rows are data denoted by open circles in Fig. 3.

it agrees better with contemporaneous paleomagnetic data from elsewhere in Gondwana (Robert et al., 2017). Moreover, this polarity choice for the poles of Gondwana allows a paleogeographic reconstruction relative to Laurentia that is consistent with conventional models of Rodinia breakup (Fig. 4a; Li et al., 2008). This polarity option is associated with a larger arc distance between the AT and FT poles, but adoption of the opposite polarity for AT also yields extremely fast rates of APW (Supp. Fig. S4).

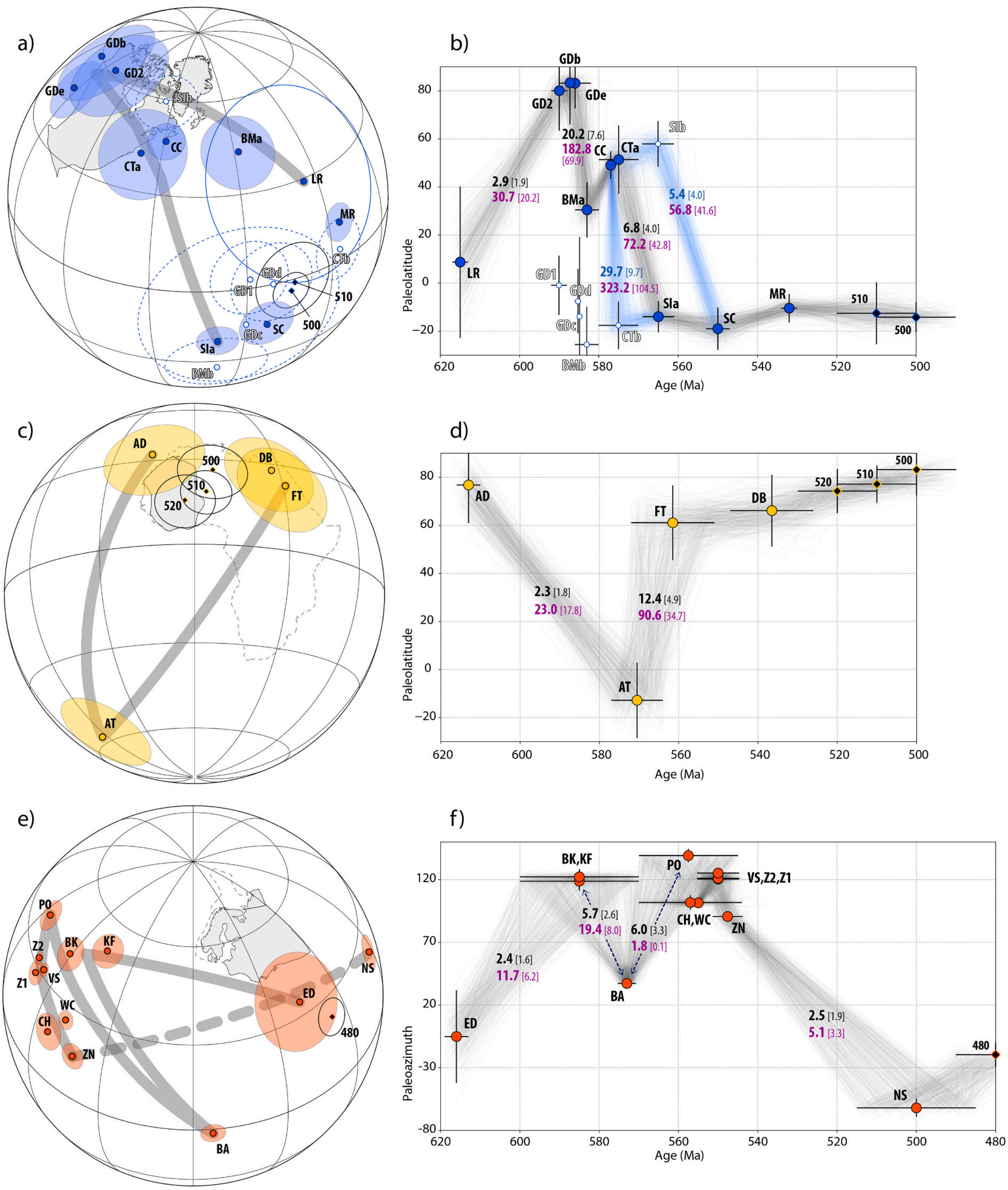

Fig. 3. Ediacaran and Cambrian paleomagnetic data discussed in text. a) Paleopoles from Laurentia and a simplistic APWP (grey path). Pole abbreviations correspond to labels assigned in Table 1. Poles denoted with dashed A_{95} envelopes are not considered in the APWP shown; their inclusion would require much higher rates of oscillatory APW. Poles denoted with black diamonds are Cambrian mean poles from Torsvik et al. (2012). b) The Laurentian paleomagnetic data cast into a paleolatitude vs. time plot, using an arbitrary reference point of 55°N/235°E. The grey lines connecting the solid blue poles show 500 realizations of Monte Carlo simulations of the APWP, wherein each constituent pole is re-drawn from a Fisher distribution with the same mean and K, and its associated age is re-drawn from a normal or uniform distribution with the same mean and standard deviation as the observed age estimate. The black values reported for select segments of the Monte Carlo paths are median APW rates (reported in degrees Ma^{-1}) from 10,000 draws (the lower 95% confidence bound is reported in brackets). The purple values report the corresponding linear drift rate (in cm a^{-1}) of the centroid. Blue strands show two alternative paths incorporating either the shallow Catoctin result or the steep Sept-Iles result. c-d) The same as in a-b) but for data from Northwest Africa and using a reference point of 30°N/0°E. e-f) same as in a-b) but for data from Baltica. However, note that the poles in panel f) are plotted in terms of paleoazimuth (relative to point 60°N/40°E) rather than paleolatitude. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

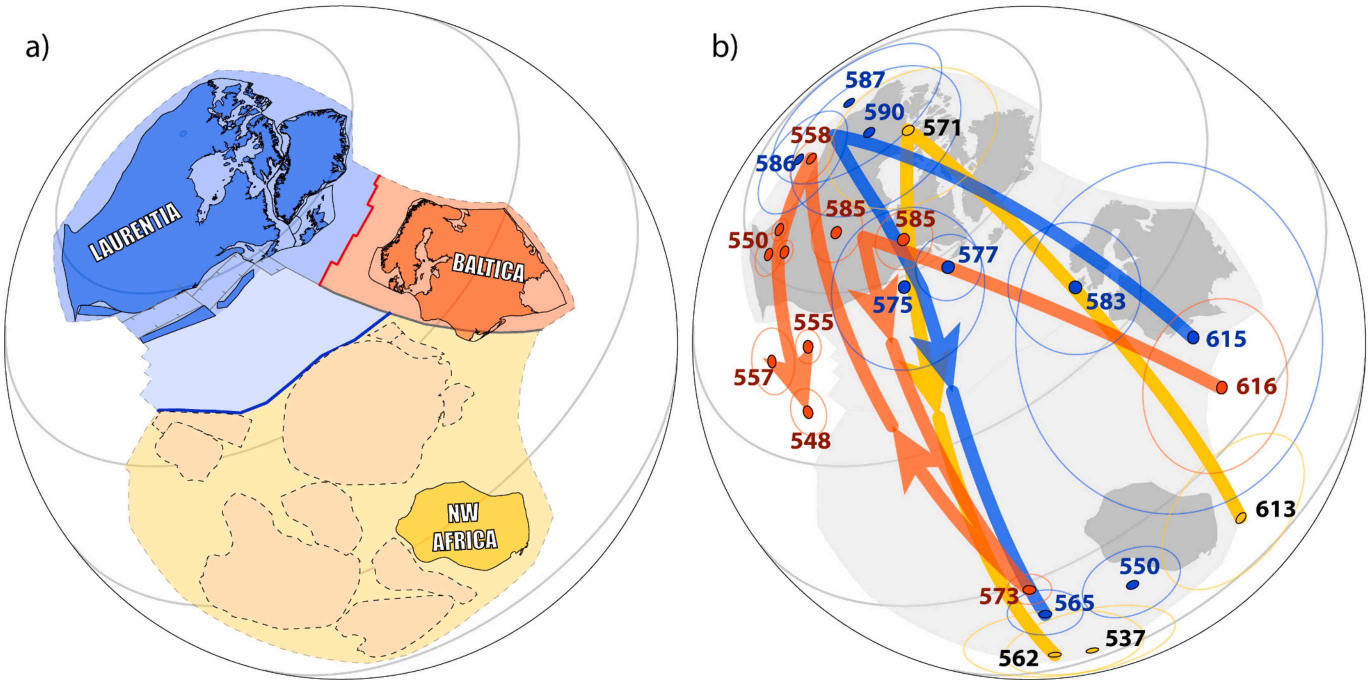

Fig. 4. a) Mid-Ediacaran (590 Ma) reconstruction of Laurentia, Baltica and Northwest Africa (together with some other blocks of proto-West Gondwana as dashed outlines) after Robert et al. (2021). The relative position of the continental blocks is supported by geologic observations and inferences (i.e. independent of paleomagnetism), but they are together reconstructed in a paleomagnetic reference frame using data from the Grenville dikes (see Robert et al., 2021). b) The Ediacaran paleomagnetic poles from Laurentia (blue), Baltica (red) and Northwest Africa (yellow) and their simplified APWPs, as shown in Fig. 3, reconstructed according to panel a. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The situation appears yet more complex in Baltica, where the Ediacaran to middle Cambrian APWP oscillates two times across half a hemisphere: one oscillation occurs from ~615 to 573 Ma, and then a second from 573 to 500 Ma (Fig. 3e). The dataset from Baltica further differs from that of Laurentia and Northwest Africa in that the reliable paleopoles are mostly derived from sedimentary rocks. The only reliable pole from an igneous unit is the oldest one—from the 616 ± 3 Ma Egersund dikes (ED) (Walderhaug et al., 2007). From there, the APWP swings >65° to the next youngest poles reported from mid-Ediacaran sedimentary rocks in the South Urals (BK, KF) (Lubnina et al., 2014). The APWP subsequently swings ~75° between 585 and 573 Ma before swinging back ~90° by 555 Ma (Levashova et al., 2015). A final ~90° swing in the APWP then occurs between 550 and 500 Ma, although the middle and late Cambrian segments of the path are poorly defined (Meert, 2014). Again, these directional changes imply rates of APW in excess of 4° Ma^{-1} (Fig. 3f).

Summarizing these observations: possibly coincident episodes of very rapid (> 4° Ma^{-1}) APW are documented from multiple independent continents in the Ediacaran, and the associated APWPs from these continents exhibit similar, oscillatory trajectories. Interestingly, if these three continents are relatively re-positioned so that their APWPs broadly align (Fig. 4), we arrive to a geologically justifiable paleogeography following Rodinia breakup (Robert et al., 2021); although it is important to emphasize that this result is dependent on our polarity determinations, which are not strictly known. We now turn to consider the alternative hypotheses that have been formulated to explain these observational records (Fig. 2). To ease this discussion, we will draw on the results of some toy kinematic models, whose setup is described in the Supplementary Materials.

3. Principal hypotheses: predictions, appraisals & implications

3.1. Fast plate motion

According to this hypothesis, the rapid Ediacaran paleomagnetic directional changes can be interpreted in the conventional way—that they faithfully record the motion of tectonic plates relative to a stable GAD field (Meert et al., 1993). It also implies that the bulk of the paleomagnetic signal is attributable to differential plate motion, rather than TPW. Given the observational data presented above (Table 1), this hypothesis suggests that multiple plates drifted at rates of ≥35 cm a^{-1} during the Ediacaran; is this reasonable?

The velocity of plates is governed by the balance of forces acting on their boundaries and the shear tractions exerted on their base by the convecting mantle below (Forsyth and Uyeda, 1975). Analyses of modern plate motions and efforts to numerically reproduce them have revealed the velocity of plates to be largely controlled by the sinking of lithospheric slabs through the upper mantle (Conrad and Lithgow-Bertelloni, 2002), suggesting that plate speeds should not generally exceed the rate at which slabs can sink. Considering a range of upper mantle viscosities and slab densities, Goes et al. (2008) estimated maximum modern upper mantle slab sinking velocities to be on the order of 5–15 cm a^{-1}, comparable to the velocities of subducting oceanic plates at present-day (Zahirovic et al., 2015). Owing to the secular cooling of the mantle, convection was likely more vigorous in the geologic past, and the rate of slab sinking could have been higher in the Precambrian. However, this does not necessarily mean that plates moved faster because modern slab pull forces may already be close to the yield strength of cold lithosphere (Conrad and Lithgow-Bertelloni, 2002), and slabs descending into a hotter mantle could lose their coherence by dripping (Fischer and Gerya, 2016) or break-off (van Hunen and van den Berg, 2008). A hotter, less viscous mantle would also have reduced convective stresses that could have inhibited plate tectonics (Moresi and Solomatov, 1998; O'Neill et al., 2007). For example, O'Neill et al. (2007) showed that fast plate motions (up to 25 cm a^{-1}) could occur on a hotter Earth episodically transitioning between mobile- and stagnant-lid tectonic regimes, but a still hotter mantle led to a shutdown of differential plate motion.

These inferences assume that the effective yield stress of the lithosphere has remained constant through time. When the lithosphere subducts, it is subjected to resistive forces associated with its bending, and by coupling of the subducting and overriding plates along the subduction interface (Behr and Becker, 2018; Conrad and Hager, 1999). Because these resistive forces are confined to the lithosphere, they are largely insensitive to the temperature and viscosity of the mantle, and so could have imposed the same effective speed limit on plates in the past, even if the mantle was convecting more vigorously (Conrad and Hager, 1999). The contribution of plate bending to the dissipation of the total energy available to drive subduction is now thought to be minor (Buffett and Becker, 2012), but changes in the friction coefficient along subduction zones could play a major role in modulating the effective strength of the lithosphere (Behr and Becker, 2018; Behr et al., 2022), enabling plate motion under lower convective stresses (or faster plate motions under the same convective stresses). Sobolev and Brown (2019) proposed that the intermittent accumulation of sediments in trenches acts to lubricate subduction zones and noted that the 'Snowball Earth' glaciations immediately preceding the Ediacaran were associated with unprecedented rates of global crustal erosion (Keller et al., 2019) that could have mechanically weakened plate boundaries globally.

The fastest motion of a large plate that is recorded by paleomagnetic data but also independently well-constrained (by marine magnetic anomalies) is that of India in the Late Cretaceous-early Paleogene, which briefly approached a speed of 18 cm a^{-1} (Cande and Stegman, 2011; Klootwijk et al., 1992; Patriat and Achache, 1984). That swift motion of India has been related to a mantle plume (Cande and Stegman, 2011; van Hinsbergen et al., 2011) and a 'double subduction' system (Jagoutz et al., 2015), but the effects of both are spatially exceptional. The impingement of a mantle plume on the base of a plate can accelerate its velocity both by exerting a viscous drag from below, but also through tilting of the plate, causing it to slide down a gravitational potential (Eagles and Wibisono, 2013; van Hinsbergen et al., 2011). However, these contributions will only endure while the high plume flux lasts and while the plate remains proximal to the plume conduit from which it is being driven, and the net effect may only augment plate speed by a few cm a^{-1} (van Hinsbergen et al., 2011). Likewise, numerical simulations of 'double subduction' systems (the coupling of two closely spaced subduction zones of the same polarity), have shown they can achieve elevated convergence rates relative to single subduction systems, but they have not yielded plate speeds beyond ~12 cm a^{-1} (Pusok and Stegman, 2020). The subduction zones in double subduction systems moreover have to be close enough to enable coupling, but as they evolve toward one another the viscous pressure between the slabs grows (inhibiting subduction), and ultimately they will collide (Jagoutz et al., 2015; Pusok and Stegman, 2019).

Looking into deeper time, the recognition of fast plate speeds becomes more challenging and ambiguous owing to limitations in the paleomagnetic record and the difficulty of distinguishing between signals of differential plate motion and TPW. However, a particularly rich and temporally well-resolved record of paleomagnetic data derived from rocks of the late Mesoproterozoic Midcontinent Rift in North America enabled Swanson-Hysell et al. (2019) to estimate that Laurentia reached rates of differential plate motion (i.e. excluding TPW contributions) of 20 to 30 cm a^{-1} between 1109 and 1083 Ma. Swanson-Hysell et al. (2019) attributed that fast plate motion to a 'slab avalanche'—a sudden foundering of slab material that had accumulated at the boundary between the upper and lower mantle. Seismic tomography has shown that some slabs stagnate at this boundary (Fukao and Obayashi, 2013), and slab avalanches have been observed in numerical convection models (O'Neill et al., 2015; Tackley et al., 1993; Zhong and Gurnis, 1995). However, hypothesized examples of such events in the Phanerozoic are associated with much lower plate speeds (East et al., 2020; Pysklywec et al., 2003; Yang et al., 2018). It remains unclear what plate speeds such events could have instigated in the Precambrian, and for how long those plate speeds could have been maintained. Moreover, as with double subduction, fast plate motion associated with a slab avalanche event would be effectively restricted to the subducting plate itself, unless it otherwise triggered or coincided with some catastrophic transition in the style of global mantle convection (Condie, 1998; Stein and Hofmann, 1994).

Turning to considerations of the Ediacaran specifically, Zahirovic et al. (2015) suggested that the swiftly moving continents (hosting the enigmatic paleomagnetic data) could have been embedded within larger, dominantly oceanic plates. This could explain velocities modestly larger than those typical for modern continents but cannot explain speeds in excess of modern slab sinking rates in the upper mantle. Alternatively, Gurnis and Torsvik (1994) suggested that the high speeds could have been reached by thick continents whose keels became anchored in swift convective currents in the lower mantle. Although this circumvents the rate-limitations imposed by sinking slabs, the convective vigor required to increase continental (plate) speeds by ~20 cm a^{-1} via this mechanism necessitates lateral mantle temperature gradients of some 500 K (Gurnis and Torsvik, 1994). By contrast, estimates of large-scale thermal gradients arising from known plate-mantle dynamics, for example by supercontinent insulation, are an order of magnitude smaller (Gurnis and Torsvik, 1994; Karlsen et al., 2021).

3.1.1. *Predictions & appraisals*

The fast plate motion hypothesis predicts that Ediacaran paleomagnetic directional changes, visualized as paleopoles, should generally trace small- to great-circle segments (Fig. 5c), as is typical for paleomagnetic records of plate motion in the Phanerozoic (Gordon et al., 1984). This is because the Euler poles that describe individual plate motions are locally determined by plate boundary forces, and so are not confined to the equatorial plane (in contrast to the axis of TPW; section 3.3). In the absence of rapid, large amplitude TPW, the trajectories and change points of individual plate motions should be uncorrelated (Fig. 5a,b), excepting coincident changes arising from regional plate reorganizations. Without excluding the possibility of synchronous changes to the background average plate speed—for example, following changes in the sediment loading of trenches, globally—this hypothesis also predicts each plate to drift at its own rate, individually relatable to its network of plate boundaries. Thus, a collection of APWPs from distinct plates should be largely uncorrelated in both space and time (Fig. 5c,d and Supp. Figs. S2, S3). There is no reason to expect oscillatory APWPs to be favored. In contrast, recall that the paleomagnetic data outlined above seem to exhibit (i) similarly oriented APWPs characterized by (ii) oscillatory motion (Fig. 4). One key question is whether the 'hairpins' seen in the APWPs of Laurentia, Northwest Africa and Baltica are truly temporally coincident. Unfortunately, the existing age constraints preclude a rigorous test for time-series correlations. Improving age constraints on these paleomagnetic poles presents a critical objective for future work.

Some of the aforementioned mechanisms of fast plate motion make attendant geologic or geodynamic predictions. For example, the impingement of a strong plume on one or more plates could be expected to leave associated magmatic and structural records. If the overriding plate(s) were accelerated away from the plume conduit, the magmatic episode could be expected to quickly abate. A relevant case-study is the emplacement of the Central Iapetus Magmatic Province from ~615 Ma, which has been attributed to a mantle plume that may have driven Laurentia, Baltica and Amazonia apart (Robert et al., 2021; Tegner et al., 2019). The emplacement of that large igneous province is temporally similar to the initial swings in the APWPs of Laurentia, Northwest Africa and Baltica starting after 615 Ma. However, plume-related magmatism endured in Laurentia for more than 20 Ma (Puffer, 2002), in contrast to what would be expected if that continent was rapidly accelerated away from the plume conduit (Hodych et al., 2004; McCausland et al., 2011; Mitchell et al., 2011). As another example, if rapid plate motions were driven by large thermal gradients in the lower mantle according to the model of Gurnis and Torsvik (1994), the plates would be expected to move toward dynamic topographic lows, which could be recorded as stratigraphic records of sea-level rise. Presently, estimates of relative

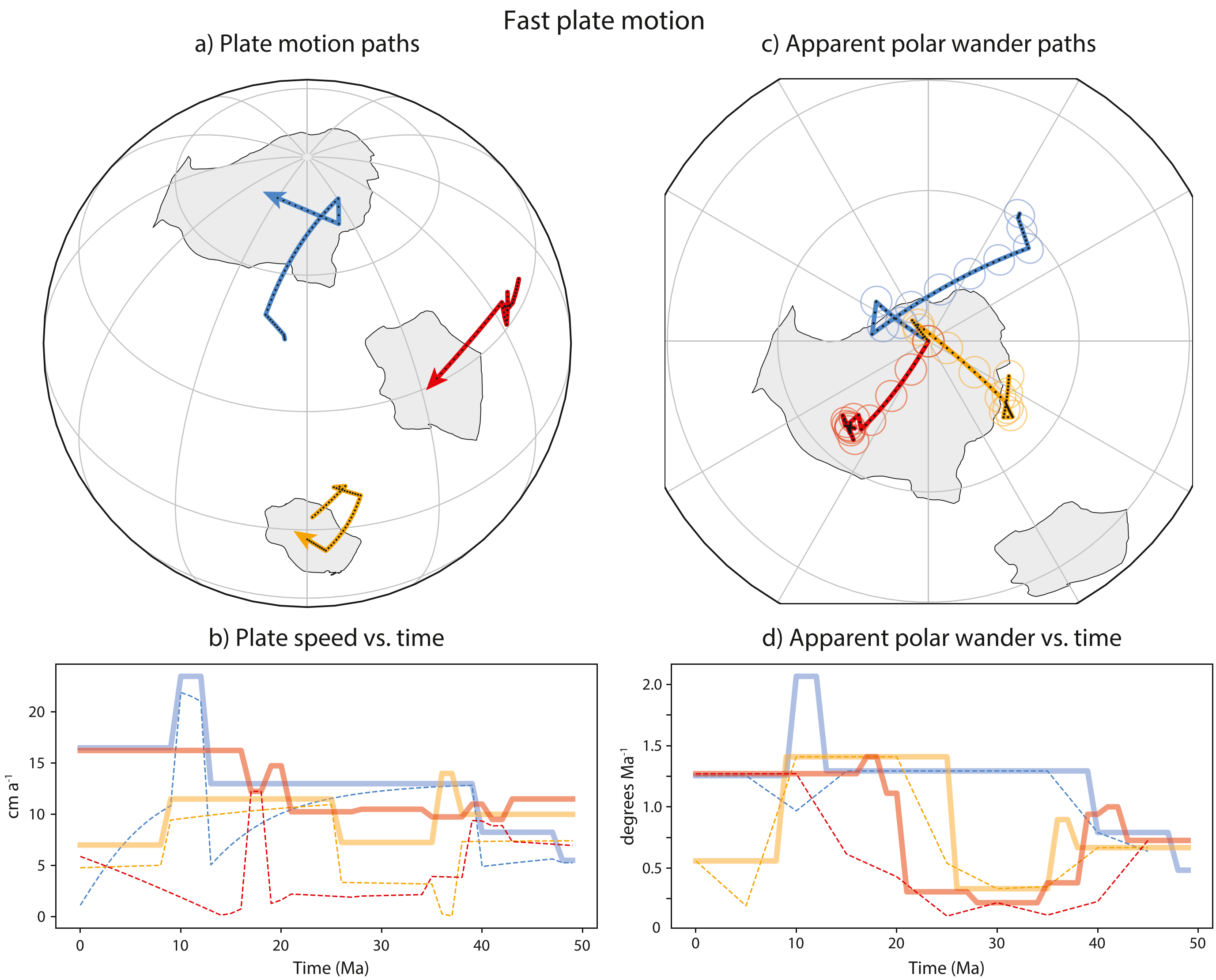

Fig. 5. A synthetic scenario of fast plate motions. A base kinematic plate model (Supp. Fig. S1) is randomly generated with plate speeds that range between 2 and 10 cm a^{-1} (methods described in Supp. Mat.). This base model is then converted into a 'fast' plate motion model by increasing all the plate motions by a factor of 2.5 (resulting in plate speeds that range between 5 and 25 cm a^{-1}). The panels depict one example output of such a random model, executed using three plates (arbitrarily being the outlines of Laurentia, Northwest Africa and Baltica in their positions as in Fig. 4) and run over 50 Ma (see Supp. Mat. for additional results). a) Motion paths of the centroids of the three plates from t = 50 Ma to t = 0 Ma. Black dots show the 1-Ma increments of motion. b) Full plate speeds vs. time (solid lines) and the paleomagnetically resolvable north-south component of those motions vs. time (dashed lines). c) APWPs of the three plates from t = 50 Ma to t = 0 Ma. Black dots show the 1-Ma increments of the APWP, whereas A95s (arbitrarily set to a standard size of 3°) are shown at 5 Ma intervals to indicate what might be practically observable from a series of high-resolution paleomagnetic studies. d) Complete rates of APWP vs. time (solid lines) and a lower-resolution version (dashed lines) determined only from poles with A95s in panel c (i.e. at 5 Ma intervals). Note that rates of APW and the their change points are uncorrelated.

(continent-specific) sea-level change for Ediacaran time are wanting, owing to limited inter-correlations between sedimentary records (in turn due to the lack of precise biozonation), but sustained transgressive records are not obvious (e.g. Segessenman and Peters, 2022). Further tests of such geologic/geodynamic predictions against the observational record could present valuable new insights.

A final, discriminating aspect of this hypothesis is that plate motions are fundamentally speed-limited by the rate at which the mantle can deform. In principle we could reject the fast plate motion hypothesis on the basis of any pair of paleomagnetic results from any arbitrary plate, if they reveal motion in excess of this limit. Unfortunately, the absolute theoretical limit remains unknown, but following from the information assembled in the previous section, we provisionally assume it to be on the order of 25 cm a^{-1}. Determination of a corresponding maximum rate of APW is dependent on the amount of toroidal motion (spin) that can contribute to plate motion. When poloidal motion dominates, Euler poles will lie far from their plate's centroid, and the maximum rate of APW will be similar to the maximum plate speed (i.e. maximum of 25 cm $a^{-1} \approx 2.25^{\circ}$ Ma^{-1}), whereas a proximal Euler pole associated with toroidal motion can yield APW rates greatly exceeding that of the plate's (linear) drift. Theoretical considerations and observational records suggest that the toroidal component is largely minimized (Čadek and Ricard, 1992; O'Connell et al., 1991), especially for large, energetic plates (Matsuyama and Iwamori, 2016; Spada and Alfonsi, 2000). However, to establish a possible uppermost range for APW associated with especially fast plate motion: we consider a circular plate with a radius of 15° (yielding an area of $\sim 8.5 \times 10^6$ km^2, comparable to the size of Baltica and Northwest Africa) moving about an Euler pole located 30° from the plate centroid, as with the Cocos Plate at present (Olson and Bercovici, 1991). If the plate and Euler pole are positioned at the equator and the plate moves at an average rate of 25 cm a^{-1}, the observed rate of APW will be approximately twice as fast ($\sim$50 cm $a^{-1} \approx 4.5^{\circ}$ Ma^{-1}) (see

Supp. Fig. S2 for an example of strong toroidal motion).

Although these 'speed limits' are rudimentary, they provide a useful metric. Note that the Ediacaran paleopoles from both Laurentia and Northwest Africa yield minimum drift rates that exceed our linear plate speed limit (25 cm a^{-1}), and the paleopoles from Baltica include rates of APW that exceed the corresponding drift-related APW speed limit (4.5° Ma^{-1}) (Fig. 3). Furthermore, as individual paleomagnetic data do not constrain longitude, rates of plate motion derived from simple comparisons between paleomagnetic data are minima (Fig. 5b; although total plate motion estimates are potentially recoverable from very rich paleomagnetic datasets (Gallo et al., 2022; Gordon et al., 1984; Rose et al., 2022))—APW rates close to this speed limit may thus already reflect 'impossibly fast' differential plate motions. Given the discrepancies between the paleomagnetic observations and these predictions, it presently seems unlikely that the paleomagnetic data purely reflect fast plate motions. Nevertheless, the absolute plate tectonic speed limit remains to be defined, and further investigations into how it could have varied through time are warranted.

3.1.2. *Implications*

The hypothesis of especially fast plate motion in the Ediacaran, followed by significantly and consistently slower plate speeds throughout the Phanerozoic, would imply that a dramatic change in the plate-mantle system occurred around the Precambrian-Phanerozoic transition. Conventional thermal evolution models for the mantle do not anticipate any abrupt changes in cooling or heat production across this interval (e.g. Herzberg et al., 2010). However, a sudden change in global plate motion rates could manifest a tipping point related to plate-mantle coupling (O'Neill et al., 2007), slab avalanches through the transition zone (Stein and Hofmann, 1994) or the sedimentary loading of subduction zones (Sobolev and Brown, 2019). In any case, such a transition would have important consequences for our understanding of plate-mantle dynamics, and resolution of the timing, rates and patterns of the fast plate motions would be key to unraveling its origin.

If the average plate motion was much faster in the Ediacaran, globally-integrated rates of subduction and seafloor production must have been higher then too, in turn implying that solid Earth degassing would have been elevated (Domeier et al., 2018; Marcilly et al., 2021; McKenzie et al., 2016). Increased CO_2 degassing would have had an influence on Ediacaran climate, but also could have contributed to the unusual carbon isotopic records and/or the proposed rise of atmospheric oxygen at this time (Williams et al., 2019). Rapid differential plate motion would have also led to locally rapidly changing environmental conditions, which could have promoted the high rates of biological innovation associated with this interval.

3.2. *Widespread data corruption*

This hypothesis contends that many Ediacaran paleomagnetic data have been compromised by one or more unrecognized pathologies, such as remagnetization, which can occur when rocks are subjected to high temperatures (thermal remagnetization), strong magnetic fields (e.g. lightning strikes) and/or are chemically modified (resulting in the alteration of primary magnetic minerals or allowing the growth of new ones). Additional pathologies include inclination shallowing, inaccurate structural restorations, vertical axis rotations, and erroneous age estimates. This is arguably the most conservative of the four hypotheses, as it implies that records of a well-behaved GAD field and 'moderate' (Phanerozoic-like) rates of plate drift and true polar wander have simply been obscured by a veil of data bias. Unsurprisingly, this hypothesis has been the default for many years, but it is becoming increasingly harder to maintain in the face of repeat studies and growing evidence that (at least some of) the enigmatic directions represent primary magnetizations of high-fidelity. Nevertheless, there remain legitimate, lingering questions about specific aspects of numerous key constraints. To this point, it is worth noting that the original hypothesis of an Ediacaran equatorial dipole (Abrajevitch and Van der Voo, 2010) was formulated in part from magnetic directions from the Fen complex of Baltica that have long been suspected (although not proven) to be Permo-Triassic remagnetizations (Meert, 2014).

For many common paleomagnetic afflictions, the notion of a systemic Ediacaran 'infection' (that is, the widespread corruption of the data by any one of the aforementioned pathologies) can be summarily dismissed. For example, whether inclination shallowing is prevalent among Ediacaran sedimentary units is rather irrelevant since the Ediacaran paleopoles from Laurentia and Northwest Africa are derived from igneous rocks. Similarly, although some results could have suffered from unrecognized vertical axis rotations, this cannot explain the distinct directional populations in the Laurentian or Northwest African datasets, which predominantly differ in inclination. Data pathologies are not restricted to the spatial dimension, and the apparently rapid rates of APW could be attributed to systematic age assignment errors. This is an important concern for Ediacaran sedimentary sections, especially those devoid of fossils and interbedded volcanics, but the paleopoles from Laurentia and Northwest Africa are derived from igneous units that have been directly dated (mostly by U-Pb methods). The ages of several Ediacaran sedimentary-based poles from Baltica are likewise constrained by interbedded tuffs that have been isotopically dated. Pervasive age errors among these paleomagnetic data are thus unlikely.

If Ediacaran paleomagnetic data were not universally corrupted by a single mechanism, perhaps multiple data pathologies together conspired to corrupt the global dataset. An obvious challenge to this hypothesis is the question of why Ediacaran paleomagnetic data should be more susceptible to data pathologies than data from earlier or later times (although perhaps the sparse data from earlier times are less reliable than we think?). One possibility is that the Ediacaran magnetic field was especially weak and yielded feeble primary magnetizations more easily masked by any subsequent partial remagnetizations. Further consideration of this hypothesis mandates careful scrutiny of all aspects of both extant and future paleomagnetic constraints. Of note is that non-conventional and developing methodologies, such as the study of magnetic inclusions in single crystals (Bono and Tarduno, 2015), scanning magnetometry (Glenn et al., 2017; Weiss et al., 2007) and micromagnetic tomography (de Groot et al., 2019; de Groot et al., 2018) provide novel pathways to evaluate the fidelity of these magnetic records anew.

3.2.1. *Predictions & appraisals*

This hypothesis fundamentally differs from the others in that it does not necessarily appeal to a single mechanism. Indeed, potential problems with paleomagnetic data are legion, and this hypothesis allows for any combination of them. This may give the sobering impression that we cannot execute tests of this hypothesis without exhaustively scrutinizing every aspect of every pole, one-by-one. Fortunately, this is not the case. Although the identification of a specific pathology in any constraint certainly requires such a meticulous approach, we can more easily evaluate the possibility that the global dataset has been pervasively corrupted by random biases according to how the directions vary in time and space (Fig. 6 and Supp. Figs. S2, S3). Directional changes observed at remote locations are not expected to be temporally correlative, nor will their spatial evolution follow a systematic pattern. Locally, however, there may be recurring directional clusters in space that correspond with episodes of remagnetization in time; this reflects one of the reliability criteria for paleomagnetic data (Meert et al., 2020) which considers a paleomagnetic result 'suspicious' if it resembles a younger result from the same region. 'Instantaneous' directional changes (occurring with no apparent intermediate state; Fig. 6) may occur across lithological boundaries (e.g. separating units variably affected by remagnetization), across structural boundaries (e.g. separating differentially rotated blocks), or between sections erroneously assigned equivalent ages. Apparently oscillatory directional changes could also be anticipated in stratigraphic sections variably affected by bias—for

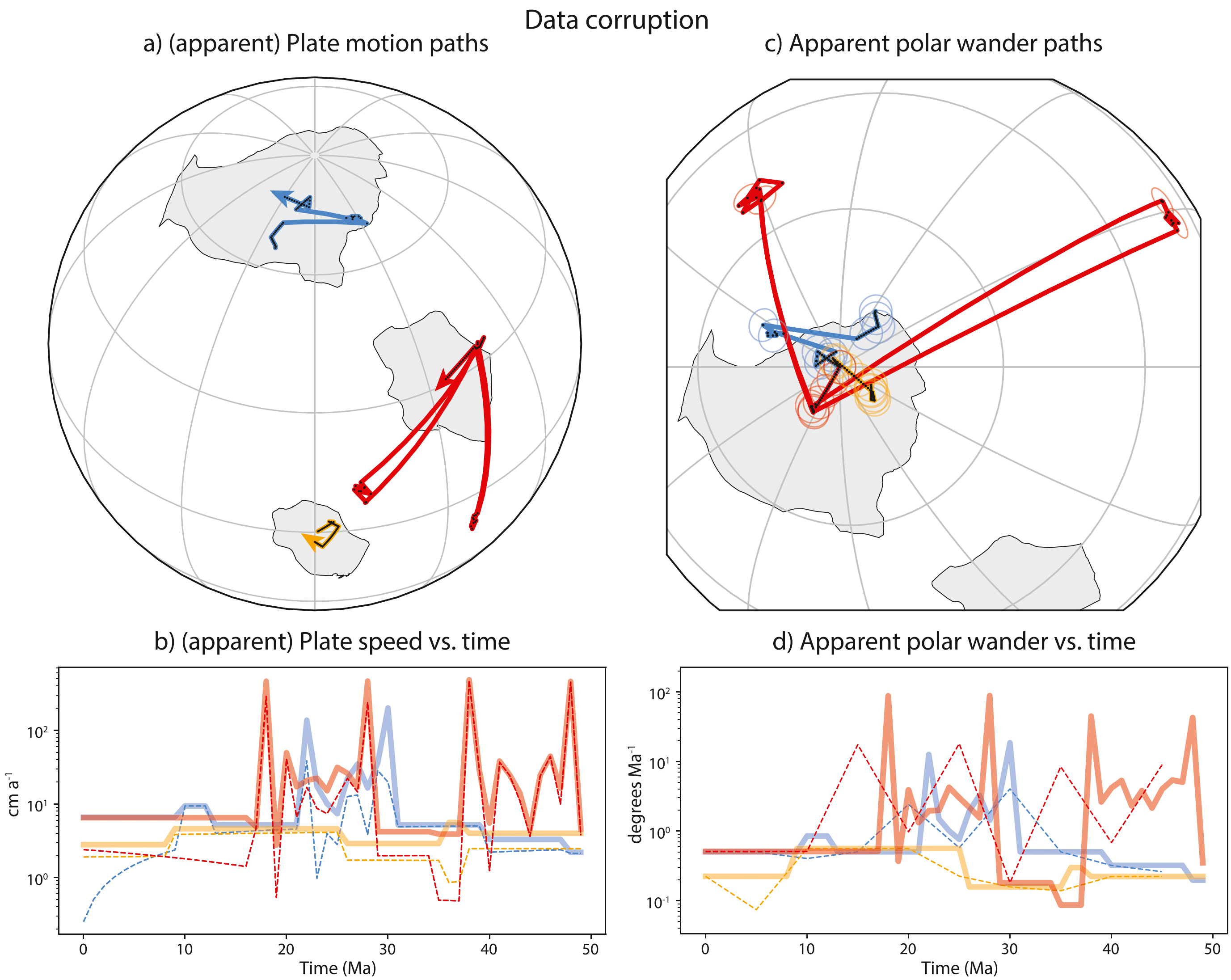

Fig. 6. A synthetic scenario of apparent plate motions derived from randomly corrupted paleomagnetic data. This model is constructed from the same randomly-generated base kinematic plate model as used in Fig. 5 (Supp. Fig. S1). In this case, the base model is corrupted by replacing a randomly selected sub-set of the paleomagnetic poles with randomly generated directions, to simulate differential remagnetization (see Supp. Mat. for further details and additional results). a) (Apparent) motion paths of the centroids of the three plates from t = 50 Ma to t = 0 Ma. Black dots show the 1-Ma increments of motion. Note that there are no dots along the 'excursions' because these occur instantaneously. The 'yellow' plate in this particular model drew zero corruption events, so its motion purely reflects the underlying base kinematic model. b) (Apparent) full plate speeds vs. time (solid lines) and the paleomagnetically resolvable north-south component of those motions vs. time (dashed lines). Note the log scale of the y-axis. c) APWPs of the three plates from t = 50 Ma to t = 0 Ma according to the corrupted paleomagnetic data. Black dots show the 1-Ma increments of the APWP, whereas A95s (arbitrarily set to a standard size of 3°) are shown at 5 Ma intervals to indicate what might be practically observable from a series of high-resolution paleomagnetic studies. Note again there are no dots along the 'excursions'. d) Complete rates of APWP vs. time (solid lines) and a lower-resolution version (dashed lines) determined only from poles with A95s in panel c (i.e. at 5 Ma intervals). The rates of APW and their change points are uncorrelated. The lower-resolution estimates of APW vs. time do not capture the true rate of the APW 'excursions', but even the damped estimates in this case are $> 5^\circ$ Ma^{-1}. If corrupted directions are selected so as to be approximately orthogonal to the true directions, the lower-resolution rates of APW are always $> 10^\circ$ Ma^{-1}.

example where a remagnetized unit is positioned between more resilient lithologies with primary magnetizations.

Considered in isolation, the rapid directional changes observed in the datasets from Laurentia, Northwest Africa and Baltica appear to conform to some of these expectations. However, the broadly similar timing of the directional excursions, and their similar geometry (both in length and orientation, following a geologically-informed relative reconstruction of the continents; Fig. 4) are at odds with these expectations. Because the largest directional swings among the Ediacaran paleopoles are dependent on a handful of results, it is instructive to inspect some of these and their potential shortcomings in greater detail.

For the data from Laurentia, much discussion has focused on the nature of the steep vs. shallow components found to be co-existing in several Ediacaran units (Bono and Tarduno, 2015; Halls et al., 2015; Hodych et al., 2004; McCausland et al., 2011; McCausland et al., 2007; Meert and Van der Voo, 2001; Meert et al., 1994; Pisarevsky et al., 2000; Pisarevsky et al., 2001; Symons and Chiasson, 1991; Tanczyk et al., 1987). As the units of scrutiny (Grenville dikes, Baie des Moutons complex, Catoctin volcanics, Sept-Îles intrusion) are exclusively igneous, there is no concern of inclination shallowing. There is no ambiguity about the structural coherence of these units with respect to the Laurentian craton (excepting a small tilt correction applied to the Sept-Îles intrusion by Symons and Chiasson (1991)). The emplacement ages of all four units are also well-determined (Aleinikoff et al., 1995; Halls et al., 2015; Higgins and Breemen, 1998; McCausland et al., 2011), and being rapidly cooled shallow intrusives and volcanics (excepting the Sept-Îles intrusion), their isotopic ages should closely approximate the age of their original thermal remanent magnetization. Debate has therefore focused on the interpretation of component primacy, with the innate assumption that one of the two components (if not both) must be a remagnetization or a composition of unresolved components. In most cases, the discussion hinges on differing interpretations of partial or otherwise imperfect paleomagnetic field tests or the lack thereof.

In the case of the Grenville dikes, baked contact tests suggest the steep component is primary, whereas a primary origin of the shallow component is only inferred from circumstantial evidence (Halls et al., 2015; Hyodo and Dunlop, 1993). Both the steep and shallow components from the Baie des Moutons complex have been interpreted as primary based on rock magnetic arguments and a dissimilarity with any possible younger magnetization direction for Laurentia (steep component), and the presence of reversals (shallow component), but neither is supported by a paleomagnetic field test (McCausland et al., 2011). In the Catoctin volcanics, the shallow component exhibits dual polarities and was clearly acquired prior to Ordovician folding on the basis of a positive fold test (Meert et al., 1994). The steep component also exhibits dual polarities, passes the fold test at 92% confidence and is associated with a suggestive (but imperfect) positive baked contact test (Meert and Van der Voo, 2001). The lingering ambiguity left by the latter tests, however, has given rise to conflicting interpretations of steep vs. shallow component primacy there (Meert and Van der Voo, 2001; Pisarevsky et al., 2000; Pisarevsky et al., 2001). In the Sept-Îles intrusion, the steep component exhibits dual-polarities and has been interpreted as primary given its directional similarity to the steep Catoctin and Callander components (Meert and Van der Voo, 2001; Symons and Chiasson, 1991), but this inference is not backed by a paleomagnetic field test. By contrast, the shallow component, which may also be dual-polarity (Bono and Tarduno, 2015), is associated with a positive baked contact test (Tanczyk et al., 1987). Here, the steep component is also associated with a distinctly lower coercivity than the shallow component, and has been attributed to viscous overprinting (Bono and Tarduno, 2015; McCausland et al., 2007).

A critical inference is that it is highly doubtful that widespread remagnetization could explain *all* of the steep or *all* of the shallow directions. After all, field tests support steep primary directions in the Grenville dikes and Callander complex (where there is no shallow counterpart) and shallow primary directions in the Sept-Îles intrusion and Skinner Cove volcanics (where there is no steep counterpart). And as demonstrated above (section 2), *any* combination of steep and shallow directions from the assembled Ediacaran data from Laurentia will effectuate extremely rapid APW ($> 4^\circ$ Ma^{-1}; Fig. 3b). Thus, while there are undoubtedly problems with unrecognized bias among the extant Ediacaran paleomagnetic data, it is not straightforward to ascribe the larger problem to magnetic fidelity issues alone.

We do not wish to dwell on interrogations of individual data, but a brief detour to Baltica is useful to consider this hypothesis from another perspective. In contrast to the dataset from Laurentia, the Ediacaran data from Baltica come almost exclusively from sedimentary rocks. One might thus suspect that unrecognized inclination shallowing could be distorting the directional dataset. However, the disparate directional groups differ predominantly in declination, and so cannot be explained as inclination bias (Fig. 3f). On the other hand, declination differences could result from differential vertical axis rotations. Given that the single 'anomalous' late Ediacaran pole from Baltica comes from the structurally disrupted continental margin in the South Urals (Basu Fm; BA in Fig. 3e,f), there is good reason to be skeptical of this result (Meert, 2014). However, there is no geologic evidence of the substantial block rotation needed to explain the Basu Fm. result as a structural perturbation (Levashova et al., 2015). Furthermore, a slightly younger Ediacaran unit from the same region (Zigan Fm; ZN) bears a dual-polarity magnetization that does not resemble any younger directions from the region, but whose pole falls among those of the similarly-aged late Ediacaran poles from the White Sea region ~1600 km away (Levashova et al., 2013) (Fig. 3e,f). The Zigan Fm. also bears a Permian overprint that directionally coincides with contemporaneous results derived from elsewhere on the craton. It is unlikely that the Basu Fm. has been remagnetized given its dual-polarity and positive fold and slump tests (Levashova et al., 2015), and its age is established from directly dated interbedded ashes (Razumovskiy et al., 2020). Thus, while the argument for the Basu Fm. pole being representative of the craton in the late Ediacaran is not iron-clad, it is not readily dismissed as fallacious either. However, if the Basu Fm. pole is recognized as flawed, the Baltican dataset would be 'cleansed' of aberrant late Ediacaran data (although fast APW would still be implied by early Ediacaran and Cambrian constraints)—so this dataset provides a more compelling case in support of the hypothesis of data corruption than that of Laurentia.

3.2.2. Implications

Initially, this hypothesis might seem to bear the least significant ramifications. After all, it could allow the GAD hypothesis to prevail, and moderate plate motion and true polar wander rates could be revealed beneath a veneer of bias. But the realization that the present Ediacaran dataset is widely compromised by (as-yet) unrecognized artefacts implies major shortcomings in our ability to identify pathological data with presently standard instrumentation and methodologies. This would pose challenges to our confidence in paleomagnetic interpretations drawn from regions of space and time where the data are sparse and cannot otherwise be independently evaluated.

3.3. Rapid true polar wander

True Polar Wander (TPW) is a rotation of the entire solid Earth (crust and mantle) that occurs in response to redistributions of mass that perturb the planetary moment of inertia (Evans, 2003; Gold, 1955; Goldreich and Toomre, 1969). TPW specifically acts to restore the principal moment of inertia to the planetary spin-axis, and so the axis of TPW is bound to the equatorial plane. TPW is occurring at present-day at ~10 cm a^{-1}, with about 40% of the driving perturbation arising from deglaciation (Adhikari et al., 2018; Vermeersen et al., 1997). Estimates of TPW back to the Cretaceous have been made through direct comparisons of paleomagnetic and hotspot-based reference frames (Andrews, 1985; Besse and Courtillot, 2002; Doubrovine et al., 2012), whereas estimates of TPW derived from integrated global plate/continental motions (Jurdy and Van der Voo, 1974) have been computed back into the Paleozoic (Steinberger and Torsvik, 2008; Torsvik et al., 2014). These estimates suggest that TPW has operated in a consistent way throughout the Phanerozoic, characterized by periodic oscillations of alternating sense about an equatorial axis, and occurring at rates on the order of 1° Ma^{-1} or less (Torsvik et al., 2014). However, controversial episodes of more rapid, large amplitude TPW have been proposed for various intervals of the Mesozoic (Fu and Kent, 2018; Muttoni et al., 2013; Prévot et al., 2000; Sager and Koppers, 2000; Yi et al., 2019; but see also Kulakov et al., 2021) and mid- to late Paleozoic (Le Pichon et al., 2021; Marcano et al., 1999; Piper, 2006; Van der Voo, 1994). In deeper time, proposed episodes of still faster and larger amplitude episodes of TPW have been attributed to inversions of the principal and intermediate planetary moments of inertia—so called 'inertial interchange' TPW (Evans, 2003; Fisher, 1974; Kirschvink et al., 1997; Maloof et al., 2006). Notably, controversial estimates of TPW in the earliest Paleozoic that were the first to be attributed to an inertial interchange event have since been downward revised to rates on the order of ~1.4° Ma^{-1} (Mitchell et al., 2010).

The rate at which TPW proceeds is a function of the magnitude of the mass perturbation and the viscosity structure of the mantle (Rose and Buffett, 2017; Tsai and Stevenson, 2007). Mantle viscosity dictates how fast mass can be redistributed and thus the timescale over which a perturbation can be applied, but the viscosity structure also controls the amplitude (and sign) of the effective perturbation (Ricard et al., 1993; Robert et al., 2018; Spada et al., 1992). Mantle viscosity also determines how quickly the rotational bulge of the solid Earth, which otherwise acts to resist TPW, can viscously adjust to changes in the location of the spin-axis (Creveling et al., 2012; Ricard et al., 1993). Because there are significant uncertainties on our knowledge of the rheological parameters of the mantle and the historical range of mass heterogeneity structures is unknown, an estimation of the TPW 'speed limit' is difficult. Numerical investigations have determined that TPW could potentially reach rates of ~5–10° Ma^{-1} given an extreme mass heterogeneity distribution (Greff-Lefftz and Besse, 2014; Robert et al., 2018), a substantially increased convective vigor (Rose and Buffett, 2017), or a more isoviscous mantle viscosity structure (Spada et al., 1992). However, the rate of polar wander during a TPW event is not expected to remain constant (Tsai and Stevenson, 2007), and these rates represent maximum 'instantaneous' rates of TPW that may not be paleomagnetically resolvable. By contrast, 'integrated' rates of TPW (as averaged over an entire TPW episode) may be more directly comparable to the sparse paleomagnetic record, but their temporal definition is inherently ambiguous. From numerical studies where such integrated TPW rates are reported (or are otherwise determinable), the maximum value is often estimated to be on the order of ~1–4° Ma^{-1} (Phillips et al., 2009; Robert et al., 2018; Steinberger and O'Connell, 2002; Tsai and Stevenson, 2007). Nevertheless, integrated TPW rates in excess of 4° Ma^{-1} may still be attainable under extreme conditions associated with very large convective loads, a strongly prolate non-hydrostatic figure, or a much lower mantle viscosity (Creveling et al., 2012).

3.3.1. Predictions & appraisals

During a TPW episode, all locations on Earth's surface are subjected to a common angular displacement about an equatorial axis. Global paleomagnetic directions, if mapped to paleopoles, would manifest such an event as a common arcuate distribution. If TPW proceeded significantly more rapidly than differential plate motions (as this hypothesis

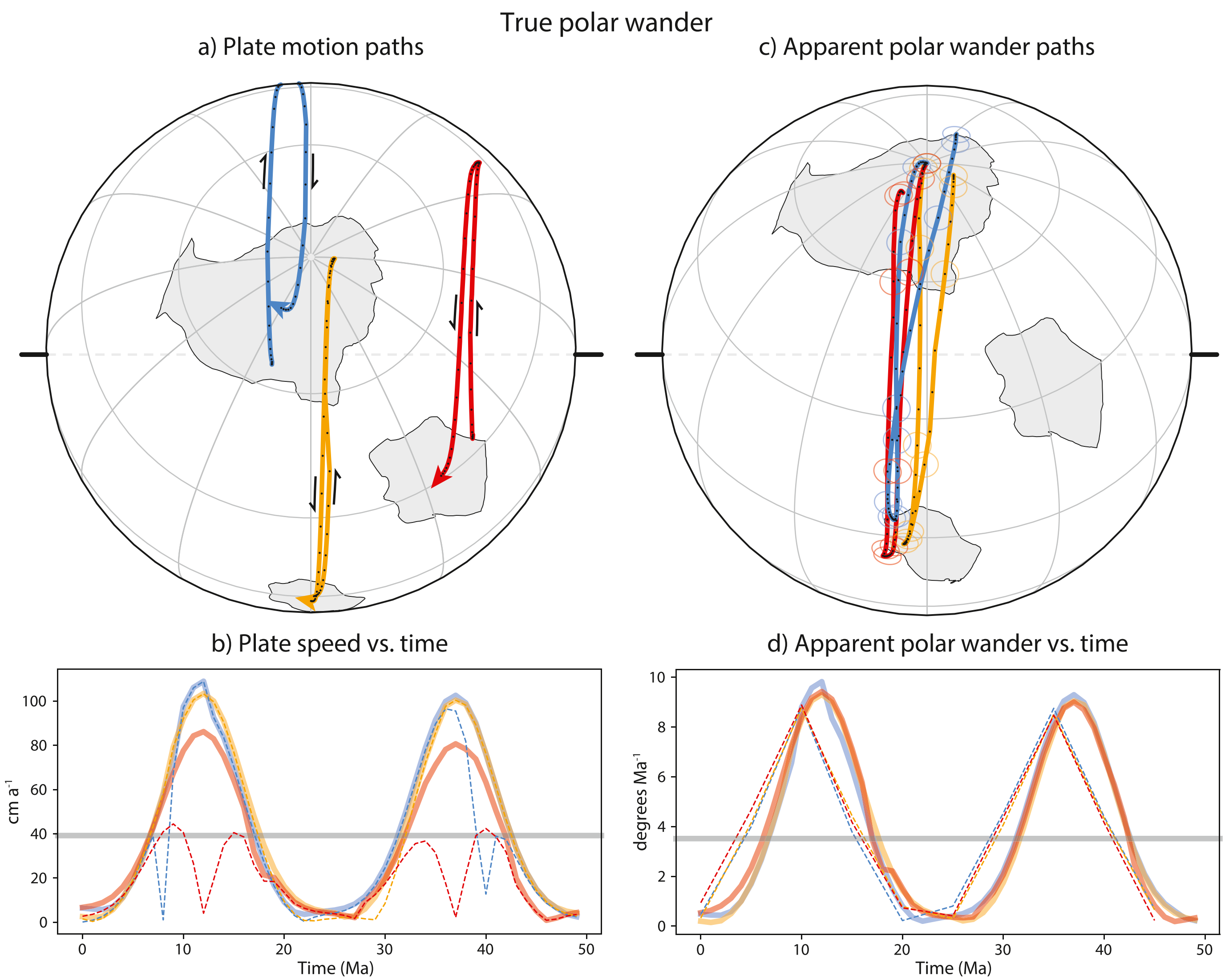

Fig. 7. A synthetic scenario of rapid TPW. This model is constructed from the same randomly-generated base kinematic model as used in Fig. 5 (Supp. Fig. S1). In this case, an oscillatory TPW event (two consecutive rotations of 90° about the same axis but with opposite sign) is then superimposed on the base model; each TPW event has a time-dependent velocity with a maximum 'instantaneous' polar wander rate of 9° Ma^{-1} (see Supp. Mat. for further details and additional results). a) Motion paths of the centroids of the three plates from t = 50 Ma to t = 0 Ma. Black dots show the 1-Ma increments of motion. Dashed line with solid black ends shows the location of the TPW axis. b) Full plate speeds vs. time (solid lines) and the paleomagnetically resolvable north-south component of those motions vs. time (dashed lines). The grey horizontal line shows the integrated TPW rate. c) APWPs of the three plates from t = 50 Ma to t = 0 Ma. Black dots show the 1-Ma increments of the APWP, whereas A95s (arbitrarily set to a standard size of 3°) are shown at 5 Ma intervals to indicate what might be practically observable from a series of high-resolution paleomagnetic studies. Note that the shape of the APWPs are highly similar (the small differences being due to the underlying differential plate motions of the base model). d) Complete rates of APWP vs. time (solid lines) and a lower-resolution version (dashed lines) determined only from poles with A95s in panel c (i.e. at 5 Ma intervals). The rates of APW are systematically time-dependent and highly correlated.

implies), those arcs would specifically approximate great-circle distributions of the same length (Meert, 1999). If the individual continents were reassembled into the relative positions they occupied at the beginning or end of the TPW event, those paleopole arcs would tend to collapse into a single swath—although with small deviations due to individual plate motions (Evans, 2003) (Fig. 7c and Supp. Figs. S2, S3). The timing of directional changes, and the rate of apparent polar motion, would thus be the same at all locations, globally (although again with some modulatation by superimposed plate motion; Fig. 7d). TPW is fundamentally rate-limited by the mantle's viscosity, and in lieu of an exact integrated TPW speed limit, we can take the maximum instantaneous rate (~5–10° Ma^{-1}) as an upper bound. The rate of polar wander during any given TPW event will also be non-linear in time (Tsai and Stevenson, 2007). During an inertial interchange event, the rate will reach a maximum when the principal moment of inertia is offset from the instantaneous rotation axis by 45° (Robert et al., 2018; Rose and Buffett, 2017). This means that the rotation axis will spend comparatively more time at either end of a TPW arc than it will in the space between (Fig. 7). Although the fundamental paleomagnetic resolution imposed by secular variation may preclude the definition of specific non-linear rate changes from paleomagnetic data, a variable rate of polar wander could be discernable from high-resolution data (Fig. 7d). The directional changes could also be oscillatory, as oscillatory TPW can arise from 1) stresses in the elastic lithosphere, 2) transient perturbations to an otherwise stable, triaxial mantle density structure, or 3) a change in the sign of the effective perturbation as a density anomaly passes vertically through the mantle (Creveling et al., 2012; Robert et al., 2018). These effects may also impart an asymmetry on the distribution of TPW rates across an oscillatory event (Creveling et al., 2012).

The compiled paleomagnetic data exhibit several conspicuous features that closely conform to these predictions. The occurrence of possibly coincident directional excursions on multiple continents that seem to follow an arc approaching 90° (Fig. 3) is certainly suggestive of a TPW signal. The hairpin shapes of the APWPs are readily explainable as oscillatory TPW. That the hairpin-shaped APWPs approximately collapse into a common path when the continents are re-assembled into a geologically-informed relative configuration is also compelling (Fig. 4). The distribution of poles along the paths themselves—specifically their tendency to occur near the cusps of the hairpins rather than along the corridors connecting them—is furthermore congruent with the prediction that TPW should proceed non-linearly, with the pole spending comparatively little time between the end-points (assuming we have captured the end-points of a ~ 90° TPW event). However, this broad accordance aside, the rate of APW implied by some of the Ediacaran paleopoles appear to approach the limit of what could be reasonably attributed to TPW (Fig. 3). Another challenge for the TPW hypothesis is posed by the directional excursion observed in Baltica in the latest Ediacaran-early Cambrian, which is not reflected in the data from any other continent (Robert et al., 2021).

Beyond the paleomagnetic predictions, rapid TPW could be expected to leave some diagnostic traces in global paleo-environmental records. During TPW, the hydrosphere responds immediately to changes in the orientation of the rotational equator, whereas the solid Earth response lags by the timescale of its viscous relaxation. Continents driven toward the rotational equator by TPW will thus experience a transient sea-level rise (until the solid Earth 'catches up'), whereas continents driven toward the spin-axis will experience transient regression (Mound and Mitrovica, 1998; Mound et al., 1999; Wegener, 1929). This pattern reflects a surface spherical harmonic of degree 2, order 1, aligned with the TPW axis and rotational equator (Fig. 8). The largest amplitude sea-level changes are expected along the meridian perpendicular to the TPW axis, while no sea-level variations will occur along the axis itself. The absolute amplitudes of these sea-level variations are dictated by the rate of TPW, as slower rates provide more time for the solid Earth to respond viscously. Fast TPW could give rise to local, transient sea-level variations on the order of 50–200 m (Mound et al., 1999; Mound et al., 2001). Because TPW rotates the solid Earth through the celestially-fixed climate zones, a similar pattern (spherical harmonic degree 2, order 1) of change could be anticipated from paleoclimate and paleobiologic records (Evans, 2003; Kirschvink et al., 1997; Mitchell et al., 2015; Raub et al., 2007), and may be distinguishable from zonal paleo-environmental changes arising from eustatic adjustments and global climate change unrelated to TPW. An example application of these concepts can be seen in the study of Maloof et al. (2006), who related stratigraphic and carbon isotopic changes observed in Tonian sedimentary sections in northeast Svalbard to a pair of putative TPW events, inferred from paleomagnetic data, that are proposed to have occurred around 800 Ma.

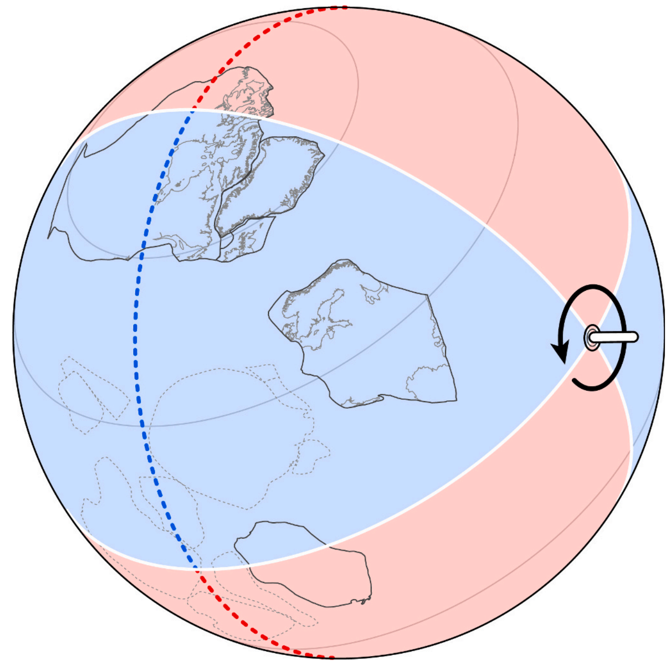

Fig. 8. Quadrants where sea-level is expected to rise (blue) or fall (red) relative to the axis and sense of TPW (thick white bar encircled by black arrow showing sense of rotation). The blue/red stippled line shows the meridian normal to the TPW axis, where sea-level changes will be at a maximum. The polygons in grey show the same mid-Ediacaran (590 Ma) reconstruction as in Fig. 3, from Robert et al. (2021), with the relative location of the TPW axis chosen to explain their APWPs (in Fig. 3b) as resulting from TPW. The sense of the rotation follows the trajectory of the APWPs from the mid-Ediacaran into the late Ediacaran (~585–550 Ma); whereas the rotation from the early to mid-Ediacaran would have had the opposite sense. The depicted rotation suggests that Laurentia would have experienced a transient sea-level rise from the mid- to late Ediacaran, whereas Northwest Africa would have experienced regression. Baltica, being closer to the TPW axis, would have experienced more muted changes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

With respect to a simplified model of rapid, oscillatory TPW fit to the compiled paleomagnetic observations and paleogeographic reference model we adopt here (Fig. 4), we could anticipate relatively muted changes in Ediacaran sea-level and/or paleo-environmental records from Baltica (which would have been relatively close to the axis of TPW) and larger amplitude changes in the records from Northwest Africa and Laurentia (the latter being ~90° away from the TPW axis) (Fig. 8). More specifically, between the early and mid-Ediacaran (~615–585 Ma), Laurentia would have experienced regression, and between the mid- and late Ediacaran (~585–550 Ma) it would have experienced transgression (Fig. 8); whereas for Northwest Africa these sea-level changes would be reversed. With respect to Baltica, some studies have argued for a stability of the paleo-environment during the mid-to-late Ediacaran (Bojanowski et al., 2021; Dudzisz et al., 2021), but the records are sparse and in need of further scrutiny. For Laurentia, Mitchell et al. (2011) suggested that a mid-Ediacaran oolitic horizon (~580 Ma) in the Johnnie Fm. (southwestern USA) could reflect a transgressive-regressive episode associated with TPW then, but it could alternatively reflect sea-level fluctuations driven by regional tectonics (Segessenman and Peters, 2022; Yonkee et al., 2014) or a global (eustatic) signal tied to glacial dynamics or plate reorganizations (Busch et al., 2022; Witkosky and Wernicke, 2018). In general, Ediacaran estimates of relative (continent-specific) sea-level and paleo-environmental change are still in their infancy; further investigation of stratigraphic and climatically-sensitive records and comparisons with TPW predictions present another important opportunity for future work. In particular, continued chronostratigraphic improvements are needed to enable robust correlations.

3.3.2. Implications

As with the hypothesis of fast plate motion, the occurrence of rapid TPW in Ediacaran time followed by significantly slower TPW in the Phanerozoic implies that a dramatic change in the solid Earth occurred around the Precambrian-Phanerozoic transition. However, conventional thermal evolution models of the mantle do not anticipate any rapid changes to its viscosity structure or convective vigor at this time. Alternatively, an extraordinary mantle mass heterogeneity structure could have developed, perhaps imposed by episodic changes to the global subduction system (Greff-Lefftz and Besse, 2014; Robert et al., 2018). Intriguingly, if the rate of such TPW could be deduced from high-quality paleomagnetic data, it could be used to constrain the properties of the mantle at this time (Evans, 2003; Raub et al., 2007). The common trajectory followed by all continents during the TPW event would also enable the construction of a robust relative paleogeography (including relative longitude) during the event (Kirschvink et al., 1997; Robert et al., 2017) (e.g. Fig. 4).

Rapid changes to the latitudinal distribution of land and sea, the reorientation of oceanic gateways and topographic barriers relative to the climate zones, and the reordering of ecological niches could have had a profound effect on the climate and biosphere (Kirschvink and Raub, 2003; Mitchell et al., 2015; Raub et al., 2007). Although many of the specific linkages remain controversial (in part because the occurrence/timing of rapid TPW remains controversial), the confirmation of rapid TPW in Ediacaran time would provide several concrete opportunities to connect changes in the solid Earth to the dramatic global changes observed on Earth's surface. For example, if TPW were responsible for the mid-Ediacaran transgressive sequences reported from several continents, it could have played a direct role in instigating the Shuram carbon isotope anomaly (Busch et al., 2022; Grotzinger et al., 2011).

3.4. Anomalous magnetic field

According to this hypothesis, the Ediacaran paleomagnetic directional excursions do not represent changes in the solid Earth, but rather manifest an anomalous geomagnetic field. Our use of the term 'anomalous' is intentionally nondescript, as the Ediacaran magnetic field could conceivably have taken many forms, but it is convenient to consider two principal end-members: i) a non-GAD structure (Abrajevitch and Van der Voo, 2010), or ii) a GAD field that is extremely weak (Bono et al., 2019; Shcherbakova et al., 2019) and rapidly reversing (Bazhenov et al., 2016; Halls et al., 2015; Levashova et al., 2021; Meert et al., 2016). Note the distinction between these alternatives is somewhat arbitrary since non-GAD terms are strengthened relative to the decaying axial dipole during a reversal, but it is nevertheless useful to distinguish between a 'structured' non-GAD field and an 'unstable' GAD field (the latter being regularly perturbed by 'unstructured' non-GAD fields).

The dipole represents the largest component of the modern geomagnetic field, and although there are myriad contributions from higher-order fields, they mostly vanish when considering time-averaged (~10^4–10^5 a) expressions of the field. Investigations of paleomagnetic records of the last 5 Ma (Johnson and McFadden, 2015; McElhinny et al., 1996; Merrill and McFadden, 2003) and since 200 Ma (Besse and Courtillot, 2002) have determined the largest persistent non-dipole term (the geocentric axial quadrupole) to represent ≤5% of the GAD term. Direct tests of GAD dominance in deeper time have proven more challenging. Studies of both global inclination frequency (Evans, 1976; Veikkolainen et al., 2014) and the distribution of paleomagnetic directions across large igneous provinces (Panzik and Evans, 2014) have concluded that the Phanerozoic and Precambrian paleomagnetic record is consistent with that of a GAD field. In contrast, other studies applying the same tests have concluded that significant higher-order geomagnetic field structures are evident from those data (Kent and Smethurst, 1998; Williams and Schmidt, 2004). These differing conclusions in part reflect the fact that these tests are significantly impaired by limitations in both the volume of observational paleomagnetic data and the finite interval over which they have been sampled (McFadden, 2004; Meert et al., 2003; Panzik and Evans, 2014). Nevertheless, the symmetry of geomagnetic reversals in the Mesoproterozoic (Kulakov et al., 2014; Swanson-Hysell et al., 2009) and the congruency of paleomagnetic and paleoclimatic data back to ~2 Ga (Evans, 2006) present compelling support for the GAD hypothesis back into Proterozoic time.

There has been some debate about possibly larger non-dipole fields in Permian-Triassic time, which were invoked to explain paleogeographic discrepancies related to the supercontinent Pangea (Torsvik and Voo, 2002; Van der Voo and Torsvik, 2001). The paleogeographic problem was subsequently shown to be attributable to inclination shallowing and inaccurate reconstruction poles (Domeier et al., 2011, 2012; Van der Voo and Torsvik, 2004), but the original proposals are nevertheless illuminating: they invoked an axial octupolar term representing ~10–20% of the GAD to explain apparent deflections (from the expected direction) of some 10–15°. By comparison, some of the Ediacaran paleomagnetic data are associated with seemingly contemporaneous directions that are orthogonal to one another. The attribution of one of those directional sets to non-dipole contributions would thus require higher-order fields grossly exceeding the power of the dipole at the Earth's surface. Geodynamo simulations have suggested that a stronger axial octupole could have been sustained by the purely thermal convective regime operating in the core prior to nucleation of the inner core, but it still would have been subordinate to the dipole (Heimpel and Evans, 2013; Landeau et al., 2017). A stronger, multipolar field could have been generated by more vigorous top-driven convection, but given the secular cooling of the core and mantle, such a regime may have been restricted to pre-Mesoproterozoic time (Driscoll, 2016).

Another possibility is that a dominant non-GAD field arose from an equatorial (i.e. non-axial) dipole term (Abrajevitch and Van der Voo, 2010). A magnetic dipole oriented at high angle to the planetary rotation axis is evidently favorable under some conditions, as the dipoles of both Uranus and Neptune are inclined in excess of 45° from their rotation axes (Holme and Bloxham, 1996). Notably, both of those planetary fields are also strongly multipolar (with quadrupole and octupole components rivaling or exceeding the dipole at the surface) and may arise from convection within a thin shell enveloping a stably stratified fluid core (Holme and Bloxham, 1996; Stanley and Bloxham, 2004) and so are not readily comparable with the geodynamo. Nevertheless, equatorial dipoles have been produced by more Earth-like numerical dynamos, wherein they have been found to relate to weak thermal convection (Ishihara and Kida, 2002), the size of the inner core (Aubert and Wicht, 2004) and heterogeneous heat-flow across the core-mantle boundary (Gissinger et al., 2012).

The timing of inner core nucleation (ICN) may be of key importance. ICN presented a major transition in the core's convective regime (by the introduction of chemical buoyancy arising from light elements rejected from the crystallizing solid) that increased the power provided to the geodynamo, allowing it to sustain a strong field dominated by an axial dipole (as today) since at least ICN time. Driscoll (2016) showed that a weak-field regime dominated by an equatorial dipole could have been present immediately before ICN, when top-driven thermal convection would have been at its weakest. Many thermal evolution models now place ICN in the late Proterozoic or early Phanerozoic (Davies, 2015; Labrosse, 2015; Nimmo, 2015; Olson et al., 2015), thus permitting the Ediacaran paleomagnetic record to be interpreted as the manifestation of a weak and/or unstable field leading up to that transition. In contrast, simulations by Landeau et al. (2017) suggest that the geomagnetic field could have maintained a strong axial dipole for the last ~2 Ga, and that ICN may have had comparatively little effect on the structure and strength of the field.

As an alternative to a non-GAD origin, the Ediacaran magnetic field could have simply been hyperactively reversing. In this case, some of the enigmatic paleomagnetic directions could represent transitional directions captured during frequent polarity inversions of an otherwise stable GAD field. A difficulty with this explanation is the occurrence of relatively well-organized directional 'groups' that led to Ediacaran paleomagnetic data being recognized as unusual in the first place. Why should transitional directions recur at approximately the same locations? A salient observation by Halls et al. (2015) is that this explanation is not exclusive to an equatorial dipole (Abrajevitch and Van der Voo, 2010). With reference to the numerical results of Gissinger et al. (2012), Halls et al. (2015) conjectured that the Ediacaran paleomagnetic data could reflect transient, episodic appearances of an equatorial dipole as an intermediate step in the reversal process of a hyperactive but otherwise axially-aligned main (dipole) field. Constable (1992) presented a similar model to explain seemingly recurring ('preferred') paths traversed by transitional virtual geomagnetic poles (VGPs) during the last few reversals.

The transient appearance of an equatorial dipole amidst frequent reversals of a hyperactive GAD seems to salvage the GAD hypothesis while also explaining well-grouped directions orthogonal to the axial dipole. However, this explanation only pushes the stumbling block a bit further from view: like the aforementioned quandary of ascribing recurring directions to (erratic) transitional fields, why should the equatorial dipole be stable in space? Of the dynamo simulations that have thus far exhibited an equatorial dipole, all observe it to precess in the equatorial plane due to prevailing flow in the outer core. Abrajevitch and Van der Voo (2010) speculated that a large differential heat flux across the core-mantle boundary, perhaps caused by the departure of a mantle plume, might have 'pinned' the equatorial dipole in place. Their hypothesis builds on the notion that preferred VGP paths or recurring transitional VGP 'clusters' could reflect some non-GAD field structure that is maintained (or at least favored) by lower mantle structure, which dictates the heterogeneous pattern of heat flow across the core-mantle boundary and thus influences flow in the outer core (Hoffman and Singer, 2004; Kirscher et al., 2018; Kutzner and Christensen, 2004; Laj et al., 1991). Another intriguing possibility is presented by Costin and Buffett (2004), who show that preferred VGP paths could be generated by currents induced in a conducting layer at the base of the mantle during a reversal. If the lateral conductivity of this layer is relatable to core-mantle boundary topography (Buffett et al., 2000), one could expect lower mantle structure to impose long-term trends in transitional field behavior. However, both the nature and the statistical significance of preferred VGP paths or transitional VGP clusters remains a point of ongoing debate (Langereis et al., 1992; Love, 2000; McFadden et al., 1993; Valet and Fournier, 2016).

3.4.1. Predictions & appraisals

Here we maintain our convenient (if arbitrary) distinction between an 'unstable' GAD vs. a 'structured' non-GAD field. If the GAD remained intact but was simply hyperactive, the associated paleomagnetic directional changes would be extremely rapid ($\gg 10^\circ$ Ma^{-1}) and—aside from the antiparallel directions imposed by the dipole—could be frequently directionally erratic. The intensity of the hyperactively reversing field could moreover be very low (or otherwise unusually variable). The notion of a weak field at this time has recently gained support from a series of paleointensity investigations of Ediacaran igneous rocks from both Laurentia and Baltica. Ultra-low virtual dipole moment estimates of $\leq 1 \times 10^{22}$ Am^2 have been reported from the ~600–585 Ma Grenville dikes (Thallner et al., 2021a), ~580 Ma lavas among the Volyn series in Ukraine (Shcherbakova et al., 2019; Thallner et al., 2022) and the ~565 Ma Sept-Îles intrusion (Bono et al., 2019). For the late Ediacaran, virtual dipole moment estimates from ~560 Ma lavas of the Volyn series and the 550 Ma Skinner Cove volcanics reach slightly higher (but still very low) values, ranging from ~0.3–2.2 $\times 10^{22}$ Am^2 (Shcherbakova et al., 2019; Thallner et al., 2021b; Thallner et al., 2022).

Those 'ultra-low' intensities are significantly lower than field strength estimates from earlier Precambrian time and are an order of magnitude weaker than the present-day field (Fig. 1e), and so could reflect a progressive weakening of the dynamo just prior to ICN (Bono et al., 2019; Driscoll, 2016). Rising paleointensities in the late Ediacaran and into the early Cambrian could reflect a renewal of the geomagnetic field following ICN (Zhou et al., 2022), although ultra-low paleointensities have also been reported from the earliest Cambrian (Lloyd et al., 2022). Intriguingly, comparably weak, and directionally complex data are emerging from investigations of Devonian rocks too (Hawkins et al., 2019; Shcherbakova et al., 2017; van der Boon et al., 2022), and low paleointensities have been reported from an interval associated with frequent reversals in the mid-to-Late Jurassic (Kulakov et al., 2019; Tauxe et al., 2013). It has been suggested that these complex, ultra-weak fields could reflect a long-term (~200 Ma) cyclicity of the geodynamo (Biggin et al., 2012a; Meert et al., 2016), in which case the Ediacaran paleomagnetic record may not relate to ICN. Alternatively, if ICN occurred in the Ediacaran, then the weak Devonian field could reflect a later transition in the geodynamo related to the size of the growing inner core (Lhuillier et al., 2019), although weak to strong field transitions may also have occurred in earlier Precambrian time (Zhang et al., 2022). Further scrutiny of these alternative models is critically needed.

In addition to the evidence for a weak field, observations of hyperfrequent reversals in Ediacaran to middle Cambrian paleomagnetic records have been used to argue that the field was unstable then (Bazhenov et al., 2016; Duan et al., 2018; Gallet et al., 2019; Halls et al., 2015; Levashova et al., 2021; Shatsillo et al., 2015) (Fig. 1e). In two cases, cyclostratigraphic constraints accompanying magnetostratigraphic results have permitted quantitative estimates of the reversal rate in the Ediacaran: a rate of ~13 reversals per Ma (rpMa) was estimated from the mid-Ediacaran Rainstorm member of the Johnnie Fm. of southwestern Laurentia (Kodama, 2021) and a rate of ≥20 rpMa was estimated from the ~548 Ma Zigan Fm. of the South Urals (Bazhenov et al., 2016; Levashova et al., 2021). Gallet et al. (2019) similarly estimated a reversal rate of ≥20 rpMa from a biostratigraphically well-constrained middle Cambrian section in northeast Siberia, but it remains unclear whether the reversal rate remained continuously high between those times or whether it was only episodically so. In any case, these estimated rates are exceptionally rapid. For reference, the average reversal rate since the late Cambrian has been estimated to ~2.7 rpMa, and examples of rates approaching or possibly exceeding 10 rpMa are known only from brief intervals in the mid-Jurassic (170–160 Ma) and latest Devonian (~365 Ma) (Fig. 1e) (Hounslow et al., 2018). An outstanding question is whether the reversal rate intrinsically varies with the strength and stability of the dipole (Kulakov et al., 2019), but Gallet and Pavlov (2016) have suggested that these exceptionally high rates may represent a distinct 'hyperactive' state of the geodynamo.

Despite this evidence that the Ediacaran field was weak and hyperactive, it isn't straightforward to ascribe its complex paleomagnetic data to frequent transitional directions. One reason is because transitional directions still appear to constitute the minority in temporally near-continuous datasets: even in the magnetostratigraphic record from the late Ediacaran Zigan Fm. (≥ 20 rpMa), Bazhenov et al. (2016) and Levashova et al. (2021) estimated the fraction of transitional directions to comprise only ~10% of the dataset. A second issue relates to the apparent consistency among the observed paleopole groups (Fig. 4)—irrespective of which is deemed 'transitional'—because transitional records from the last few millions of years appear highly complex and whether they exhibit any statistically meaningful VGP corridors or clusters remains disputed (Love, 2000; McFadden et al., 1993; Valet and Fournier, 2016).

If the GAD was instead temporarily overpowered by a non-GAD field (e.g. an equatorial dipole), there must have been a transitional period between those two states. Given the timescales associated with secular variation and polarity reversals, this transition could be expected to be very rapid, resulting in rates of APW $\gg 10^\circ$ Ma^{-1} (Fig. 9 and Supp. Figs. S2, S3). If the non-GAD field was specifically dominated by an equatorial dipole, it could explain orthogonal directional datasets, as the position of the geomagnetic pole would shift by 90°. Such a change, being related to the global geomagnetic structure, should be observed at all locations at the same time, and the apparent polar displacements should be everywhere of the same magnitude (Fig. 9). If the equatorial dipole was furthermore stable ('pinned') in the equatorial plane, the reassembly of the individual plates back to their correct relative longitudes around the time of the transition would cause their contemporaneous paleomagnetic poles to collapse into two groups (Fig. 9c). Alternatively, if the equatorial dipole precessed about the equatorial plane, the corresponding assemblage of paleopoles would be expected to form a girdle normal to the spin-axis.

The compiled paleomagnetic observations exhibit several compelling similarities to the predictions associated with a 'pinned' equatorial dipole: (i) possibly simultaneous and (ii) extremely rapid directional changes on multiple plates involving (iii) a ~ 90° shift in the apparent

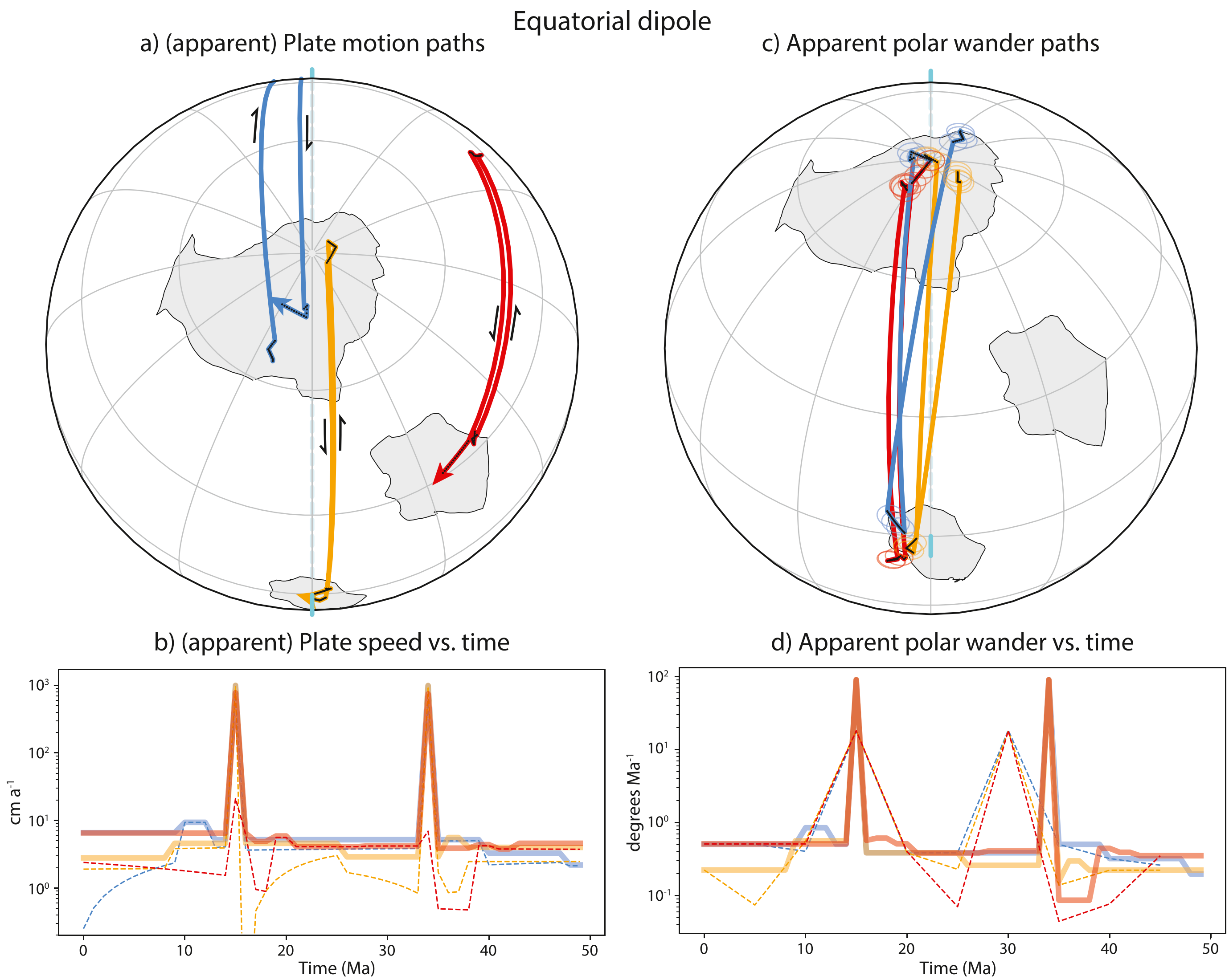

Fig. 9. A synthetic scenario of a transition from a geocentric axial dipole (GAD) to an equatorial dipole and back. This model is constructed from the same randomly-generated base kinematic model as used in Fig. 5 (Supp. Fig. S1). In this case, a temporary switch from a GAD to an equatorial dipole (arbitrarily oriented along the 0° meridian) is then superimposed on the base model. The transition time between these field states occurs in less than 1 Ma (yielding 'true' APW rates of $> 90^\circ$ Ma^{-1}; see Supp. Mat. for further details and additional results). a) (Apparent) motion paths of the centroids of the three plates from t = 50 Ma to t = 0 Ma. Black dots show the 1-Ma increments of motion. There are no black dots along the 'excursions' (which do not reflect any true motion of the solid Earth) because the transition rate occurs below their resolution. The light blue line along the central meridian shows the axis of the equatorial dipole. b) (Apparent) full plate speeds vs. time (solid lines) and the paleomagnetically resolvable north-south component of those motions vs. time (dashed lines). Note the log scale of the y-axis. c) APWPs of the three plates from t = 50 Ma to t = 0 Ma. Black dots show the 1-Ma increments of the APWP, whereas A95s (arbitrarily set to a standard size of 3°) are shown at 5 Ma intervals to indicate what might be practically observable from a series of high-resolution paleomagnetic studies. Note that the shapes of the APWPs are highly similar (the small differences being due to the underlying differential plate motions of the base model), but also that no poles actually capture the transition (which occurs below their temporal resolution). d) Complete rates of APWP vs. time (solid lines) and a lower-resolution version (dashed lines) determined only from poles with A95s in panel c (i.e. at 5 Ma intervals). The rates of APW are highly-correlated. Although the low-resolution APWPs do not capture the exact time or amplitude of the field transitions, they capture rates of APW $> 10^\circ$ Ma^{-1}.

position of the pole to (iv) another seemingly common and stable position (Fig. 4). The oscillatory motion of the APWPs in this case would represent the equatorial dipole giving way to GAD dominance again. The relative lack of paleomagnetic poles between these orthogonal directional groups is also anticipated by this hypothesis, given the pace at which the transition could have occurred ($\gg 10^\circ$ Ma^{-1}) (Fig. 9). However, there remain at least two significant challenges to this interpretation. The first is observational: the latest Ediacaran to early Cambrian paleomagnetic data from Baltica suggest another directional excursion occurred at that time, but no indication of this has yet been recognized in Laurentia or Northwest Africa. Is this signal from Baltica reliable? If so, does a second directional excursion remain to be discovered among the other continents? The second challenge is theoretical: how could an equatorial dipole remain pinned for long enough so as to be detected from such sparse paleomagnetic records? These questions present important opportunities for further investigation.

3.4.2. *Implications*

If the magnetic dipole was oriented at high-angle to the spin-axis during the Ediacaran, even if only for a few million years, the GAD-hypothesis would be rendered invalid for that time, and it would be questionable for all earlier times in Earth history. This would present an additional challenge to the construction of paleomagnetic-based paleogeographic reconstructions in Precambrian time—requiring independent evaluations of paleolatitude (Evans, 2006) and/or near-continuous paleomagnetic records anchored back to a known field structure. A greatly weakened and rapidly reversing magnetic field would also have allowed much more intense solar and cosmic radiation to reach the surface, with consequences for early life immediately prior to the Cambrian radiation—including possibly elevating the mutation and speciation rates (Fig. 1) (Meert et al., 2016). The occurrence of an equatorial dipole, ultra-low paleointensity and/or reversal hyperactivity would furthermore present unique constraints for geodynamo models that could be applied to constrain the physical properties of the core in the latest Precambrian.

4. Outlook

The various hypotheses proposed to explain the Ediacaran paleomagnetic data make distinguishable predictions for how the paleomagnetic directions should evolve through time and space (Table 2; Fig. 10). Hypotheses 1 (fast plate motion) and 3 (TPW) involve processes rate-limited by mantle viscosity, and thus predict rates of APW of $\lesssim$5–10° Ma^{-1}, whereas hypotheses 2 (widespread data corruption) and 4 (anomalous magnetic field) predict much faster APW rates ($\gg 10^\circ$ Ma^{-1}). Paleomagnetic records of fast individual plate motions can furthermore be distinguished from those of TPW according to their different predicted patterns of directional change at the global scale (uncorrelated sequences of small to great circles vs. correlated great circle trajectories). Likewise, records left by an anomalous field can be discriminated from corrupted records in that the former will have global, temporally coincident changes, whereas the latter are unlikely to be correlated at the global scale.

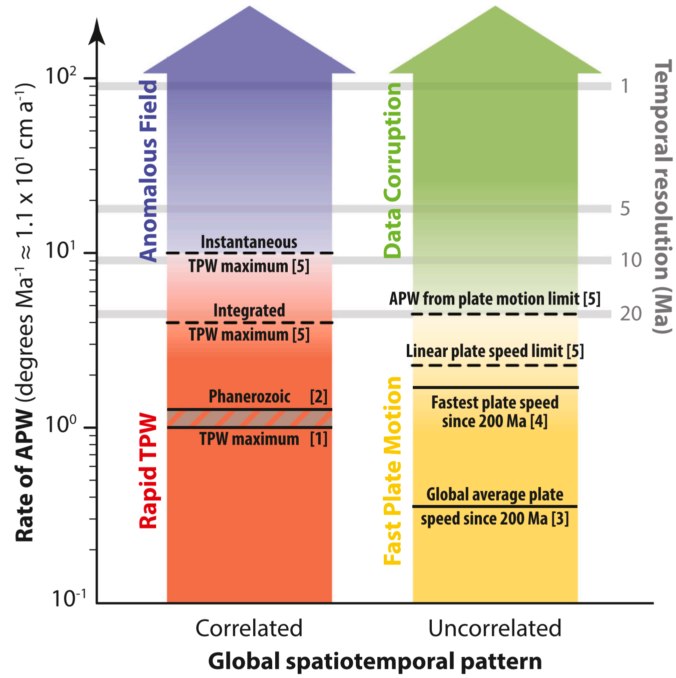

Fig. 10. Summary of predictions for how magnetic directions should evolve in space and time according to the four alternative hypotheses of: 1) fast plate motion, 2) data corruption, 3) rapid true polar wander (TPW), and 4) an anomalous magnetic field. Hypotheses 1 and 2 are not expected to exhibit any correlated changes in space or time at the global scale, whereas hypotheses 3 and 4 are globally-organized processes that should result in highly correlated signals. The horizontal black lines denote specific 'speed limits' associated with TPW and plate motion. Solid (dashed) lines denote estimates derived from observations (theoretical considerations), according to references in brackets: 1 = Torsvik et al. (2014); 2 = Mitchell et al. (2010); 3 = Zahirovic et al. (2015); 4 = Cande and Stegman (2011); 5 = discussed in this paper. 'Linear plate speed limit' is the rate of APW associated with pure translation, whereas the 'APW from plate motion limit' is the maximum rate including plate spin (see main text). Horizontal grey bars and corresponding y-axis on the right side show the minimum paleomagnetic resolution needed (in Ma) to recognize the corresponding APW rates on the left y-axis. Note that a resolution of ~ 20 Ma is sufficient to distinguish between fast differential plate motion and data corruption, whereas a resolution of ~ 10 Ma may be needed to distinguish between rapid TPW and an anomalous magnetic field.

Our analysis has revealed that fast plate motions are unlikely to be the main cause of the complex paleomagnetic data if the plate speed limit is on the order of 25 cm a^{-1}, but this theoretical limit—and how it may have varied through time—remains to be rigorously established. Widespread data corruption also appears unlikely to be able to entirely explain the enigmatic dataset, given the present collection of field test results and the observation that possibly spatiotemporally correlative directional changes are recorded on several distinct plates. However, continued scrutiny of the individual magnetic records, and especially

Table 2
Summarized predictions of the alternative hypotheses

Hypothesis	1. Fast plate motion	2. Data corruption	3. Rapid true polar wander	4. Anomalous magnetic field
Rate of APW	$\le 5^\circ$ Ma^{-1}	$\gg 10^\circ$ Ma^{-1}	$\le 10^\circ$ Ma^{-1}	$\gg 10^\circ$ Ma^{-1}
Local APW Pattern	Small to great circle segments (continuous)	Random (non-continuous)	Great circle arc (continuous)	Orthogonal groups or random (continuous)
Global APW Pattern	Random (uncorrelated)	Random (uncorrelated)	Common great circle arc	Common orthogonal groups or random (but correlated)
Geomagnetic effects	None	None	None	Hyper-activity? Ultra-low intensity?
Major expressions in other Earth systems	Large sea-level variations and/or plume eruptions on fast plates?	None	Quadrature pattern of sea-level variation and environmental change	Elevated rates of biological mutation?

novel studies of their fidelity, is warranted. The spatiotemporal APW pattern evident from the paleomagnetic data considered here is most consistent with the predictions made by the TPW and anomalous field (non-GAD) hypotheses, but additional high-resolution paleomagnetic data paired with precise geochronological constraints will be needed to further test (and distinguish) them. Temporally continuous directional datasets would be especially valuable. This presents a challenge, because although sedimentary successions can provide such temporally continuous records, they are often difficult to date. Fortunately, as the Ediacaran directional changes are of large amplitude (~90°), a temporal resolution of ~10 Ma should be sufficient to distinguish between processes rate-limited by mantle viscosity and those which are not (Fig. 10).

It is possible that more than one hypothesized mechanism operated at the same time. Indeed, some combination of plate motion, TPW, data corruption and non-GAD field behavior (i.e. secular variation) has occurred throughout the Phanerozoic, and the intensification of one of these processes in the Ediacaran could have resulted in amplification of another. For example, a larger subduction flux associated with faster plate motions could have driven swifter TPW (Robert et al., 2018). Rapid TPW could have significantly modified the pattern of heat flux across the core-mantle boundary, destabilizing the geodynamo and giving rise to an anomalous geomagnetic field (Biggin et al., 2012b). And an especially weak magnetic field would have yielded feeble primary magnetizations that could have been more easily masked by partial remagnetizations. In any case, given the distinct predictions made by these different phenomena, their relative contributions are likely separable with sufficient data. For this, the further development and analysis of records of relative sea-level and environmental change (which could reflect fast plate motions or TPW) and the strength and stability of the magnetic field (which could help constrain the field state) would provide valuable additional insights.

Although a number of alternative paleogeographic models for Ediacaran time have been published, they invariably arbitrarily dismiss some subset of the paleomagnetic data or otherwise struggle to explain them, and so at best these models should only be considered as relative paleogeographic models. However, if the nature of the rapid Ediacaran paleomagnetic directional changes can be established, the paleomagnetic data can be applied to build quantitative Ediacaran paleogeographic models with absolute paleolatitude. A global-scale, quantitative Ediacaran spatial framework is critically needed to resolve a series of major tectonic events—including the final dispersal of Rodinia and the assembly of Gondwana—to test the hypothesis of a fleeting late Ediacaran-early Cambrian supercontinent (Pannotia), and to contextualize the immense climatic, geochemical and biological changes that were occurring on Earth's surface across this period. If hypotheses 1, 3 or 4 (or some combination therein) are validated, the entire paleomagnetic dataset could be practically useful for paleogeographic application, whereas the validation of hypothesis 2 would require filtering to remove corrupted data. The validation of hypothesis 3 and/or 4 would further enable the quantitative determination of relative longitude in deep-time, which is otherwise not possible prior to the breakup of Pangea in the Early Jurassic. The validation of hypothesis 4 would also grant important new insights into the evolution of the geodynamo and the core, with relevance for ongoing debates concerning the timing of ICN. The testing of these four hypotheses is thus of central importance to understanding this critical transition from the Precambrian to the Phanerozoic, with implications potentially encompassing all the envelopes of the planet, from core to atmosphere. We therefore encourage the wider community to take up some of the many research questions raised herein, so that we may collectively solve this enduring enigma.

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.

Data availability

The code used to generate the simulations presented are available at: https://github.com/matdomeier/Ediacaran_enigma

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.earscirev.2023.104444.

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