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SUTTON HOTSPOT: RESOLVING EDIACARAN-CAMBRIAN TECTONICS AND TRUE POLAR WANDER FOR LAURENTIA

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ABSTRACT. Hotspot tracks represent plate motions relative to mantle sources, and paleomagnetic data from magmatic units along those tracks can quantify motions of those mantle anomalies relative to the Earth's magnetic field and rotational axis. The Ediacaran Period is notable for rapid and large paleomagnetic apparent polar wander (APW) for many continents. Whereas magmatic units attributed to the "Sutton" mantle plume suggest a practically stationary hotspot track, paleolatitudes of Laurentia for that interval vary dramatically; geologic and paleomagnetic data are at odds unless true polar wander (TPW) is invoked to explain a majority of APW. Here we test the plume-TPW hypothesis by generating the predicted Sutton hotspot track for a stationary plume under a moving plate along the Laurentian margin during the interval from 615 to 530 Ma. Our model is the first to provide a kinematic framework for the extensive large igneous province associated with opening the Iapetus Ocean.

Key words: Laurentia, Ediacaran, apparent polar wander (APW), true polar wander (TPW), plate tectonics, hotspot

INTRODUCTION

Hotspot tracks on Earth have been used to quantify motions of tectonic plates, under the assumption that the magmatism defining hotspot tracks is sourced from stationary plumes in the deep mantle (Morgan, 1968; Morgan, 1971; Wilson, 1973; Müller and others, 1993). Whereas recent paleomagnetic data (Tarduno and Cottrell, 1997; Tarduno, 2007) and mantle convection models (Steinberger and others, 2004) indicate non-negligible relative motion between plumes, such motion occurs at slow rates of $\sim$1 cm yr^{-1}, allowing the use of a "hotspot" mantle reference frame with precision of that order—somewhat crude by the standards of plate reconstructions for the past 200 million years that are obtained precisely by magnetic anomalies and fracture zone patterns on extant seafloor, but potentially useful for older periods of Earth history lacking those datasets (Irving, 1981).

The ancient geological record abounds with large igneous provinces (LIPs; most preserved as dike swarms), many of which are thought to originate from mantle plumes (Ernst and others, 2005). Only a few instances of hotspot tracks with coherent age progressions, however, have been postulated from times older than 200 Ma (Betts and others, 2007; Halls and others, 2008; French and Heaman, 2010). In principle, if a mantle plume is stationary relative to Earth's time-averaged geomagnetic field reference frame (and the geomagnetic and rotational reference frames are coincident as

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verified for the Quaternary (McElhinny and others, 1996) and older periods (Evans, 2006), then its hotspot track recorded on a uniformly-rotating tectonic plate should define a segment of a small circle about the same Euler pole as another small-circle segment defined by that plate's paleomagnetic poles (Gordon and others, 1984). If a mantle plume is in motion relative to the geomagnetic reference frame, either through individual motion (for example, Steinberger and others, 2004) or TPW rotation, then such relationships vanish.

The Ediacaran-Cambrian interval is characterized by paleomagnetic data that imply, for each paleocontinent, rapid rotations or translations equivalent to or exceeding 10 to 20 cm yr^{-1} (Gallet and others, 2003; Llanos and others, 2005; McCausland and others, 2007; Mitchell and others, 2010; Schmidt and Williams, 2010), in marked contrast to more typical continental rates of a few cm yr^{-1} (Meert and others, 1993). TPW has been proposed as a mechanism for such rapid motions (Evans, 1998; Evans, 2003), which are dynamically permitted if absolute mantle viscosity were sufficiently low to accommodate dissipative flexure through Earth's rotational bulge (Tsai and Stevenson, 2007). Alternatively, a more rapid style of plate tectonics driven by traction on deep continental roots (Gurnis and Torsvik, 1994) or non-uniformitarian geomagnetic field behavior—specifically an equatorial-axial dipole oscillation (Abrajevitch and Van der Voo, 2010)—could be invoked to explain the data.

Identification of an Ediacaran-Cambrian plume track across a paleocontinent could help distinguish among these alternatives. The rapid plate motion model predicts a long hotspot track while the plate moves relative to a fixed mantle source. The TPW model predicts a short hotspot track, *contra* fast motion implied by the paleomagnetic data, while the plate moves together with the fixed mantle source.

In eastern Laurentia, voluminous and long-lived Ediacaran-Cambrian magmatism, largely mafic but with subordinate felsic units, has been attributed to a mantle plume, named "Sutton" after an area with prominent potential-field geophysical anomalies (Kumarapeli and others, 1981; Kumarapeli, 1993; Puffer, 2002; Hodych and Cox, 2007). These magmatic units yield a wide range of paleomagnetic inclination, implying large changes in paleolatitude under the assumption of a geocentric-axial dipole magnetic field and inspiring several nonuniformitarian hypotheses for Ediacaran-Cambrian geodynamics. Both high- and low-paleolatitude subsets of data include reliable, demonstrably primary magnetizations dating to initial post-crystallization cooling of the host rocks. Broad-scale ($<$1000 km) fixity of magmatism along the eastern Laurentian margin would appear to support the TPW model (Hodych and Cox, 2007). Those authors specifically reasoned that the large amounts of APW without evidence for a long hotspot track supported the notion that APW may be predominantly attributable to TPW.

Here we propose a more refined plume model for Ediacaran-Cambrian eastern Laurentian magmatism, using the paleomagnetic data to isolate a TPW component of motion that is nearly orthogonal (by happenstance) to a component of individual plate rotation relative to the Sutton plume. Our model is compatible with a single stationary Sutton plume.

Evidence for Sutton hotspot?

Over 30 mafic magmatic events intrude the eastern margin of Laurentia during Ediacaran-Cambrian time, *ca.* 615 to 530 Ma. Various datasets suggest that these intrusions orignated at depth from a common hotspot magma source (Kumarapeli, 1993; Puffer, 2002; Hodych and Cox, 2007). First, the Sutton Mountains magnetic and gravity anomaly, due to an 8 km pile of Tibbit Hill volcanics, is epicentral to the postulated plume source and lends its name to the putative hotspot (Kumarapeli and others, 1981). Second, dike trends fan over $\sim$180° as preserved on the margin of

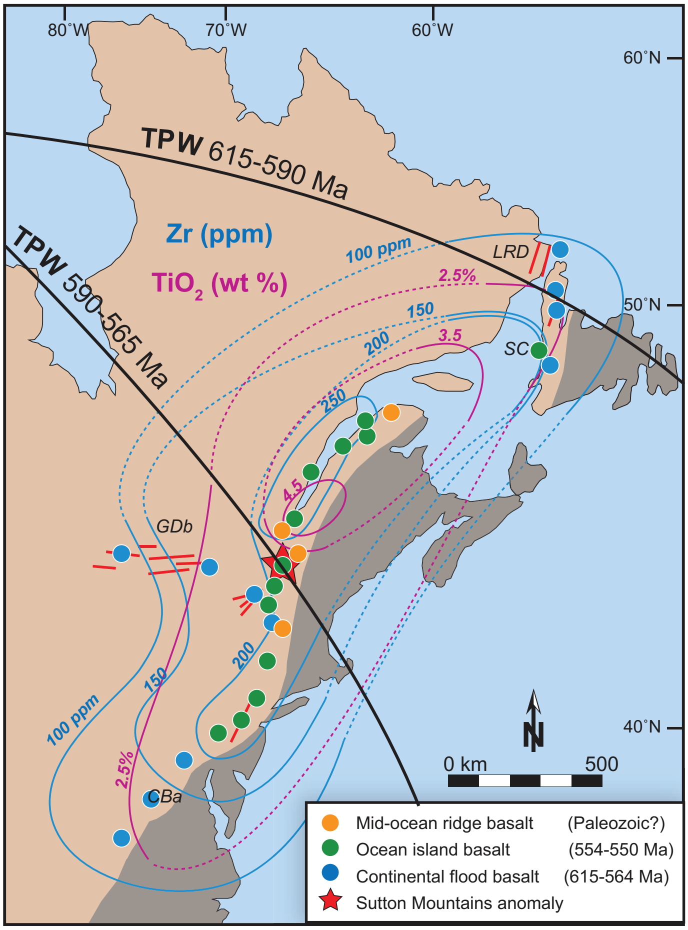

Fig. 1. Distribution and type of circum-Sutton magmatism. Contour plots of high field strength elements Ti (as wt% TiO_2) and Zr (ppm). Red lines depict the average strike of various dike swarms. Intrusions are color-coded (blue, orange, green) according to distinct geochemical groups (Puffer, 2002) in legend. Paleozoic mid-ocean ridge basalt (green) volcanics are not involved in contouring. Gray shading on North American continent denotes subsequently accreted Phanerozoic crust. Italicized abbreviations refer to units with paleomagnetic poles (table 1).

Laurentia, between south-trending New Jersey Highlands dikes near the eastern margin of Laurentia, west-trending Adirondack Mountain dikes southwest of Sutton Mountain, and north-trending Long Range dikes to the north in Newfoundland's Humber Zone (fig. 1). Comparison between terrane-derived and cratonic paleomagnetic poles suggests that Long Range dikes in Newfoundland and Labrador are subparallel instead of fanning (McCausland and others, 2009). In general, these Sutton-associated dikes and the west-trending Grenville dikes could be interpreted as an ephemeral triple junction (Burke and Dewey, 1973; Kumarapeli, 1993). Third, contour plots of the high field strength elements, Ti (as wt % TiO_2) and Zr (ppm), independently reveal a focal region centered about (~100 km north of) the dike convergence at the Sutton Mountains anomaly (fig. 1). High field strength elements are considered for this purpose owing to their resilience to metasomatism and hydrothermal alteration (relatively mobile elements such as Ba or Sr, for example,

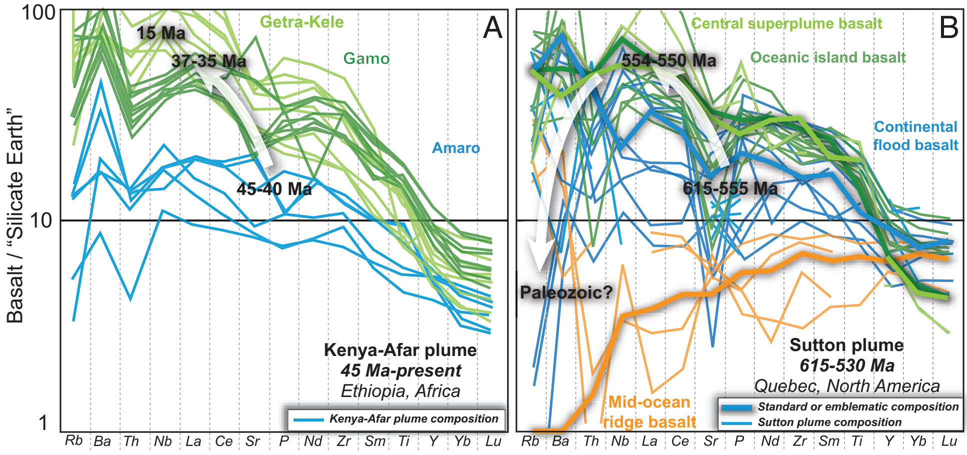

Fig. 2. Trace element concentration compilation for (A) the Kenya-Afar plume, a modern analog for (B) the Sutton plume. These depict the "ascent trend" or geochemical evolution (thick white arrow) from continental flood and central superplume basalt, to oceanic island basalt, to post-plume mid-ocean ridge basalt. Data from Laurentia (thin lines) are normalized to the "silicate Earth" of McDonough and Sun (McDonough and Sun, 1995) (a.k.a. "primitive mantle"). Data interpreted as continental flood basalt (blue) come from table 3 of Puffer (2002); data interpreted as oceanic island basalt (dark green) come from table 2 of Puffer (2002); data interpreted as central superplume (light green) come from ankaramite flows of the Skinner Cover Formation, Newfoundland (Baker, 1979) and alkaline basalts of the Sillery Formation, Quebec (Vermette and others, 1993; Olive and others, 1997); data interpreted as mid-ocean ridge (orange) come from table 4 of Puffer (Puffer, 2002); and data from Matapédia and St. Anselme flows (Hodych and Cox, 2007) have been appended to Puffer's compilation. Emblematic or standard geochemical data of each type of basalt (bold lines) are plotted for comparison with Ediacaran-Cambrian data and are accordingly colored as above: oceanic island and mid-ocean ridge basalts (Sun and McDonough, 1989), Columbia River continental flood basalt (Hooper and Hawkesworth, 1993), and Cenozoic Hiva Oa central superplume basalt (Kogiso and others, 1997).

have comparatively large standard deviations, likely a side-effect of secondary alteration; see tables in Puffer (2002) and figure 2B. Although Ti and Zr abundances are by themselves, not diagnostic of a plume origin, their relative abundance in Ediacaran-Cambrian mafic rocks near Sutton and the pattern of decreasing concentrations radially away from Sutton along the coast of Laurentia suggest a long-lived source of magma that was centered below the Sutton Mountains area. Invoking more than one plume to explain the coincidence of radiating dikes, concentrated high field strength elements, and both gravity and magnetic anomalies is less parsimonious than a stationary hotspot track hypothesis.

The fixed Sutton hotspot interpretation is consistent with an evolutionary trend in magma composition (rare earth elements), diagnostic of a deep mantle source that rises and assimilates increasing amounts of partial melt from ever-shallower lithosphere (fig. 2B). Schematic representation of a modern analog, the Kenyan-Afar plume (George and Rogers, 2002), is provided in figure 2A for comparison. First, the Amaro tholeiites, of continental flood basalt affinity, erupted in southern Ethiopia from 45 to 40 Ma. Second, the Gamo transitional tholeiites, of ocean island affinity, erupted from 40 to 35 Ma. Third, and coincident with the onset of Miocene extension, the Getra-Kele alkali basalts of central superplume basalt affinity erupted from 19 to 11 Ma. For the Kenya-Afar plume the geochemical "ascent trend" has lasted as of now 45 Myr—compared to, as we will see, ~65 Myr for the Sutton plume. Eventually, if the East African rift develops a spreading ocean basin, trace element concentrations will evolve to resemble mid-ocean ridge basalt, as observed in the Sutton plume case (fig. 2B).

Widespread Sutton events from 615 to 555 Ma characterize a continental flood basalt composition, consistent with a plume head impinging on the base of the lithosphere and incorporating subcontinental sources. Later, from 554 to 550 Ma, less-widespread events are characteristic of ocean island basalt (OIB) compositions. OIB compositions should follow those of continental flood basalt in time as the lithosphere thins. [Note that the ~10 Myr gap between flood basalt and OIB compositions of Puffer (2002) has been bridged subsequently with new data from the *ca.* 565 to 556 Ma Lac Matapédia basalts (Hodych and Cox, 2007); however, additionally note that we interpret Matapédia as continental flood-derived instead of OIB (Hodych and Cox, 2007).] The compositions of Skinner Cove Formation ankaramite flows and Sillery Formation alkaline basalts, which occur near the center of the Sutton hotspot, are indistinguishable from the diagnostic superplume composition as exemplified by Cenozoic Hiva Oa basalts from the Polynesian superswell and superplume (Puffer, 2002). Finally, circum-Sutton magmatism evolves into mid-ocean ridge basalt compositions, signaling the cessation of hotspot-derived melt.

One crucial test of the Sutton hotspot hypothesis has not been conducted yet: is the paleomagnetically-derived Ediacaran-Cambrian plate motion of Laurentia compatible with the Sutton hotspot track that remains stationary with respect to Laurentia? Hodych and Cox, (2007) point out that if we are to interpret circum-Sutton mafic magmatism as a deep-mantle hotspot, then we must interpret a majority of the appreciable Ediacaran APW as TPW because TPW allows lower mantle plume conduits to move in latitude while remaining fixed with respect to the lithosphere.

EDIACARAN TRUE POLAR WANDER

Detailed discussion of the highest-quality paleomagnetic data for Ediacaran time from Laurentia can be found in McCausland and others (2007) and Hodych and Cox (2007). Our pole list closely resembles that of McCausland and others (2007) (table 1; fig. 3) except only rock units directly dated by U-Pb geochronology are included (one exception being the pole from the Johnnie Formation). Two Ar-Ar results, 583 Ma Baie des Moutons syenite (McCausland and others, 2011) and 533 Ma Mont Rigaud stock (McCausland and others, 2007), are excluded because direct comparison to U-Pb results is not straightforward. The Grenville dikes, for example, yielded both a U-Pb age of 590 ± 2 Ma (Kamo and others, 1995) and an Ar-Ar age of 570 ± 3 Ma (Hyodo and others, 1993). Age constraints and references for all poles can be found in table 1. As has long been observed (McCausland and Hodych, 1998; McCausland and others, 2006; McCausland and others, 2007; Pisarevsky and others, 2008; Buchan and Hamilton, 2009), Ediacaran poles for Laurentia spread between low and high latitudes (fig. 3).

Rates of Ediacaran APW for Laurentia exceed both the observed maximum long-term rate of plate tectonics [~15 cm yr^{-1} northward drift of India following Gondwana breakup (Besse and Courtillot, 2002; Besse and Courtillot, 2003)] and the theoretical decimeter-per-year speed limit associated with bending stresses on a subducting slab (Conrad and Hager, 2001). The geometry, magnitude, and rate of Ediacaran APW displacements, on the other hand, are reconcilable with the theoretical understanding of TPW (Tsai and Stevenson, 2007), provided sufficiently small lower mantle viscosity.

Using the pole list in table 1, with a reference location (60°N, 270°E) near the center of Laurentia, we track the continent's paleolatitude through time (fig. 4A). The paleolatitude path implies a pair of symmetric rotations that translate Laurentia from the equator, over the pole, and back. Both rotations are very rapid (~35-140 cm yr^{-1}). It should be noted that these TPW rates, like others proposed for Neoproterozoic time (Maloof and others, 2006), exceed the calculated "speed limit" of 27 cm yr^{-1} for TPW as parameterized by present-day mantle viscosity structure and an average mantle

Table 1

Paleomagnetic poles for Laurentia for Ediacaran-Cambrian (615-530 Ma) time

Rock Unit and Remanences	ID	Slat (°N)	Slong (°E)	Plat (°N)	Plong (°E)	A95 (°)	Dec* (°)	Inc* (°)	Age (Ma)	± (Myr)	Age (Max)	Age (Min)	Paleomagnetic Reference	Age Reference	Comments
Long Range dikes	LRD	53.7	303.4	-6	165	9.8	280	-24	615	2	617	613	McCausland and others (2010)	Kamo and others (1989)	
Grenville dikes B	GDb	46.0	282.0	-62	70	14	110	-85	590	2	592	588	Murthy (1971); Buchan and others (2004); Hyodo and Dunlop (1993)	Kamo and others (1995)	
Callander Complex syenite	CC	46.2	280.6	-51	103	8	315	-84	577	1	578	576	Symons and Chiasson (1991)	Kamo and others (1995)	composite result broken apart
Catoctin basalts A	CBa	38.5	281.8	-42	117	18	305	-77	572	5	577	567	Meert and others (1994)	Aleinikoff and others (1995)	regarded as primary magnetization; pole longitude corrected
Sept Iles Complex A	SIa	50.2	293.5	20	141	8	313	0.1	565	4	569	561	Tanczyk and others (1987)	Higgins and van Breemen (1998)	
Johnnie Rainstorm Member (rotated)	JO	36.8	244.7	5	151	5.3	298	-19	ca. 560		570	550	Van Alstine and Gillett (1979)	Corsetti and Kaufman (2003); Le Guerroué (2010)	correction for oroclinal rotations; overlain by δC^{13} correlation to end of Shuram excursion;
Skinner Cove Formation	SC	49.5	302.0	15	157	9	297	4.1	551	3,2	554	549	McCausland and Hodych (1998)	McCausland and others (1997)	
Unicoi (rotated)	UV	36.6	298.2	15	166	15	290	12	ca. 541		546	536	Brown and van der Voo (1982)	Walker and Driese (1991)	recalculation with Taconic correction for Ordovician: account for 20° CW rotation to restore Taconic overprint to other Ordovician poles; then add 5° uncertainty

* Calculated for reference locality at 60°N, 270°E near the Sutton anomaly (figs. 3 and 4).

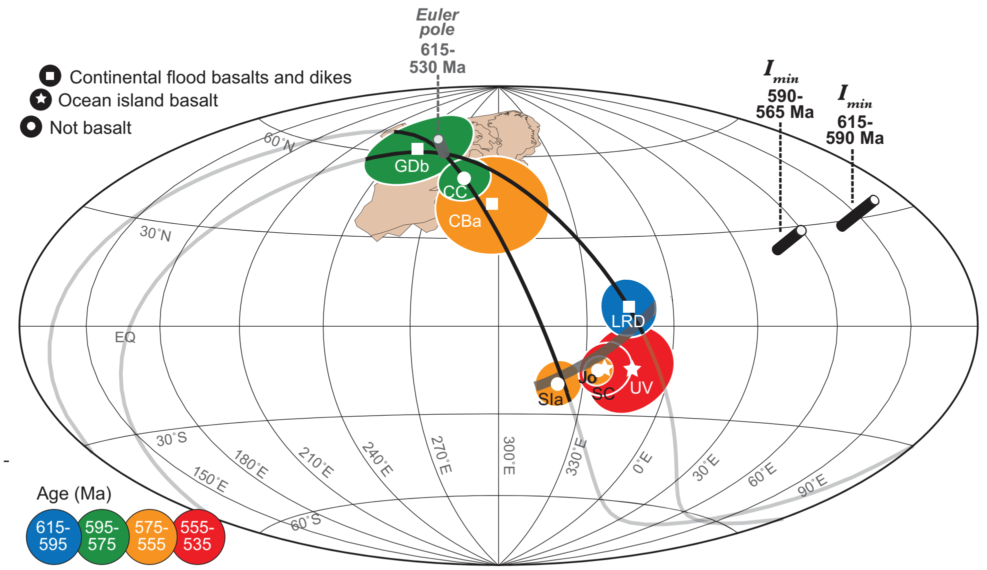

Fig. 3. Ediacaran-Cambrian (615-530 Ma) paleomagnetic poles for Laurentia. All poles (except Jo, Johnnie Rainstorm Formation) are dated by U-Pb methods and earn Q-values (Van der Voo, 1990) of reliability of ≥3: LRD, Long Range dikes; GDb, Grenville dikes "B" remanence; CC, Callander Complex mean syenite direction; CBa, Catoctin basalts "A" remanence; SIa, Septs-Îles mafic suite "A" remanence; SC, Skinner Cove volcanics; and UV, Unicoi volcanics. Poles are color-coded according to ages and references listed in table 1. Black great circles and associated poles respectively represent the TPW tracks and minimum moments of inertia (I_{min}'s) for two Ediacaran TPW events. Gray small circle and associated pole is Euler pole for Ediacaran-Cambrian plate motions. Symbols at pole centers indicate rock composition, relevant to Sutton hotspot (fig. 1).

viscosity of 10^{22} Pa s (Tsai and Stevenson, 2007). Although a theory is beyond this contribution, it may be possible that lower mantle viscosity, which chiefly limits TPW rate, is sensitive to secular and cyclic changes in global heat budget. We note that the putative TPW events oscillate (that is, a TPW roundtrip), just like the two TPW events bracketing the ~800 Ma Bitter Springs Stage (Maloof and others, 2006) and the two TPW roundtrips during the rifting phase of Pangea (Steinberger and Torsvik, 2008).

The pair of Ediacaran paleomagnetic shifts, if TPW events, predict two significant albeit transient global sea level changes (Mound and others, 1999). The first poleward TPW rotation predicts a transient sea level drop for Laurentia sometime between 610 and 590 Ma. The second equator-bound TPW rotation predicts a transient sea level rise in Laurentia sometime between 590 and 560 Ma. Laurentia's stratigraphic and paleomagnetic records can be integrated with the paleomagnetic pole from the Rainstorm Member of the Johnnie Formation in Death Valley. Unfortunately, radiometric constrains on the age of the Rainstorm Member are coarse and indirect. The Rainstorm pole is stratigraphically constrained to be younger than the Sentinel Peak Member cap dolostone of the Noonday Formation (Petterson and others, 2011), which is lithostratigraphically correlated to Marinoan cap dolostones dated at ~635 Ma in Namibia (Hoffman and others, 2004) and South China (Condon and others, 2005). The upper Rainstorm Member pole likely is older than a minimum age constraint of 550.5 Ma on the recovery from the Shuram-Wonoka negative $\delta^{13}C$ anomaly in South China (Condon and others, 2005). The "Johnnie Oolite" within the Rainstorm Member marks a major marine transgression and increase in carbonate deposition in southwest Laurentia (Verdel and others, 2011). One interpretation consistent with the

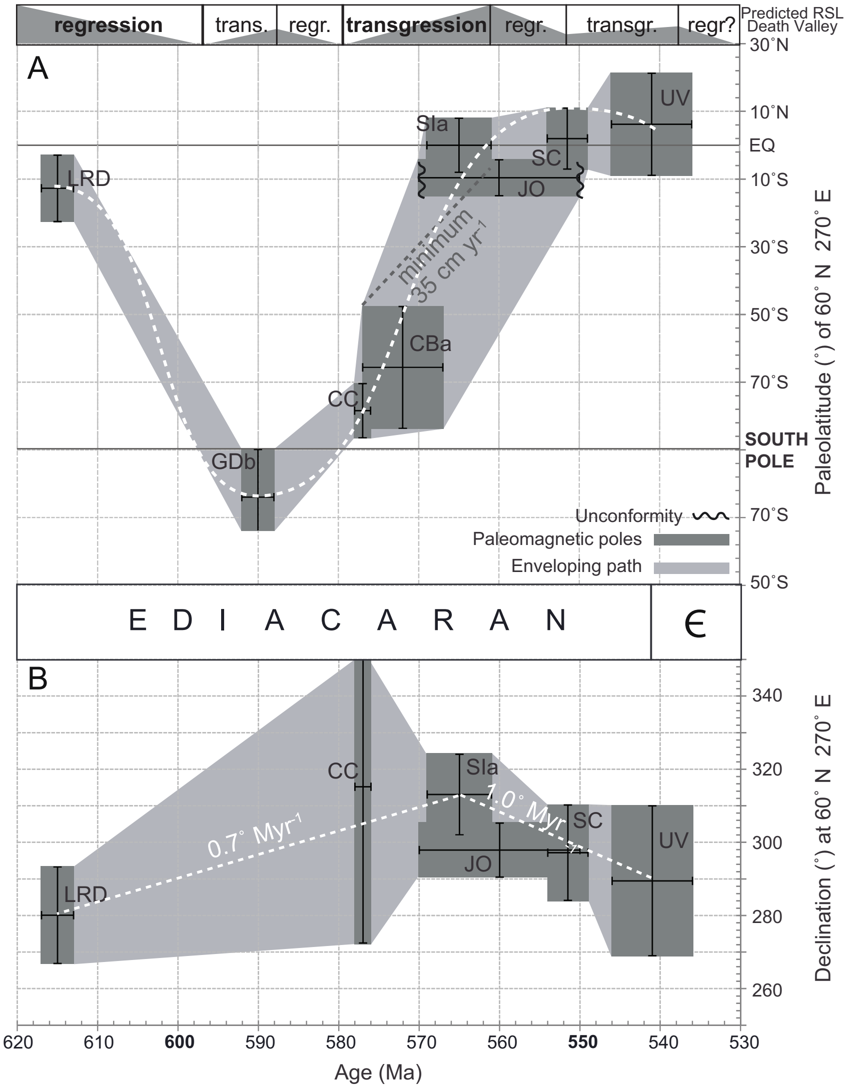

Fig. 4. Components of Laurentia's motion through Ediacaran-Cambrian (615-530 Ma) time. (A) Paleolatitude of Laurentia (relative to a reference locality at 60°N, 270°E near center of Laurentia), which can be considered a proxy for TPW because that continent is roughly orthogonal with I_{min} (fig. 3). Dashed gray line illustrates the minimum slope, implying at least 35 cm yr^{-1} TPW rate. This rate, we argue, must be TPW and not tectonics, because the hot spot magmatism from which the paleomagnetism is derived is fixed relative to Laurentia. Dashed white sinusoid modeled after expected waveform if interpreted as TPW (Tsai and Stevenson, 2007). Predicted RSL Death Valley: the TPW contribution to regional sea level in Death Valley is depicted above the paleolatitude curve. For the only stratigraphically constrained paleomagnetic data (Jo), a flooding surface marks the base of the "Johnnie Oolite", and an erosional unconformity marks the top of the Rainstorm Member of the Johnnie Formation in Death Valley. See text for discussion of stratigraphic evidence for/against sea level predictions. (B) Declination of Laurentia (as observed from same reference locality), which can be considered a proxy for plate motion because the Euler pole is proximal (fig. 3). Dashed line illustrates average angular velocities of Ediacaran-Cambrian plate motions. Dark gray boxes are poles and their respective uncertainties; light gray background fields indicate the trend for each component of motion. Pole abbreviations from table 1.

paleomagnetic data and coarse age constraints (fig. 4A) is that deposition of the Johnnie Oolite began during transient sea level rise when southwestern Laurentia rotated equatorward and into the carbonate belt. The erosional unconformity overlying the Johnnie Formation could be partly associated with post-TPW dissipation of the transient sea level rise.

The strength of the Sutton-hotspot-TPW hypothesis is that it can be tested further by generating continuous paleomagnetic records across stratigraphic intervals containing the Shuram-Wonoka negative $\delta^{13}C$ excursion, which, whether related to primary seawater dissolved organic carbon or diagenetic processes, appears to be a broadly synchronous event globally (Grotzinger and others, 2011). For now, we can start by looking at existing physical and chemostratigraphic records. South Australia [Wonoka Formation (Calver, 2000; Schmidt and Williams, 2010)] and Oman [Shuram Formation (Fike and others, 2006)] should have been geographically close to I_{min}, based on rapid late Ediacaran APW shifts from the former region (Schmidt and Williams, 2010), which are permissible as TPW given lax age constraints on the host sedimentary units. Therefore, the lack of significant transient sea level change associated with the Shuram-Wonoka isotope anomaly in South Australia and Oman is consistent with geographic predictions for large changes in declination without significant sea level change.

Non-uniformitarian magnetic fields could provide an alternative explanation to TPW for Ediacaran APW. Specifically, an alternation between axial and equatorial dipoles has been proposed to explain Laurentia's apparent oscillation between low and high latitudes (Abrajevitch and Van der Voo, 2010). Equatorial dipoles, however, have only been observed on giant gas planets, Neptune and Uranus, with very low outer core Rayleigh numbers (Aubert and Wicht, 2004) and unusually large conducting inner cores (Stanley and Bloxham, 2004). We cannot discount all non-uniformitarian magnetic field hypotheses to explain anomalous Ediacaran APW, but the long durations (fig. 4A) and dual polarities observed in both pole groups suggest their common stability far exceeds that of observed Cenozoic equatorial dipole flux patches on Earth (Hoffman and Singer, 2006).

Ediacaran tectonic motions of Laurentia

The pole to the great circle fit to paleomagnetic poles recording a TPW rotation should represent the location of Earth's instantaneous minimum moment of nonhydrostatic inertia (I_{min}). For Laurentia during Ediacaran time, we note that the great circles fitted to the two TPW events are offset from each other (fig. 3). We interpret this offset as representing Laurentia's true plate tectonic drift relative to the reference frame of Rodinia's stable I_{min}. That the I_{min} offset is largely azimuthal for a continent remaining essentially orthogonal with I_{min} conveys that Laurentia rotated about a nearby Euler pole in that reference frame. It is illustrative to consider how paleomagnetic declination changed through time. By definition, declination must be considered in local coordinates, so we once again employ our reference locality (60°N, 270°E) (table 1). Near the poles, declination becomes ambiguous, which is why we omit the highest latitude poles from Grenville dikes and Catoctin basalts (errors are too large for data to be guiding).

The declination data display two clear linear trends back and forth from 615 to 530 Ma (fig. 4B). The strength of these declination trends amplifies the quality of Ediacaran paleomagnetic poles for Laurentia, which often have been considered exclusively for their inclinations (McCausland and Hodych, 1998; Hodych and others, 2004; Hodych and Cox, 2007; McCausland and others, 2007). In contrast, our analysis considering both inclinations and declinations indicates that trends are surprising, but nonetheless clear: two symmetric Ediacaran TPW events (largely affecting inclination) (fig. 4A) were accompanied and followed by two back-and-forth plate rotations (largely affecting declination) (fig. 4B).

In order to characterize precisely the plate motions during Ediacaran TPW and in the Cambrian, we fit a small circle to those (low-latitude) poles of the APW track that are minimally affected by TPW (fig. 3). Although many different small circles are possible or different circles could be fit to several APW segments, we note that one small circle with an Euler pole at a reference location of 60°N, 270°E, near the center of Laurentia and proximal to the Sutton plume magmatism, successfully intersects all poles and implies that the Sutton hotspot track could have been essentially stationary (Puffer, 2002; Halls and others, 2009). The rotational velocities of Laurentia's Ediacaran plate motions are ~1° Myr^{-1} (fig. 4B), on par with present-day rates (Stampfli and Borel, 2002). Plate motion appears to change direction once rapid TPW ceases (fig. 4), suggesting the two phenomena may be related. During TPW, Laurentia rotated counterclockwise. Subsequently, it rotated clockwise at approximately equal and opposite velocity. This 565 Ma cusp in Ediacaran plate motion of Laurentia is identifiable as the initial rift basin development prior to Early Cambrian opening of the Iapetus paleocean (McCausland and Hodych, 1998).

CONCLUSION

At least two TPW events occurred in the Ediacaran period at fast rates of ~35 to 140 cm yr^{-1}. Subtracting the effects of both TPW events from the Laurentian paleomagnetic record allows us to track the ~1° Myr^{-1} drift of that continent, relative to the deep mantle, during the TPW oscillation. By comparing the predicted stationary Sutton hotspot track to our quantified relative amounts of Ediacaran-Cambrian plate tectonics and TPW for Laurentia, we propose a potential solution to the previously paradoxical geologic and paleomagnetic records of North America. Our plume-TPW hypothesis is broadly consistent with data from the Laurentian Johnnie Formation, and is testable with new integrated stratigraphic records of paleomagnetism and sea level from contemporaneous sedimentary basins around the world.

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