4 The Precambrian paleogeography of Laurentia

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4.1 Abstract

Laurentia is the craton that forms the Precambrian core of North America and was a major continent throughout the majority of the Proterozoic. The paleogeographic position of Laurentia is key to the development of reconstructions of Proterozoic paleogeography including the Paleoproterozoic-Mesoproterozoic Nuna and Neoproterozoic Rodinia supercontinents. There is a rich record of Precambrian paleomagnetic poles from Laurentia, as well as an extensive and well-documented geologic history of tectonism. These geologic and paleomagnetic records are increasingly better constrained geochronologically and are both key to evaluating and developing paleogeographic models. These data from Laurentia provides strong-support for mobile lid plate tectonic processes operating continuously over the past 2.2 billion years.

4.2 Introduction and broad tectonic history

Laurentia refers to the craton that forms the Precambrian interior of North America and Greenland (Fig. 1). Laurentia comprises multiple Archean provinces that had unique histories prior to their amalgamation in the Paleoproterozoic, as well as tectonic zones of crustal growth that post-date this assembly (Hoffman, 1989; Whitmeyer and Karlstrom, 2007). Collision between the Superior province and the composite Slave+Rae+Hearne provinces that resulted in the Trans-Hudson orogeny represents a major event in the formation of Laurentia (Corrigan et al., 2009). Terminal collision recorded in the Trans-Hudson orogen is estimated to have been ca. 1.86 to 1.82 Ga based on constraints such as U-Pb dating of monazite grains and zircon rims (Skipton et al., 2016; Weller and St-Onge, 2017, e.g.). A period of accretionary and collisional orogenesis is recorded in the constituent provinces and terranes of Laurentia leading up to the terminal collision of the Trans-Hudson orogeny. This overall story of rapid Paleoproterozoic amalgamation of Laurentia's constituent Archean provinces, including the terminal Trans-Hudson orogeny, was synthesized in the seminal *United Plates of America* paper of Hoffman (1988) and has been refined in the time since – particularly with additional geochronological constraints. Of most relevance here are the events that led to the suturing of more major Archean provinces: the Thelon orogen associated with the collision between the Slave and Rae provinces ca. 2.0 to 1.9 Ga (Hoffman, 1989); the Snowbird orogen associated with ca. 1.89 Ga collision between the Rae and Hearne provinces and associated terranes (Berman et al., 2007); the Nagssugtoqidian orogen due to the ca. 1.86 to 1.84 Ga collision between the Rae and North Atlantic provinces (St-Onge et al., 2009); and the Torngat orogen resulting from the ca. 1.87 to 1.85 Ga collision of the Meta Incognita province (grouped with the Rae province in older compilations) with the North Atlantic province (St-Onge et al., 2009).

As for the suturing of the Wyoming province to Laurentia, many models posit that it was conjoined with Hearne and associated provinces at the time of the Trans-Hudson orogeny (e.g. St-Onge et al., 2009; Pehrsson et al., 2015) or was proximal to Hearne and Superior while still undergoing continued translation up to ca. 1.80 Ga (Whitmeyer and Karlstrom, 2007). A contrasting view has been been proposed that the Wyoming province and Medicine Hat blocks were not conjoined with the other Laurentia provinces until ca. 1.72 Ga (Kilian et al., 2016). This interpretation is argued to be consistent with geochronological constraints on monazite and metamorphic zircon indicating active collisional orogenesis associated with the Big Sky orogen on the northern margin of the craton as late as ca. 1.75 to 1.72 Ga (Condit et al., 2015) and ca. 1.72 tectonomagmatic activity in the Black Hills region (Redden et al., 1990). However, the evidence for earlier orogenesis ca. 1.78 to 1.75 in the Black Hills (Dahl et al., 1999; Hrncir et al., 2017), as well as high-grade metamorphism as early as ca. 1.81 Ga in the Big Sky orogen (Condit et al., 2015), may support the interpretation of Hrncir et al. (2017) that ca. 1.72 Ga activity is a minor overprint on ca. 1.75 terminal suturing between Wyoming and Superior. Regardless, in both of these interpretations, Wyoming is a later addition to Laurentia with final suturing post-dating ca.

1.82 Ga amalgamation of Archean provinces with the Trans-Hudson orogen further to the northeast. Overall, the collision of these Archean microcontinents between ca. 1.9 and 1.8 Ga led to rapid amalgamation of the majority of the Laurentia craton (Fig. 1).

Crustal growth also progressed in the Paleoproterozoic through accretionary orogenesis. This accretion occurred within the Wopmay orogen through ca. 1.88 Ga arc-continent collision that led to the accretion of the Hottah terrane (the Calderian orogeny) and the subsequent emplacement of the Great Bear magmatic zone from ca. 1.88 to 1.84 Ga (Hildebrand et al., 2009). Coeval with the Trans-Hudson orogeny was the peripheral Penokean orogeny during which both microcontinent blocks (the Marshfield terrane) and arc terranes accreted on the southeastern margin of the west Superior province ca. 1.86 to 1.82 (Schulz and Cannon, 2007). Firm evidence of the end of the orogeny comes from the ca. 1.78 undeformed plutons of the post-Penokean East Central Minnesota Batholith (Holm et al., 2005).

The collisions of provinces and terranes leading up to the Trans-Hudson orogeny mark the initial phase of assembly of the supercontinent Nuna in the paleogeographic model framework of Pehrsson et al. (2015). The Trans-Hudson orogeny itself is taken to be the terminal collision associated with the closure of the Manikewan Ocean that had previously been a large oceanic tract separating the Superior province from the composite Slave+Rae+Hearne+North Atlantic provinces (often referred to as the Churchill domain or plate; e.g. Skipton et al., 2016; Weller and St-Onge, 2017; Fig. 4). The paleogeographic mode of Pehrsson et al. (2015) posits that this period of terminal collision not only resulted in the amalgamation of Laurentia, but was also associated with the assembly of the supercontinent Nuna that is hypothesized to include other major Paleoproterozoic cratons including Baltica, Siberia, Congo/São Francisco, West Africa, and Amazonia.

Following the Trans-Hudson orogeny, the locus of orogenesis migrated to the exterior of Laurentia. This change marks a shift in the predominant style of Laurentia's growth as subsequent crustal growth occurred dominantly through accretion of juvenile crust along the southern and eastern margin of the nucleus of Archean provinces (Whitmeyer and Karlstrom, 2007; Figs. 1 and 2). Determining the extent of these belts is complicated by poor exposure of them in the midcontinent relative to the exposure of the Archean provinces throughout the

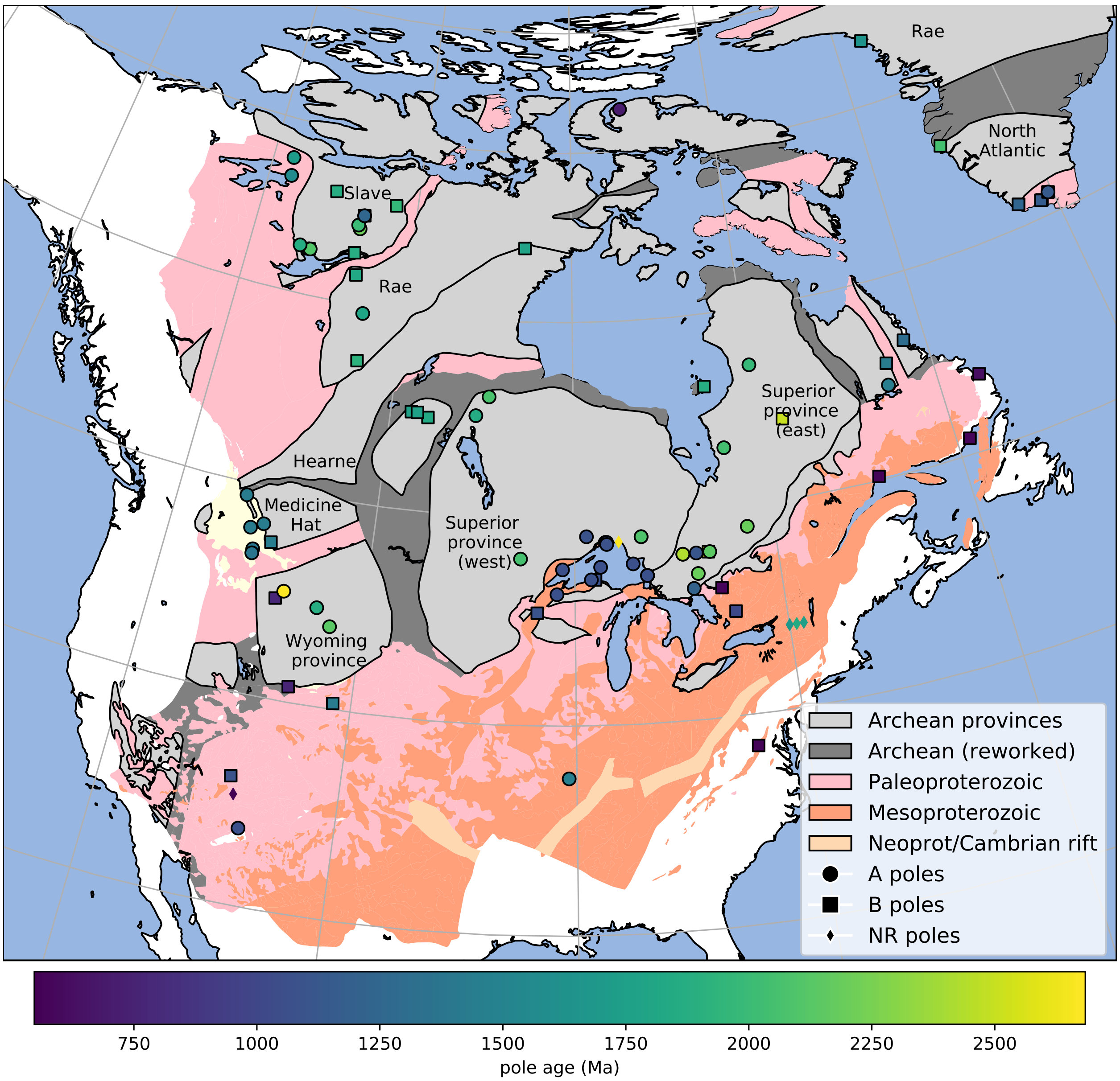

Figure 1. Simplified map of Laurentia showing the location of Archean provinces (labeled with text) and younger Paleoproterozoic and Mesoproterozoic crust (simplified from Whitmeyer and Karlstrom, 2007 with additions for Greenland based on St-Onge et al., 2009). The localities from which the compiled Precambrian paleomagnetic poles were developed are shown and colored by age. The circles (A rated poles) and squares (B rated poles) have been assessed by the Nordic workshop panel.

Canadian shield. Major growth of Laurentia following the amalgamation of these Archean provinces occurred associated with the arc-continent collision of the ca. 1.71 to 1.68 Ga Yavapai orogeny (Fig. 2). Yavapai orogenesis is interpreted to have resulted from the accretion of a series of arc terranes that collided with each other and Laurentia (Karlstrom et al., 2001). Yavapai accretion was followed by widespread emplacement of granitoid intrusions (Whitmeyer and Karlstrom, 2007). These intrusions are hypothesized to have stabilized the juvenile accreted terranes that subsequently remained part of Laurentia (Whitmeyer and Karlstrom, 2007). Subsequent accretionary orogenesis of the ca. 1.65 to 1.60 Ga Mazatzal orogeny and associated plutonism led to further crustal growth in the latest Paleoproterozoic (Karlstrom and Bowring, 1988). Laurentia's growth continued in the Mesoproterozoic along the southeast margin through further juvenile terrane and arc accretion. An interval of major plutonism occurred ca. 1.48 to 1.35 Ga leading to the formation of A-type granitoids throughout both Mesoproterozoic and Paleoproterozoic provinces extending from the southwest United States up to the Central Gneiss Belt of Ontario to the northeast of Georgian Bay (Slagstad et al., 2009). This plutonism is likely due to crustal melting within a back-arc region of ca. 1.50 to 1.43 Ga accretionary orogenesis (Bickford et al., 2015). Geologic data from northern New Mexico have been interpreted to indicate an interval of ca. 1.49 to 1.40 Ga orogenesis that has been named the Picuris orogeny (Daniel et al., 2013). Younger magmatic activity ca. 1.37 Ga of the Southern Granite-Rhyolite Province suggests a similar tectonic setting of accretionary orogenesis at that time (Bickford et al., 2015). While an active margin interpretation with magmatism in a back-arc setting has gained traction within the literature, the tectonic setting is often described as enigmatic given earlier interpretations of an anorogenic setting (see references in Slagstad et al., 2009).

Accretionary orogenesis continued along the eastern margin of Laurentia with the amalgamation and accretion of arcs associated with the ca. 1.25 to 1.22 Ga Elzevirian orogeny (McLelland et al., 2013). The subsequent ca. 1.19 to 1.16 Ga Shawinigan orogeny is interpreted to be due to the collision of terrane comprised of a previously rifted fragment of Laurentia and led to obduction of the Pyrites Complex ophiolite (McLelland et al., 2010; Chiarenzelli et al., 2011). The Shawinigan orogeny is followed by a period of tectonic quiescence on the eastern margin of Laurentia until the collisional orogenesis of the Grenvillian orogeny (McLelland et al., 2010). An

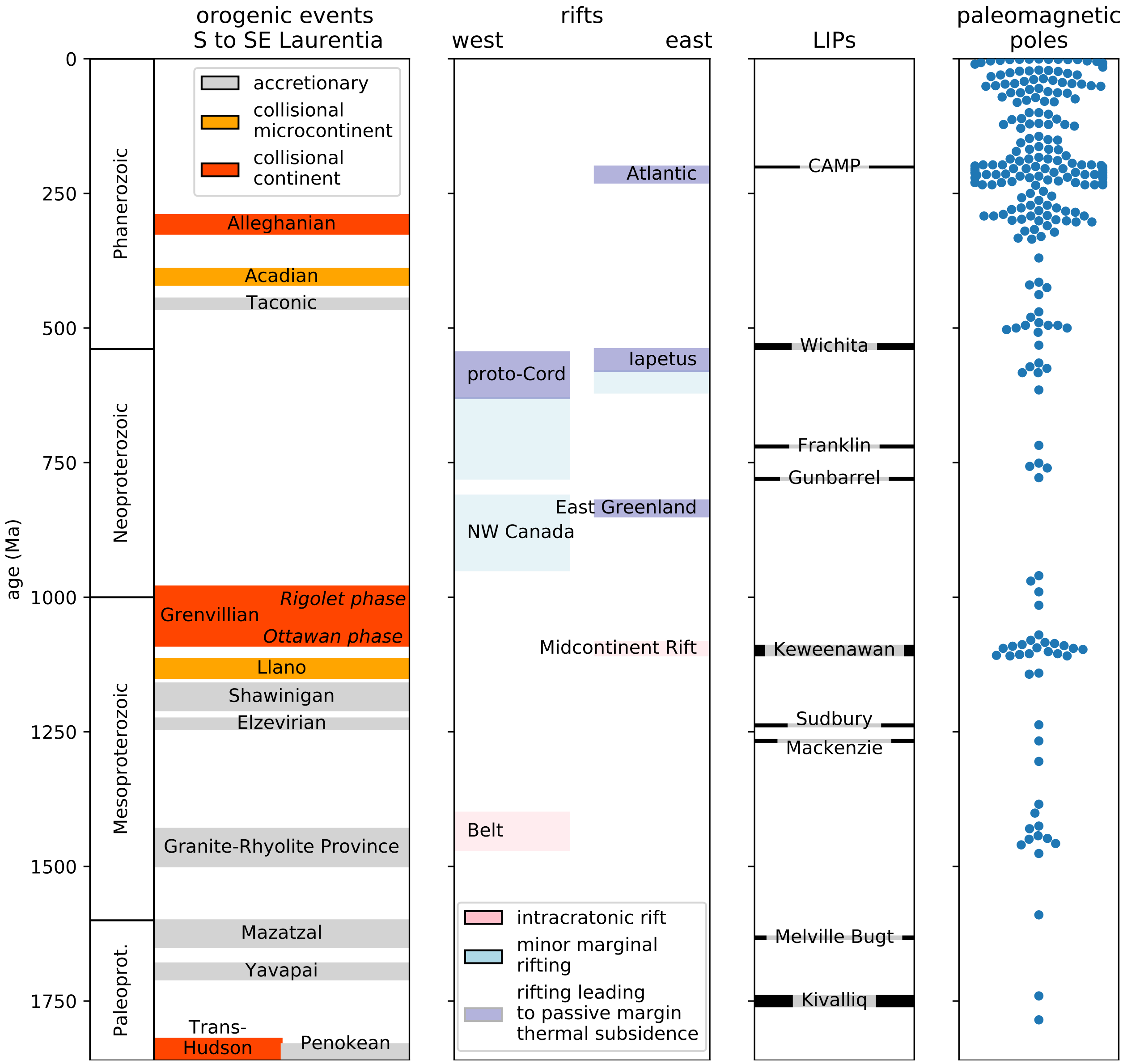

Figure 2. Simplified timeline of Laurentia's tectonic history over the past ∼1.8 billion years. Brief summaries and references related to the orogenic and rifting episodes are given in the text. A timeline of large igneous provinces (LIPs) associated with typically brief and voluminous (or interpreted to be voluminous) volcanism is also shown. The interpreted age of paleomagnetic poles for Laurentia (not including separated terranes) compiled in this study for the Proterozoic and in Torsvik et al. (2012) for the Phanerozoic is shown. Abbreviations on the figure: CAMP (Central Atlantic Magmatic Province); proto-Cord (proto-Cordilleran).

exception to this quiescence during the interval between the Shawinigan and Grenvillian orogenies is ca. 1.15 to 1.12 Ga orogenesis in the Llano uplift of the southern Laurentia margin (Mosher, 1998). Llano orogenesis is interpreted to have resulted from collision of continental lithosphere along with an accreted arc (Mosher, 1998). This orogenesis is earlier and temporally distinct from the Grenvillian orogeny, is only known from a limited spatial area, and is located in a region that experienced further orogenesis during the Grenvillian orogeny (Grimes and Copeland, 2004). Taken together, this context is suggestive of a microcontinent collision leading to Llano uplift orogenesis prior to terminal Grenvillian continental collision. If this interpretation is correct, it is similar to Paleozoic orogenesis along the margin where microcontinent collision resulted in the Acadian orogeny prior to Alleghanian orogenesis during the Appalachian orogenic interval (2).

The Grenvillian orogeny was a protracted interval of continent-continent collision (ca. 1.09 to 0.98 Ga) leading to amphibolite to granulite facies metamorphism through the orogen (McLelland et al., 2010). Evidence of large-scale continent-continent collision at the time of the Ottawan Phase of the Grenvillian orogeny is recorded in Texas (Grimes and Copeland, 2004), up through the Blue Ridge Appalachian inliers (Johnson et al., 2020), through Ontario and up to the Labrador Sea (Rivers, 2008). The orogeny is interpreted to have resulted in the development of a thick plateau associated with the Ottawan orogenic phase (ca. 1090 to 1030 Ma; Rivers, 2008). Continued convergence during the Rigolet phase of the Grenvillian orogeny led to the development of the Grenville Front tectonic zone and ended ca. 980 Ma (Hynes and Rivers, 2010).

In the latest Mesoproterozoic (ca. 1.11 to 1.08 Ga) prior to the Grenvillian orogeny, a major intracontinental rift co-located with a large igneous province formed in Laurentia's interior leading to extension within the Archean Superior province and adjacent Paleoproterozoic provinces to the south (Cannon, 1992). This Midcontinent Rift led to the formation of a thick succession of volcanics and mafic intrusions that are well-preserved in Laurentia's interior. Midcontinent Rift development ceased as major collisional orogenesis of the Grenvillian orogeny began (Swanson-Hysell et al., 2019).

There is significantly less preserved Mesoproterozoic crustal growth on the western margin of Laurentia (Fig. 1), and the tectonic history through the Mesoproterozoic Era is not as well elucidated as on the southern to eastern margin. The 15 to 20 km thick package of sedimentary rocks of the Belt-Purcell Supergroup is associated with a ca. 1.47 to 1.40 rift (Evans et al., 2000). While the rift is typically interpreted as being intracontinental (Lydon, 2004), the tectonic setting in which it formed is debated. Hoffman (1989) proposed that it may be a remnant back-arc basin trapped within a continent, while others envision it as being associated with continental rifting along the margin associated with separation of a conjugate continent (Jones et al., 2015). This region is interpreted to have been subsequently deformed during a ca. 1.36 to 1.33 Ga event known as the East Kootenay orogeny (McMechan and Price, 1982; Nesheim et al., 2012; McFarlane, 2015).

This late Paleoproterozoic and Mesoproterozoic tectonic history provides significant constraints on paleogeographic reconstructions. In particular, the long-lived history of accretionary orogenesis along the southeast (present-day coordinates) of Laurentia from the initiation of the Yavapai orogeny (ca. 1.71 Ga) to the end of the Shawinigan orogeny (ca. 1.16 Ga) requires a long-lived open margin without a major conjugate continent until the time of terminal Grenvillian orogeny collision (Karlstrom et al., 2001). This constraint is incorporated into models such as that of Zhang et al. (2012) and Pehrsson et al. (2015) which maintain a long-lived convergent margin throughout the Mesoproterozoic, but in some reconstructions other continental blocks are reconstructed into positions that are seemingly incompatible with this record of accretionary orogenesis (e.g. Amazonia in Elming et al., 2009). The high-grade metamorphism associated with the Ottawan phase of the Grenvillian orogeny itself strongly suggests a collision between Laurentia and (an)other continent(s) ca. 1080 Ma – the geological observation of which first led to the formulation of the hypothesis of the supercontinent Rodinia (Hoffman, 1991). This extensive and major collisional orogenic history recorded in Laurentia, and also present on other Proterozoic continents, at this time remains a strong piece of evidence that a supercontinent or (proto)supercontinent formed at the 1.0 Ga Mesoproterozoic to Neoproterozoic transition. Note that while the term Grenville orogeny or Grenville belt is used rather loosely throughout much of the literature to refer to any late Mesoproterozoic orogenic belt, the timeline of orogenesis on the Laurentia margin has more nuanced constraints than this usage. These constraints can be comparatively assessed when evaluating potential conjugate continents to Laurentia associated with the orogen (Fig. 2).

The subsequent Neoproterozoic tectonic history of Laurentia is dominantly a record of rifting (Fig. 2). Along the western margin of Laurentia, rifting occurred ca. 780 to 720 Ma leading to deposition in basins from the Death Valley region of SW Laurentia to the Mackenzie Mountains of NW Laurentia (Macdonald et al., 2013; Dehler et al., 2017; Rooney et al., 2017). However, this extensional basin development predates the rifting that led to well-documented passive margin thermal subsidence closer to the ca. 539 Ma Neoproterozoic-Phanerozoic boundary (Bond et al., 1984; Levy and Christie-Blick, 1991). The emplacement of the ca. 780 Ma Gunbarrel large igneous province along this margin and the subsequent extension recorded in the basins is commonly interpreted to be associated with the break-up of Laurentia and a conjugate continent to the western margin (often interpreted to be Australia). If this interpretation is correct, it is unclear why there would be minimal thermal subsidence until the Ediacaran (post 635 Ma as in Levy and Christie-Blick, 1991 and Witkosky and Wernicke, 2018). The geological evidence therefore supports prolonged active tectonism along the western margin of Laurentia (a portion of which could be strike-slip and transtensional; Smith et al., 2015), but suggests that there was significant lithospheric thinning associated with rifting later than the timing of rifting typically implemented in models of Rodinia break-up. The record of Neoproterozoic basin development lead Yonkee et al. (2014) to propose that the early ca. 780 Ma rifting was intracratonic and that while it may have led to some associated thermal subsidence that there was a second interval of rifting and thermal subsidence associated with Australia rifting away in the Ediacaran (later than in most models). Another possibility, along the lines of that proposed in Ross (1991), is that ca. 780 Ma extensional tectonism is an inboard record of rifting and passive margin development that occurred further outboard. In this model, subsequent continent rifting that drove lithospheric thinning, perhaps associated with the departure of a microcontinent fragment rather than an already departed major conjugate continent, would be the cause of Ediacaran to Cambrian thermal subsidence.

In northwest Laurentia from the Ogilvie Mountains of Yukon to Victoria Island, the sedimentary rock record is distinct from further south as it also records earlier Neoproterozoic basin development during the Tonian Period in addition to Cryogenian basin development (Macdonald et al., 2012). Tectonic extension is recorded in units of the lower Fifteenmile Group with maximum depositional ages of ca. 1050 Ma with ongoing basin development ca. 812 Ma (age constraint from a U-Pb zircon date on a tuff within the upper Fifteenmile Group; Macdonald et al., 2010) potentially through thermal subsidence (Macdonald et al., 2012). Earlier basin development in the region recorded by the Mesoproterozoic/Neoproterozoic Pinguicula Group could provide valuable insight on tectonic history as it has been interpreted to have been deposited in an extensional basin (Medig et al., 2016), however it is poorly constrained in terms of age – older than the Fifteenmile Group and younger than the ca. 1382 Ma Hart River sills (which themselves have been interpreted to be emplaced in conjunction with rifting; Verbaas et al., 2018).

Another margin that experienced rifting and associated passive margin thermal subsidence earlier in the Neoproterozoic is the northeast Greenland margin (Fig. 2). Available geochronological constraints and thermal subsidence modeling indicate ca. 850 to 820 Ma rifting followed by thermal subsidence of a stable platform (Maloof et al., 2006; Halverson et al., 2018). These data suggest that conjugate continental lithosphere had rifted away from northeast Greenland by ca. 820 Ma.

Extensive rifting followed by thermal subsidence occurred along the southeast to east Laurentia margin in the time leading up to the Neoproterozoic-Phanerozoic boundary and is interpreted to be associated with the opening of the Iapetus ocean. A record of this rifting is preserved as rift basins that were part of failed arms (Rome trough, Reelfoot rift and Oklahoma aulacogen; Fig. 1) as well as prolonged Cambrian to Ordovician passive margin thermal subsidence along the margin (Bond et al., 1984; Whitmeyer and Karlstrom, 2007). The age of igneous intrusions that have been interpreted to be rift-related play a significant role in interpretations of this history such as in the rift development model of Burton and Southworth (2010). In this model, spatially-restricted rifting occurs ca. 760 to 680 Ma in the region of modern-day North Carolina and Virginia. Rifting ca. 620 to 580 Ma initiates in the region from modern-day New York to Newfoundland and by ca. 580 to 550 Ma rifting extends along the length of Laurentia's eastern margin. The last phase of this rifting has been interpreted to be associated with the separation of the Argentine pre-Cordillera Cuyania terrane (Dickerson and Keller, 1998).

The tectonic history of terrane transfer, such as Cuyania, can provide valuable paleogeographic constraints. Cuyania is widely interpreted be a rifted fragment of southeast Laurentia that separated with this early Cambrian rifting and subsequently became part of Gondwana when it collided with other terranes in the vicinity of the Rio de Plata craton during the Ordovician Famatinian orogeny (Martin et al., 2019). As with other rifts, it is difficult to distinguish the separation of a cratonic fragment as a microcontinent from the rifting of a major craton, as the record that lingers on the craton is similar. One interpretation is that there was successful break-up along the eastern margin during the ca. 580 to 550 Ma interval of rifting prior to the ca. 539 Oklahoma aulacogen rifting that liberated the Cuyania microcontinent. The Maz-Arequipa-Rio Apa (MARA) block with which Cuyania collided (Martin et al., 2019) is likely a product of such rifting. Orogenesis between the MARA block and the Rio de Plata and Kalahari in the ca. 530 Ma Pampean orogeny (Casquet et al., 2018) predated the collision of Cuyania during the ca. 460 Ma Famatinian orogeny in West Gondwana (Rapalini, 2018).

The eastern margin of Laurentia then went through the multiple phases of Appalachian orogenesis. As is visualized in Figure 2, there are parallels between the Grenville orogenic interval and the Appalachian orogenic interval in that there was a period of arc-continent collision (Elzevirian orogeny in the Grenville interval; Taconic orogeny in the Appalachian interval) followed by microcontinent accretion (Shawinigan/Llano orogenies in the Grenville interval; Acadian orogeny in the Appalachian interval) that culminated in large-scale continent-continent collision (Grenvillian orogeny in the Grenville interval; Alleghanian orogeny in the Appalachian interval). These similarities are the consequence of an active margin facing an ocean basin that was progressively consumed until continent-continent collision. In the case of the Grenville interval, this terminal collision is interpreted to be associated with the assembly of the supercontinent Rodinia, and in the Appalachian interval it is interpreted to be associated with the assembly of the supercontinent Pangea.

Even without considering other continents on Earth, the geological record of Paleoproterozoic collisional of Archean provinces combined with accretionary orogenesis at that time and through the rest of the Paleoproterozoic and Mesoproterozoic Eras provides strong evidence for mobile plate tectonics driving Laurentia's evolution throughout the past 2 billion years. This tectonic history inferred from geological data can be enhanced through integration with the paleomagnetic record.

4.3 Paleomagnetic pole compilation

In this chapter, I focus on the compilation of paleomagnetic poles developed through the Nordic Paleomagnetism Workshops with some additions and modifications (Fig. 3 and Table 2). The Nordic Paleomagnetism Workshops have taken the approach of using expert panels to assess paleomagnetic poles and assign them grades meant to convey the confidence that the community has in these results (Evans et al., this volume). While many factors associated with paleomagnetic poles can be assessed quantitatively through Fisher statistics and the precision of geochronological constraints, other aspects such as the degree to which available field tests constrain the magnetization to be primary require expert assessment. The categorizations used by the expert panel are 'A' and 'B' with the last panel meeting occurring in Fall 2017 in Leirubakki, Iceland. The 'A' rating refers to poles that are judged to be of such high quality that they provide essential constraints that should be satisfied in paleogeographic reconstructions. The 'B' rating is associated with poles that are judged to likely provide a high-quality constraint, but have some deficiency such as remaining ambiguity in the demonstration of primary remanence or the quality/precision of available geochronologic constraints. Additional poles that were not given an 'A' or 'B' classification at the Nordic Workshops are referred to as not-rated ('NR'). These additional poles are taken from the Paleomagia database (Veikkolainen et al., 2014). Many of these poles in the Paleomagia database are quite valuable for reconstruction and should not be dismissed from being considered in paleogeographic reconstructions. However, there are ambiguities associated with many of the poles not given Nordic 'A' or 'B' ratings in terms of how well the nature of the remanence is constrained, including its age. For example, there are rich data associated with intrusive and metamorphic lithologies of the Grenville Province that are the available paleomagnetic constraints for Laurentia at the Mesoproterozoic-Neoproterozoic boundary. However, the ages of the remanence associated with these poles is complicated by the reality that the magnetization was acquired during exhumation and such cooling ages are more difficult to robustly constrain than the ages of remanence associated with dated eruptive units or shallow-level intrusions. As a result, the vast majority of Grenville Province poles are not given an 'A' or 'B' rating with the exception of the 'B' rated pole from the ca. 1015 Ma Haliburton intrusions. However, while any one of these Grenville poles could be interpreted to suffer from

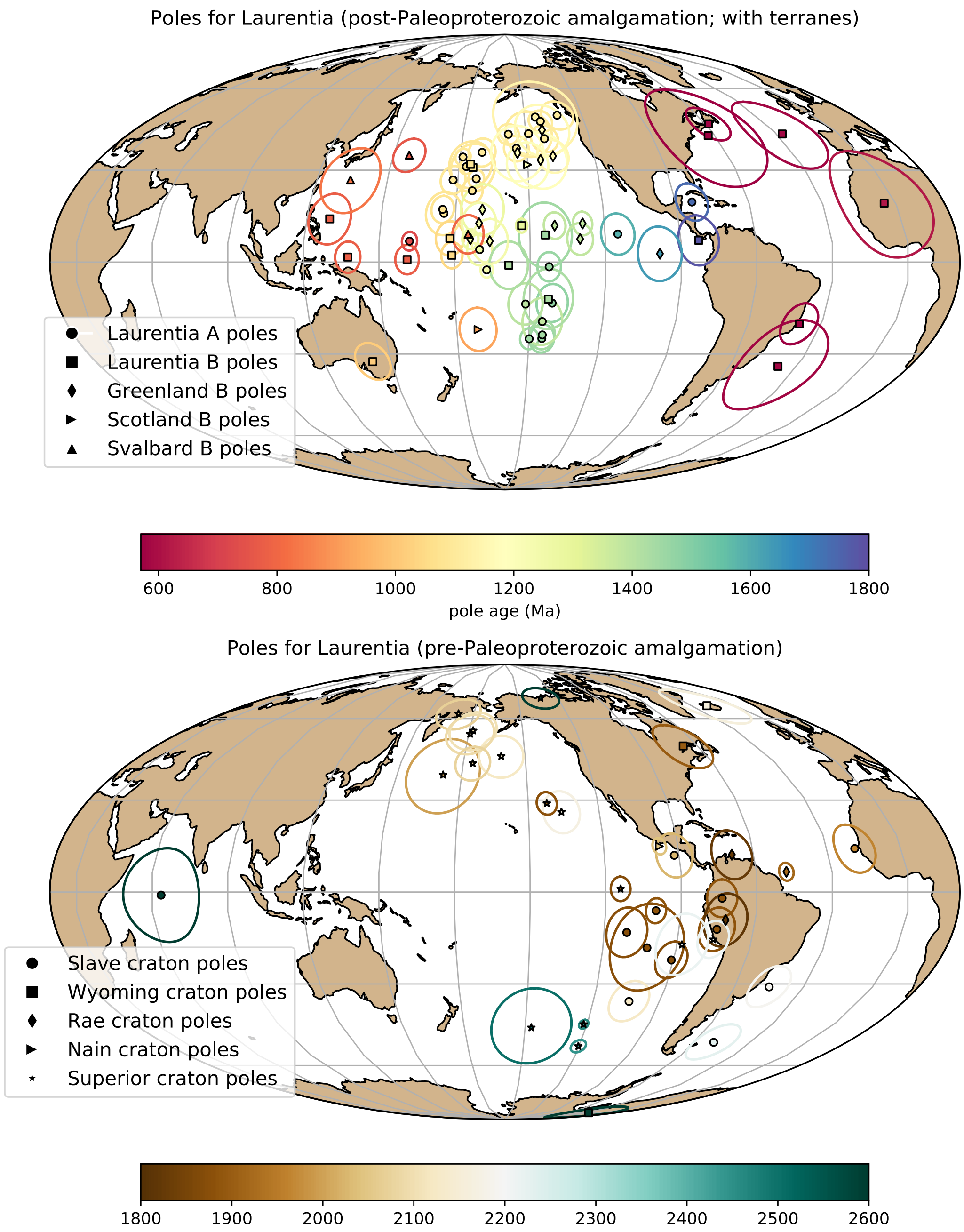

Figure 3. Top panel: Paleomagnetic poles from 1800 to 560 Ma for Laurentia (including Greenland, Scotland and Svalbard). Bottom panel: Paleomagnetic data for Archean Provinces prior to the amalgamation of Laurentia.

large temporal uncertainty, the overall preponderance of poles in a similar location at the time suggests that they need to be taken seriously within paleogeographic reconstructions of Laurentia (although an alternative view of an allochthonous origin put forward by Halls et al. (2015) is discussed below). In this compilation, the poles of Brown and McEnroe (2012) from the Adirondack highlands are used wherein the magnetic mineralogy and associated relative ages of remanence are relatively well-constrained (Table 2). An additional not-rated pole included in the present compilation is the new pole for the ca. 1144 Ma Ontario lamprophyre dikes (Piispa et al., 2018) that strengthens the position of Laurentia at the time and coincides with the position of the poles from the ca. 1140 Ma Abitibi dikes (Ernst and Buchan, 1993). This pole will likely receive an 'A' rating when assessed at the next Nordic paleomagnetism workshop. Poles from the Neoproterozoic Chuar Group of southerwest Laurentia as presented in Eyster et al. (2019) are also included.

4.4 Differential motion before Laurentia amalgamation

Prior to the termination of the Trans-Hudson orogeny (before 1.8 Ga), paleomagnetic poles need to be considered with respect to the individual Archean provinces. For the Superior province, an additional complexity is that paleomagnetic poles from Siderian to Rhyacian Period (2.50 to 2.05 Ga) dike swarms, as well as deflection of dike trends, support an interpretation that there was substantial Paleoproterozoic rotation of the western Superior province relative to the eastern Superior province across the Kapuskasing Structural Zone (Bates and Halls, 1991; Evans and Halls, 2010). This interpretation is consistent with the hypothesis of Hoffman (1988) that the Kapuskasing Structural Zone represents major intracratonic uplift related to the Trans-Hudson orogeny. Evans and Halls (2010) propose an Euler rotation of (51°N, 85°W, -14°CCW) to reconstruct western Superior relative to eastern Superior and interpret that the rotation occurred in the time interval of 2.07 to 1.87 Ga. I follow this interpretation and group the poles into Superior (West) and Superior (East). Uncertainty remains with respect to whether the ca. 1.88 Ga Molson dikes pole pre-dates or post-dates this rotation (Evans and Halls, 2010) and thus for the time being should be considered solely in the western Superior province reference frame.

There are poles in the compilation for the Slave, Wyoming, Rae, Superior and North Atlantic

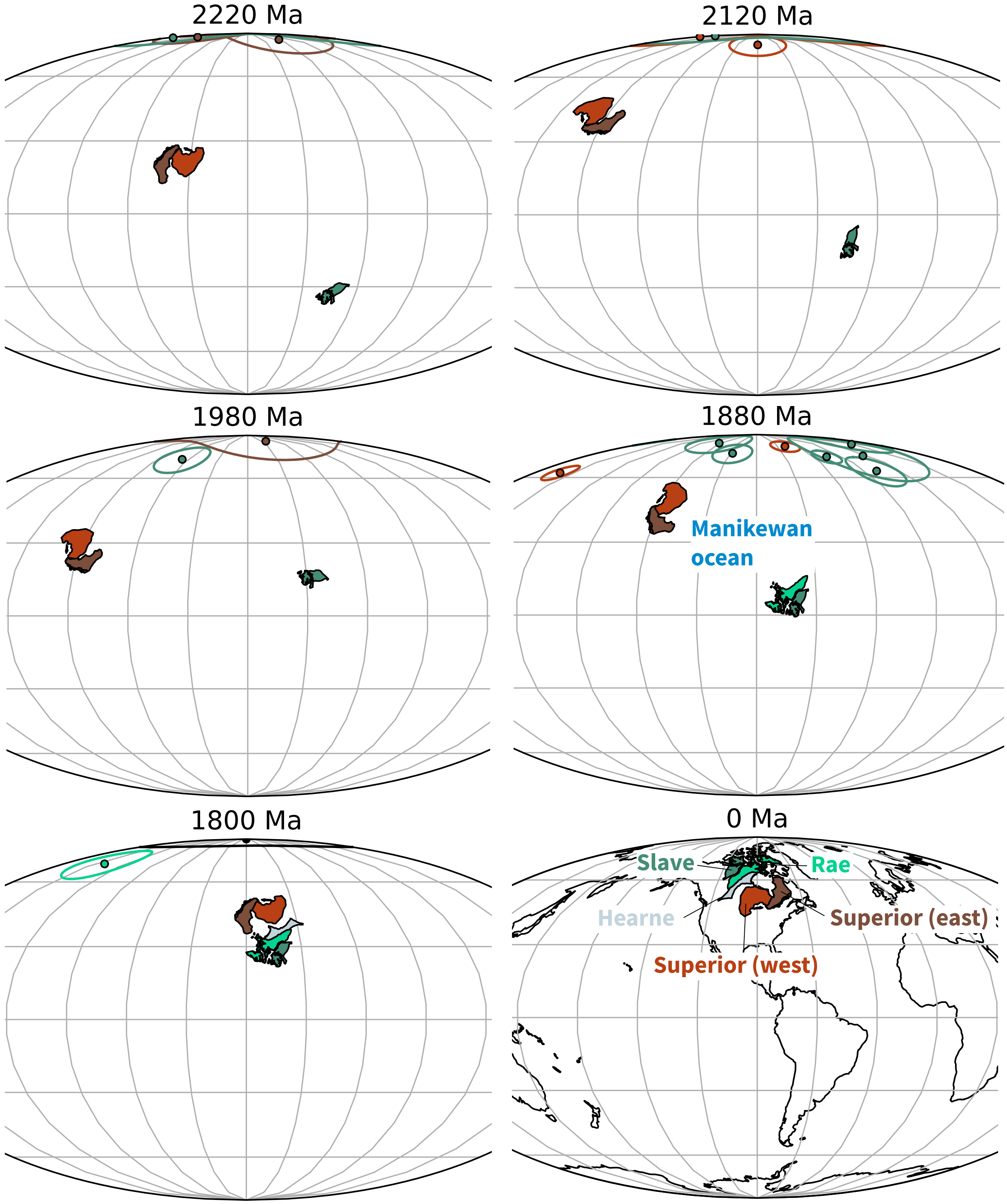

Figure 4. Paleogeographic reconstructions developed using poles from the Superior, Slave and Rae provinces. The polarity options that are chosen for the provinces are those that minimize total apparent polar wander path length. This model reconstructs a wide Manikewan ocean that underwent orthogonal closure rather than an alternative possibility of narrower Manikewan with a pivot-like closure. Paleomagnetic poles are shown colored to match their respective province with these provinces shown in present-day coordinates and labeled in the 0 Ma panel. Poles with ages that are within 25 million years of the given time slice are shown. The relatively well-resolved pole paths from the Superior and Slave provinces (Fig. 3) that are utilized for these reconstructions provide strong support for differential plate tectonic motion between 2220 and 1850 Ma.

provinces prior to Laurentia amalgamation (Fig. 3 and Table 2). Overall, these data provide an opportunity to re-evaluate the paleomagnetic evidence for relative motions between Archean provinces prior to Laurentia assembly. A lingering question raised in Hoffman (1988) is to what extent the Archean provinces each had independent drift histories with significant separation or shared histories before experiencing fragmentation and reamalgamation. The strongest analysis in this regard comes from comparisons between paleomagnetic poles between the Superior and Slave provinces (Buchan et al., 2009; Mitchell et al., 2014; Buchan et al., 2016). High-quality paleomagnetic poles from these two provinces provide strong support for differential motion between the Superior and Slave provinces between 2.2 and 1.8 Ga with the two provinces not being in their modern-day relative orientation to one another and having distinct pole paths as constrained by five time slices of nearly coeval poles from 2.23 and 1.89 Ga (Fig. 4; Buchan et al., 2016). These data provide paleomagnetic support for the Superior and Slave provinces having independent histories of differential motion. The data also support the hypothesis that the Trans-Hudson orogeny is the result of terminal collision associated with the closure of an ocean basin between the Superior province and the Hearne+Rae+Slave provinces. Reconstructions developed for this chapter of the Superior and Slave provinces using these poles are shown in Figure 4 and illustrate the difference in implied orientation and paleolatitude that results from these well-constrained poles.

4.5 Paleogeography of an assembled Laurentia

Following the amalgamation of the Archean provinces in Laurentia ca. 1.8 Ga, poles from each part of Laurentia can be considered to reflect the position of the entire composite craton. It is worth considering the possibility that poles from zones of Paleoproterozoic and Mesoproterozoic accretion could be allochthonous to the craton. Halls (2015) argued that this was the case for late Mesoproterozoic and early Neoproterozoic poles from east of the Grenvillian allochthon boundary fault. However, the majority of researchers have considered these poles to post-date major differential motion and be associated with cooling during collapse of a thick orogenic plateau developed during continent-continent collision (e.g. Brown and McEnroe, 2012). Poles with a B-rating are also included in the compilation that come from Greenland, Svalbard and Scotland.

These terranes were once part of contiguous Laurentia, but have subsequently rifted away. These poles need to be rotated into the Laurentia reference frame prior to use for tectonic reconstruction, and I apply the rotations shown in Table 1. The Euler pole and rotation is quite well-constrained for Greenland as it is associated with recent opening of Baffin Bay and the Labrador Sea (for which the rotation of Roest and Srivastava, 1989 is used). The reconstruction of Scotland is associated with the opening of the Atlantic (for which the rotation employed by Torsvik and Cocks, 2017 is used) which is well-constrained, but has more uncertainty associated with the Euler pole than that for Greenland. The reconstruction of Svalbard is more challenging given a multi-stage tectonic history involving both translation within the Caledonides and subsequent rifting. The preferred Euler pole parameters of Maloof et al. (2006) are used here for this reconstruction. This Euler rotation is designed, in particular, to honor the high degree of similarity between Tonian sediments in East Greenland (Hoffman et al., 2012) and those of East Svalbard (Maloof et al., 2006) and to reconstruct East Svalbard to be aligned with these correlative sedimentary rocks.

Through the Proterozoic, there are intervals where there are abundant paleomagnetic poles that constrain Laurentia's position and intervals when the record is sparse (shown colored by age in Fig. 3). To further visualize the temporal coverage of the poles and to summarize the motion, implied paleolatitudes for an interior point on Laurentia are shown in Figure 5. The ages of the utilized paleomagnetic poles are also shown in comparison to the simplified summary of tectonic events in Figure 2. Both collisional and extensional tectonism can result in the formation of lithologies that can be used to develop paleomagnetic poles either as a result of basin formation, magmatism or both. In addition, intraplate magmatism resulting from plume-related large-igneous provinces can lead to paleomagnetic poles in periods that are otherwise characterized by tectonic quiescence (e.g. the ca. 1267 Ma Mackenzie LIP; Fig. 2). Intracontinental rifts have led to the highest density of poles both in the case of the ca. 1.4 Ga Belt Supergroup and the ca. 1.1 Ga Midcontinent Rift (Fig. 2). The quality and resolution of the record from the Midcontinent Rift is aided by the voluminous magmatism that occurred in conjunction with basin formation that enables the development of a well-calibrated apparent polar wander path (Swanson-Hysell et al., 2019). The late Tonian Period also has a number of poles including the Gunbarrel LIP (ca. 780 Ma) and Franklin LIP (ca. 720 Ma), as well as similiarly-aged sedimentary rocks from western Laurentia basins (Eyster et al., 2019). Overall, there is internal consistency among the paleomagnetic poles within intervals for which there is high-resolution coverage. These data result in progressive paths such as ascending up to the Logan Loop, down the Keweenawan Track (Swanson-Hysell et al., 2019) to the Grenville Loop prior to a temporal gap before the late Tonian (ca. 775 to 720 Ma) path (Eyster et al., 2019).

Data from other terranes add resolution to the record. In particular, data from Greenland add 12 poles between 1385 and 1160 Ma when there are only four poles from mainland Laurentia. Given that the rotation between Greenland and mainland Laurentia is well-constrained (Table 1), once rotated these poles can be used for reconstruction of the entire continent. The reliability of this approach gains credence through the good agreement between the ca. 1633 Ma Melville Bugt diabase dikes pole from Greenland (Halls et al., 2011) and the ca. 1590 Ma Western Channel diabase pole of mainland Laurentia (Irving and Park, 1972). Similarly, there is good agreement between the ca. 1267 Ma Mackenzie dikes pole of Laurentia (Buchan et al., 2000) and coeval poles from Greenland such as the ca. 1275 Ma North Qoroq intrusives (Piper, 1992) and Kungnat Ring dike (Piper, 1977). Furthermore, the Greenland poles with ages that fall between the ca. 1237 Ma Sudbury dikes and ca. 1144 Ma lamprophyre dikes pole of mainland Laurentia are consistent with constraints on either side from the mainland while filling in the ascending limb of the path leading up to the apex of 1140 to 1108 Ma poles known as the Logan Loop.

An exception to this overall agreement between poles from Greenland and mainland Laurentia occurs ca. 1382 Ma. There are poles of this age from Greenland associated with the Zig-Zag Dal basalts and related intrusions (Marcussen and Abrahamsen, 1983; Abrahamsen and Van Der Voo, 1987). However, these poles are in a distinct location from poles of similar age associated with the Belt Supergroup (e.g. the McNamara Formation and Pilcher/Garnet Range and Libby Formations; Elston et al., 2002). Additionally, the older Belt Supergroup poles form a more southerly population than time-equivalent poles from elsewhere in Laurentia such as the Mistastin Pluton. There are potential complications associated with the Belt Supergroup being exposed within thrust sheets with significant Cenozoic Mesozoic and Cenozoic deformation. However, vertical axis rotations of the Belt region are not able to bring the Belt poles into agreement with those from Laurentia or Greenland nor is translation away from the craton. Another potential complication is that the remanence used for the development of the Belt Supergroup resides in hematite. As a result, there is the potential for inclination-flatting within the sedimentary rocks from which poles are developed. However, applying a moderate inclination factor of $f = 0.6$ also does not bring the poles into congruence with the Zig-Zag basalts. There is the potential that the hematite could be the result of post-depositional oxidation (the remanence of the lavas pole is also held by hematite), however the overall coherency of the pole directions and the presence of reversals has been taken as evidence that the remanence is primary (Elston et al., 2002). At present, it is unclear which poles are a better representation of Laurentia's position ca. 1400 Ma.

Another challenging portion of the Laurentia paleomagnetic record is that for the Ediacaran Period where there is little consistency between poles of similar age (Figs. 3 and 5). As a result, there are poles that imply both low-latitude and high-latitude positions of Laurentia between 615 and 565 Ma. One explanation for these variable pole positions is that they are the result of large-scale oscillatory true polar wander in the Ediacaran where rapid rotation of the entire silicate Earth influenced poles in Baltica and West Africa as well (McCausland et al., 2007; Robert et al., 2017). Another possibility is that the lack of congruency between poles in this point in the record is due to a particularly weak and non-dipolar geomagnetic field (Abrajevitch and Van der Voo, 2010; Halls et al., 2015; Bono et al., 2019). Regardless of mechanism, the Ediacaran data stand out as anomalous relative to the coherency of the rest of the poles in the composite (Fig. 5).

Synthesizing the compilation of paleomagnetic poles for Laurentia into a composite path over the past 1.8 billion years presents a challenge given the highly variable temporal coverage. The method typically applied in the Phanerozoic is to develop synthesized pole paths either through fitting spherical splines through the data or calculating binned running means where the Fisher mean of poles within a given interval are calculated (Torsvik et al., 2012). Applying such an approach can reduce the influence of spurious poles. Such synthesis is particularly important in regions of high data density where seeking to satisfy every mean pole position would result in jerky motion.

A synthesized pole path for Laurentia is developed here and used to develop a paleogeographic reconstruction of Laurentia constrained by the compilation of paleomagnetic poles. The

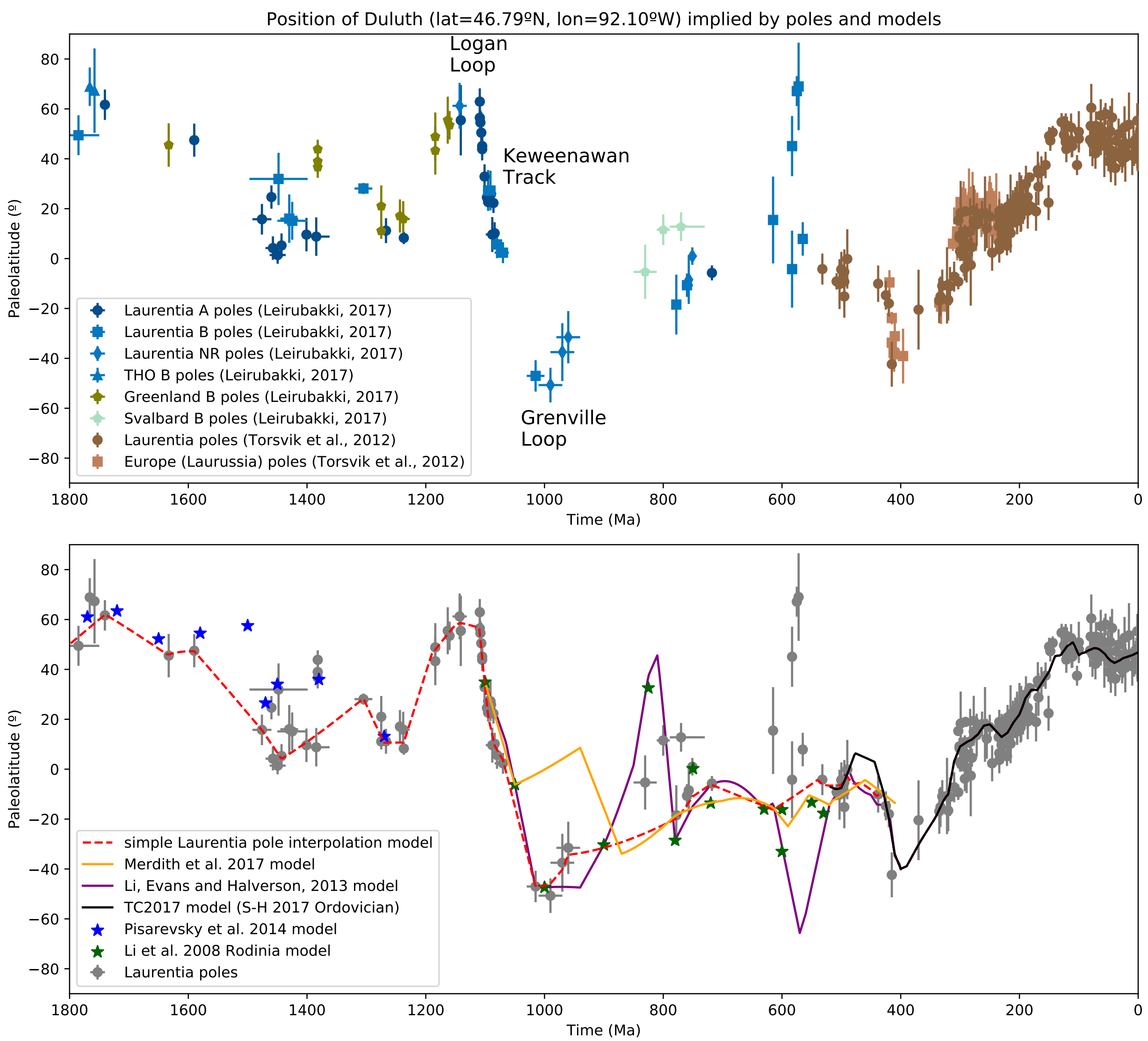

Figure 5. Top panel: Paleolatitude implied by paleomagnetic poles from Laurentia and associated blocks for Duluth (lat=46.79°N, lon=92.10°W). The paleomagnetic poles are compiled in Table 2. Bottom panel: Paleolatitude implied by Laurentia poles compared with that implied by published paleogeographic models and the simple Laurentia model used in this chapter for the reconstructions in Figure 6.

paleolatitude implied by this continuous model is shown in Figure 5. This path is based on Laurentia data alone which means that it is poorly constrained through intervals of sparse data (950-850 Ma for example). One could use interpretations of paleogeographic connections with other cratons (e.g. Baltica in the early Neoproterozoic) to fill in such portions of the path, however the result then becomes model-dependent without being constrained by data from Laurentia itself. In portions of the record with a more dense record of poles, such as ca. 1450 Ma, a calculated running mean is used to integrate constraints from multiple poles. This method follows the approach taken in the Phanerozoic (e.g. Torsvik et al., 2012 wherein all poles within a 20 Myr interval are averaged with the interval than progressively moved forward in 10 Myr steps. When there are isolated 'A' grade poles without other temporally-similar poles, these poles are fully satisfied in model. Where there are no constraints a simple interpolation between constraints is made. While data from Scotland and Svalbard are associated with Laurentia, the Scotland poles are poorly constrained in time and the Svalbard rotation to Laurentia is uncertain. These poles are not utilized in the simple Laurentia model which means that the model as shown does not include oscillatory true polar wander interpreted to have occurred ca. 810 and 790 Ma based on data from Svalbard (Maloof et al., 2006). The model of Li et al. (2013) shown in Figure 5 does seek to incorporate this true polar wander while also incorporating an interpretation of the paleomagnetic pole record from South China.

One downside of a running mean approach is that it pulls the mean to regions of high data density. As was shown in Swanson-Hysell et al. (2019), this behavior can reduce motion along an apparent polar wander path. As a result, for the portion of the reconstruction during the interval of time ca. 1110 to 1070 Ma where there is high data density from the Midcontinent Rift, I utilize an Euler pole inversion from Swanson-Hysell et al. (2019).

Paleogeographic snapshots for the past position of Laurentia reconstructed using this synthesis of the paleomagnetic poles are shown in Figure 6. These reconstructions use the tectonic elements as defined by Whitmeyer and Karlstrom (2007) with these elements being progressively added associated with Laurentia's accretionary growth. As a reminder to the reader, paleomagnetic poles provide constraints on the paleolatitude of a continental block as well as its orientation (which way was north relative to the block). While they provide constraints in this regard, they do not provide constraints in and of themselves for the longitudinal position of the block. Other approaches to obtain paleolongitude utilize geophysical hypotheses such as assuming that large low shear velocity provinces have been stable plume-generating zones in the lower mantle to which plumes can be reconstructed (Torsvik et al., 2014) or that significant pole motion in certain time intervals is associated with true polar wander axes with specified paleolongitudes that switch through time in conjunction with the supercontinent cycle (Mitchell et al., 2012). In Figure 6, Laurentia is centered on the longitudinal position of Duluth with the orientation and paleolatitude being constrained by the paleomagnetic pole compilation as synthesized in the simple Laurentia pole interpolation model (Fig. 5).

4.6 Comparing paleogeographic models to the paleomagnetic compilation

Developing comprehensive global continuous paleogeographic models is a major challenge given the need to integrate and satisfy diverse geological and paleomagnetic data types. Continually improving constraints related to tectonic setting from improved geologic and geochronologic data need to be carefully integrated with the database of paleomagnetic poles. Paleomagnetic pole compilations themselves are evolving with better data and improved geochronology. Efforts such as this volume are therefore essential to present the state-of-the-art in terms of existing constraints that can be used to evaluate current models and set the stage for future progress in Precambrian paleogeography.

There is an overall lack of models in the literature for the Proterozoic with published continuous rotation parameters that can be compared to the compilation of paleomagnetic poles presented herein. The approach in the community for many years has been to publish models as snapshots at given time intervals presented in figures without publishing continuous rotation parameters, although some studies have published the Euler rotations associated with specified times. With the further adoption of software tools such as GPlates, there has been significant progress in the publication of continuous paleogeographic models constrained by paleomagnetic poles through the Phanerozoic (540 Ma to present; e.g. Torsvik et al., 2012).

An exception to the paucity of published continuous paleogeographic models for the

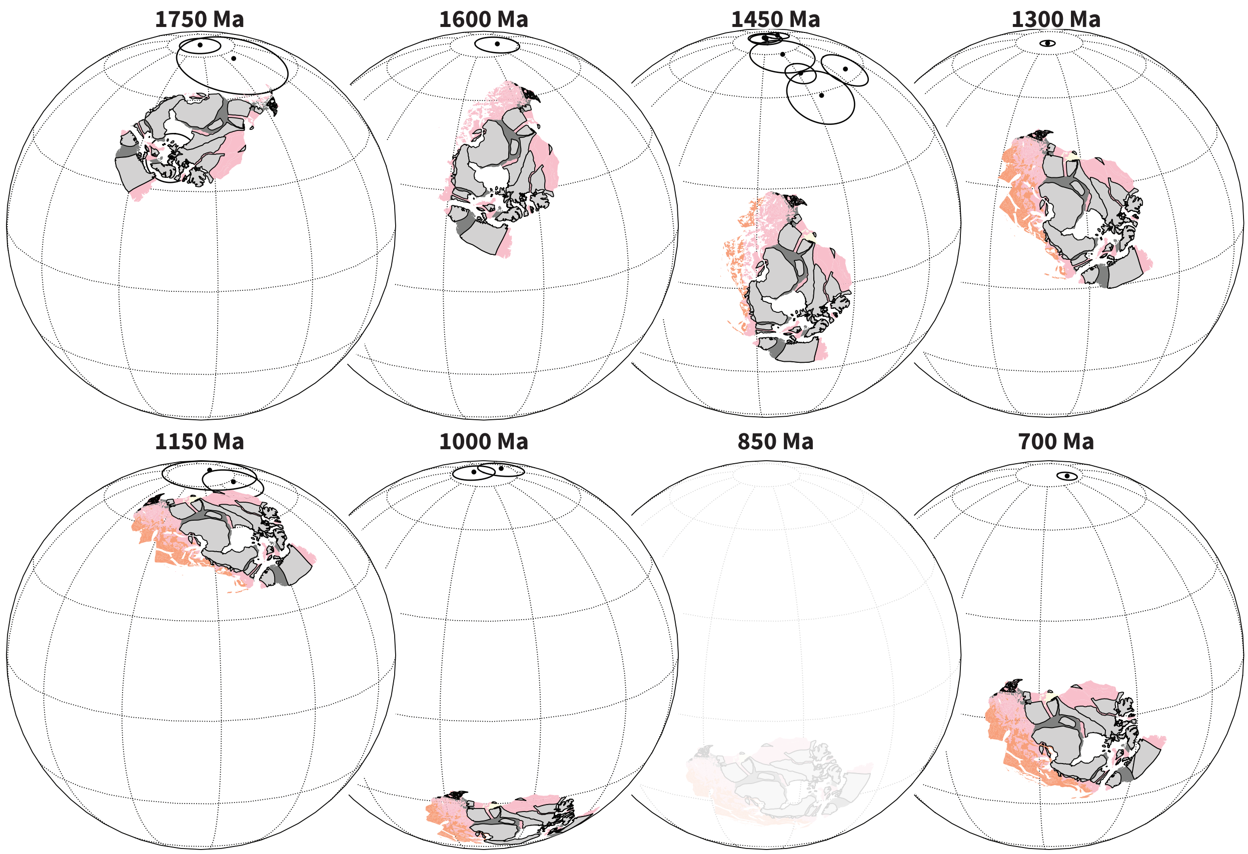

Figure 6. Paleogeographic reconstructions of Laurentia at time intervals through the Proterozoic that are well-constrained by paleomagnetic data. These reconstructions use the simple Laurentia pole interpolation model that is shown in Figure 5 and use this model to reconstruct the tectonic elements of Whitmeyer and Karlstrom (2007) shown in Figure 1. Modern coastlines are maintained in these polygons so that the rotated orientations can be interpreted by the reader in comparison to Figure 1. Paleomagnetic poles within 25 million years of each reconstruction time are plotted. All reconstructions have poles within such a time frame that provide constraints with the exception of the 850 Ma reconstruction which is shown faintly given this relative uncertainty in Laurentia's position.

Precambrian is the Neoproterozoic model of Merdith et al. (2017) which is shown in comparison to the constraints for Laurentia in Figure 5. The extent to which the implied position of Laurentia in Merdith et al. (2017) is consistent with the compiled paleomagnetic constraints can be visualized in Figure 5. As noted above, the development of such models is challenging and the researchers need to balance varying constraints. The focus here will be on the extent to which this model satisfies the available paleomagnetic poles for Laurentia. The model does not honor the Grenville loop (e.g. Laurentia going to moderately high southerly latitudes ca. 1000 Ma), which is a striking departure from the paleomagnetic record and standard paleogeographic models. Additionally, the implemented plate motion strays from the younger poles of the Keweenawan Track and does not honor the Franklin LIP pole Denyszyn et al. (2009b) despite its 'A' Nordic rating. The Franklin pole is taken to be a key constraint at the Tonian/Cryogenian boundary that provides evidence both for the supercontinent Rodinia being equatorial and for ice sheets associated with the Sturtian glaciation having extended to equatorial latitudes (Macdonald et al., 2010).

There are more published models that show snapshots and publish rotation parameters associated with given time intervals such as the Rodinia model of Li et al. (2008) and the Mesoproterozoic model of Pisarevsky et al. (2014), without providing parameters for a continuous model. The position for Laurentia implied by the Euler poles given for the model snapshots of these studies are shown in Figure 5 and can be compared to the compiled record. The figure also shows the continuous implied position of Laurentia from the late Mesoproterozoic into the early Paleozoic from the model of (Li et al., 2013; while the model parameters were not published with that study they have now been made available by the authors).

4.7 The record implies plate tectonics throughout the Proterozoic

There is strong evidence both in Laurentia's geological and paleomagnetic record for differential plate tectonic motion between 2.2 and 1.8 Ga. The continued history of accretionary orogenesis and the evaluation of Laurentia's pole path in comparison to other continents from 1.8 Ga onward supports the continual operation of plate tectonics throughout the rest of the Proterozoic and Phanerozoic as well. While this evidence fits with the majority of interpretations of the timing of initiation of modern-style plate tectonics (see summary in Korenaga, 2013), there continue to be arguments proposing that a stagnant lid persisted through the Mesoproterozoic Era (1.6 to 1.0 Ga) and into the Neoproterozoic with plate tectonics not initiating until ca. 0.8 Ga (Hamilton, 2011; Stern and Miller, 2018). These arguments rest largely on the relative lack of Proterozoic low-temperature high-pressure metamorphic rocks such as blueschists that form in subduction zones (Stern et al., 2013). An alternative interpretation for this lack of blueschists in the Proterozoic is that such a shift in metamorphic regime is the predicted result of secular evolution of mantle chemistry rather than a harbinger of the onset of plate tectonics (Palin and White, 2015). While this line of evidence is intriguing, to argue that there was not differential plate tectonic motion in the Paleoproterozoic and Mesoproterozoic is to ignore a vast breadth and depth of geological and paleomagnetic data. From a paleomagnetic perspective, there is strong support for independent and differential motion of the Slave and Superior provinces as is illustrated in Figure 4. From a geological perspective, the Trans-Hudson orogenic cycle, the Grenville orogenic cycle, and the Appalachian orogenic cycle are all well-explained with a mobilistic interpretation that includes phases of accretionary followed by collisional orogenesis (Fig. 2). One could counter that this perspective results from a plate-tectonic-centric viewpoint that lacks creativity to see the record as resulting from other processes than modern-style plate tectonics. However, in addition to the broad geological record showing an amalgamation of terranes as would be expected to arise through plate tectonics, there are also an obducted ophiolite as well as eclogites preserved in the Trans-Hudson orogen (Weller and St-Onge, 2017). These eclogites preserve evidence for high-pressure/low-temperature metamorphic conditions ca. 1.8 Ga. Similar to the Himalayan orogen, these rocks are interpreted to be the result of deep continental subduction and exhumation associated with convergent plate tectonics (Weller and St-Onge, 2017). Outside of Laurentia, there are examples of ecologites with geochemical affinity to oceanic crust such as that documented in the ca. 1.9 Ga Ubendian Belt of the Congo craton (Boniface et al., 2012).

Another perspective on Proterozoic tectonics, is that the record is one of intermittent subduction (Silver and Behn, 2008; O'Neill et al., 2013). In such a model, there are extended intervals with a stagnant lid alternating with intervals of differential plate motion. In particular, it has been argued that the Mesoproterozoic Era (1.6 to 1.0 Ga) is an interval when Earth was in

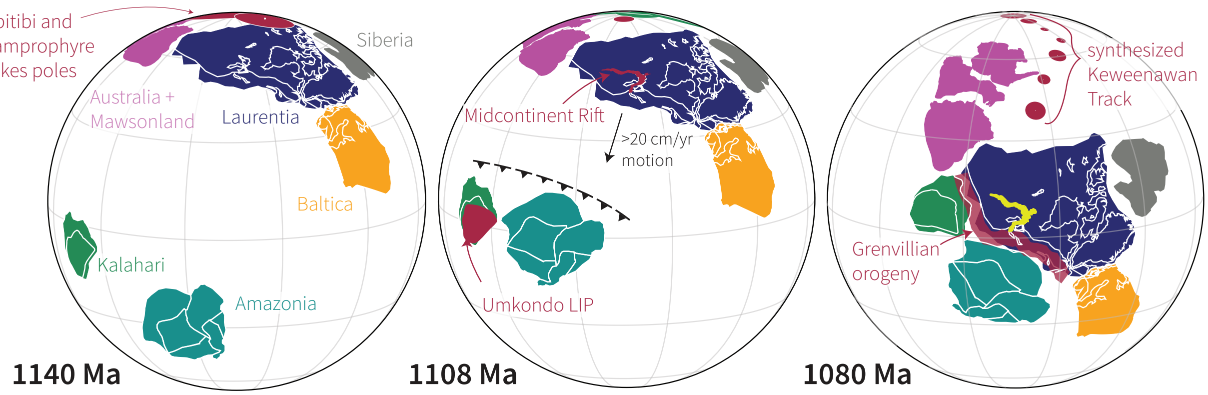

Figure 7. Paleogeographic reconstructions of Laurentia and other select Proterozoic continents leading up to Rodinia assembly in the late Mesoproterozoic modified from Swanson-Hysell et al. (2019). The record of paleomagnetic poles implies rapid motion which is consistent with the timing of collisional orogenesis associated with the Grenvillian orogeny.

a stagnant regime (Silver and Behn, 2008; O'Neill et al., 2013). The long-lived accretionary history of Laurentia following the amalgamation of the Archean provinces is difficult to reconcile with such an interpretation (Figs. 1 and 2).

An additional constraint supporting ongoing plate tectonics throughout the Proterozoic comes from the paleomagnetic record — in particular the paleomagnetic poles supported with baked contact tests (Fig. **??**). In a stagnant lid regime, there would not be sufficient heat flow across the core-mantle boundary to sustain a geodynamo (Nimmo and Stevenson, 2000; Buffett, 2000). Baked contact tests indicate that, at the time of dike emplacement, there was an appreciable field such that both the cooling magma and the heated country rock in the vicinity of a dike were able to acquire a primary coherent magnetization direction. Additionally, since paleomagnetic poles are developed from many individual cooling units across a region, the similarity of the directions across an igneous province indicates that the magnetizations were dominantly acquired from the geomagnetic field rather than being influenced by local variable crustal magnetizations. Therefore, the record supports the persistence of a geomagnetic field through the Paleoproterozoic and Mesoproterozoic (Table 2) which implies active plate tectonics that enabled sufficient core-mantle boundary heat flow to power the geodynamo. This interpretation of a significant persistent geomagnetic field through much of the Proterozoic (with the potential exception of the Ediacaran; Bono et al., 2019) is further bolstered by estimates of paleointensity obtained from mafic dikes from Laurentia (e.g. Macouin et al., 2006) and elsewhere.

The record of these poles also show that there was progressive motion of Laurentia through the Proterozoic (Figs. 5 and 6). Using data from Laurentia alone, however, it is difficult to ascertain whether this motion is due to plate tectonic motion or rotation of the entire solid Earth through true polar wander. True polar wander can lead to changing position relative to the spin axis even with a stagnant lid. One interval when the Laurentian paleomagnetic record demands that some of the motion is through differential plate tectonics is in the latest Mesoproterozoic. At that time, the pole path is very well-resolved with many high-quality paleomagnetic poles between 1110 and 1070 Ma (Table 2; 3). The progression of the poles requires rotation about an Euler pole that is distinct from a great circle path which would result if the motion were solely due to true polar wander (Swanson-Hysell et al., 2019). These poles constrain rapid motion of Laurentia leading up to collisional orogenesis associated with the Grenvillian orogeny, as illustrated in Figure 7. These data provide strong evidence for differential plate motion at the time and are inconsistent with a stagnant lid. Rather, the orogenic cycle of the Mesoproterozoic bears similarity with that of the Paleozoic and reveals Laurentia to have been a central player in the building of amalgamated continents associated with Rodinia and Pangea.

4.8 Evaluating Laurentia's paleogeographic neighbors

4.8.1 North China

The latest Mesoproterozoic to earliest Neoproterozoic pole path of the North China craton includes a swath of paleomagnetic poles with a similar arc length to the Keweenawan Track to Grenville Loop of Laurentia's APWP (Zhao et al., 2019; Zhang et al., this volume). While the chronostratigraphic age constraints on these North China poles are much looser than those from Laurentia, Zhao et al. (2019) propose that the North China poles can be aligned with the Keweenawan Track to reconstruct North China as being conjoined to the northwest margin of Laurentia from prior to ca. 1110 Ma into the early Neoproterozoic. North China would have been at polar latitudes ca. 1110 Ma and moved rapidly with Laurentia as it transited towards the equator. Zhao et al. (2019) also argued that similarity in the detrital zircon age spectra between early Neoproterozoic sediments in NW Laurentia and North China basins supports this reconstruction. In particular, sediment transport from Laurentia could provide a source for ca. 1.18 Ga zircons (from the Shawinigan orogen) and ca. 1.08 Ga zircons (from the Grenville orogen). In the Laurentia basins, ca. 1.6 Ga zircons without a clear Laurentia source could be sourced from North China craton granites (e.g. Wang et al., 2020). If North China was in this position, the timing of its arrival of North China is unclear. The ca. 1220 Ma dikes pole of the North China craton is not coincident with the ca. 1237 Ma Sudbury dikes pole in this reconstructed position leading Zhao et al. (2019) and Zhang et al. (this volume) to suggest that North China arrived on the Laurentian margin between ca. 1220 and 1110 Ma although they note a lack of evidence for known North China orogenesis at this time. In terms of departing from this position, one possibility is that

4.9 Conclusion

The paleogeographic record of Laurentia is rich in constraints through the Precambrian both in terms of the geological and geochronological constraints on tectonism and the record of paleomagnetic poles. Data from the Slave and Superior provinces of Laurentia provide what is arguably the strongest evidence of differential plate tectonics in the Rhyacian and Orosirian Periods of the Paleoproterozoic Era (2.3 to 1.8 Ga) leading up to the collision of these terranes during the Trans-Hudson orogeny. The collisions of these and other Archean provinces led to the formation of the core of Laurentia. Subsequent crustal growth occurred through multiple intervals of accretionary orogenesis through the late Paleoproterozoic and Mesoproterozoic until the continent-continent collision of the Grenvillian orogeny that was ongoing at the Mesoproterozoic-Neoproterozoic boundary (1.0 Ga). The lead-up to this orogeny was associated with rapid plate motion of Laurentia from high latitudes towards the equator recorded by the Logan Loop and Keweenawan Track of paleomagnetic poles. Following, a return to high latitudes as constrained by paleomagnetic poles of the Grenville Loop, Laurentia straddled the equator at the time of Cryogenian Snowball Earth glaciation as part of the Rodinia supercontinent. Rifting and passive margin development then isolated Laurentia in the early Paleozoic Era. Subsequent accretionary and collisional orogenesis occurred associated with the Appalachian orogenic cycle with Laurentia first colliding with Avalonia-Baltica to become Laurussia and Laurussia then uniting with Gondwana to form Pangea. While the details of the conjugate continents are better reconstructed for this last Wilson cycle, the broad features of the Trans-Hudson, Grenvillian and Appalachian orogenic cycles bear similarities. In each case, accretionary collision of arc terranes was followed by continent-continent collision. The major difference is that the collisions of the Grenvillian and Appalachian orogenic cycles resulted in relatively minor crustal growth compared to the Trans-Hudson. Break-up following the Grenvillian and Appalachian orogenic cycles occurred along the same margin as collision while the major orogens of the Trans-Hudson orogenic cycle have remained sutured. As a result, Laurentia has been a formidable continent for the past 1.8 billion years. As can be seen in the Chapters on Archean paleogeography (Salminen et al., this volume), Nuna (Elming et al., this volume) and Rodinia (Evans et al., this volume), the constraints from Laurentia are at the center of paleogeographic models through the Precambrian and will continue to be as the next generation of paleogeographic models are developed.

Acknowledgements

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Table 1. Rotations of separated terranes

Block	Euler pole longitude	Euler pole latitude	rotation angle	note and citation
Greenland	-118.5	67.5	-13.8	Cenozoic separation of Greenland from Laurentia associated with opening of Baffin Bay and the Labrador Sea (Roest and Srivastava, 1989)
Scotland	161.9	78.6	-31.0	Reconstructing Atlantic opening following Torsvik and Cocks (2017)
Svalbard	125.0	-81.0	68	Rotate Svalbard to Laurentia in fit that works well with East Greenland basin according to Maloof et al. (2006)

Table 2: Compilation of paleomagnetic poles from Laurentia

terrane	unit name	Nordic rating	site lon (°)	site lat (°)	plon (°)	plat (°)	A_{95} (°)	age (Ma)	pole reference
Laurentia-Wyoming	Stillwater Complex - C2	A	249.2	45.2	335.8	-83.6	4.0	2705^{+4}_{-4}	Selkin et al. (2008)
Laurentia-Superior(East)	Otto Stock dykes and aureole	B	279.9	48.0	227.0	69.0	4.8	2676^{+5}_{-5}	Pullaiah and Irving (1975)
Laurentia-Slave	Defeat Suite	B	245.5	62.5	64.0	-1.0	15.0	2625^{+5}_{-5}	Mitchell et al. (2014)
Laurentia-Superior(East)	Ptarmigan-Mistassini dykes	B	287.0	54.0	213.0	-45.3	13.8	2505^{+2}_{-2}	Evans and Halls (2010)
Laurentia-Superior(East)	Matachewan dykes R	A	278.0	48.0	238.3	-44.1	1.6	2466^{+23}_{-23}	Evans and Halls (2010)
Laurentia-Superior(East)	Matachewan dykes N	A	278.0	48.0	239.5	-52.3	2.4	2446^{+3}_{-3}	Evans and Halls (2010)
Laurentia-Slave	Malley dykes	A	249.8	64.2	310.0	-50.8	6.7	2231^{+2}_{-2}	Buchan et al. (2012)
Laurentia-Superior(East)	Senneterre dykes	A	283.0	49.0	284.3	-15.3	5.5	2218^{+6}_{-6}	Buchan et al. (1993)
Laurentia-Superior(East)	Nipissing N1 sills	A	279.0	47.0	272.0	-17.0	10.0	2217^{+4}_{-4}	Buchan et al. (2000)
Laurentia-Slave	Dogrib dykes	A	245.5	62.5	315.0	-31.0	7.0	2193^{+2}_{-2}	Mitchell et al. (2014)
Laurentia-Superior(East)	Biscotasing dykes	A	280.0	48.0	223.9	26.0	7.0	2170^{+3}_{-3}	Evans and Halls (2010)
Laurentia-Wyoming	Rabbit Creek, Powder River and South Path Dykes	A	252.8	43.9	339.2	65.5	7.6	2160^{+11}_{-8}	Kilian et al. (2015)
Laurentia-Slave	Indin dykes	A	245.6	62.5	256.0	-36.0	7.0	2126^{+3}_{-18}	Buchan et al. (2016)
Laurentia-Superior(West)	Marathon dykes N	A	275.0	49.0	198.2	45.4	7.7	2124^{+3}_{-3}	Halls et al. (2008)

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terrane	unit name	Nordic rating	site lon (°)	site lat (°)	plon (°)	plat (°)	A_{95} (°)	age (Ma)	pole reference
Laurentia-Superior(West)	Marathon dykes R	A	275.0	49.0	182.2	55.1	7.5	2104^{+3}_{-3}	Halls et al. (2008)
Laurentia-Superior(West)	Cauchon Lake dykes	A	263.0	56.0	180.9	53.8	7.7	2091^{+2}_{-2}	Evans and Halls (2010)
Laurentia-Superior(West)	Fort Frances dykes	A	266.0	48.0	184.6	42.8	6.1	2077^{+5}_{-5}	Evans and Halls (2010)
Laurentia-Superior(East)	Lac Esprit dykes	A	282.0	53.0	170.5	62.0	6.4	2069^{+1}_{-1}	Evans and Halls (2010)
Laurentia-Greenland-Nain	Kangamiut Dykes	B	307.0	66.0	273.8	17.1	2.7	2042^{+12}_{-12}	Fahrig and Bridgwater (1976)
Laurentia-Slave	Lac de Gras dykes	A	249.6	64.4	267.9	11.8	7.1	2026^{+5}_{-5}	Buchan et al. (2009)
Laurentia-Superior(East)	Minto dykes	A	285.0	57.0	171.5	38.7	13.1	1998^{+2}_{-2}	Evans and Halls (2010)
Laurentia-Slave	Rifle Formation	B	252.9	65.9	341.0	14.0	7.7	1963^{+6}_{-6}	Evans and Hoye (1981)
Laurentia-Rae	Clearwater Anorthosite	B	251.6	57.1	311.8	6.5	2.9	1917^{+7}_{-7}	Halls and Hanes (1999)
Laurentia-Wyoming	Sourdough mafic dike swarm	A	-108.3	44.7	292.0	49.2	8.1	1899^{+5}_{-5}	Kilian et al. (2016)
Laurentia-Slave	Ghost Dike Swarm	A	244.6	62.6	286.0	-2.0	6.0	1887^{+5}_{-9}	Buchan et al. (2016)
Laurentia-Slave	Mean Seton/Akaitcho/Mara	B	250.0	65.0	260.0	-6.0	4.0	1885^{+5}_{-5}	Mitchell et al. (2010)
Laurentia-Slave	Mean Kahochella, Peacock Hills	B	250.0	65.0	285.0	-12.0	7.0	1882^{+4}_{-4}	Mitchell et al. (2010)
Laurentia-Superior(West)	Molson (B+C2) dykes	A	262.0	55.0	218.0	28.9	3.8	1879^{+6}_{-6}	Evans and Halls (2010)

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terrane	unit name	Nordic rating	site lon (°)	site lat (°)	plon (°)	plat (°)	A_{95} (°)	age (Ma)	pole reference
Laurentia-Slave	Douglas Peninsula Formation, Pethei Group	B	249.7	62.8	258.0	-18.0	14.2	1876^{+10}_{-10}	Irving and McGlynn (1979)
Laurentia-Slave	Takiyuak Formation	B	246.9	66.1	249.0	-13.0	8.0	1876^{+10}_{-10}	Irving and McGlynn (1979)
Laurentia-Superior	Haig/Flaherty/Sutton Mean	B	279.0	56.0	245.8	1.0	3.9	1870^{+1}_{-1}	Nordic workshop calculation based on data of Schmidt (1980); Schwarz et al. (1982)
Laurentia-Slave	Pearson A/Peninsular/Kilohigok sills	A	250.0	65.0	269.0	-22.0	6.0	1870^{+4}_{-4}	Mitchell et al. (2010)
Laurentia-Trans-Hudson orogen	Boot-Phantom Pluton	B	258.1	54.7	275.4	62.4	7.9	1838^{+1}_{-1}	Symons and Mackay (1999)
Laurentia-Rae	Sparrow Dykes	B	250.2	61.6	291.0	12.0	7.9	1827^{+4}_{-4}	McGlynn et al. (1974)
Laurentia-Rae	Martin Formation	A	251.4	59.6	288.0	-9.0	8.5	1818^{+4}_{-4}	Evans and Bingham (1973)
Laurentia	Dubawnt Group	B	265.6	64.1	277.0	7.0	8.0	1785^{+35}_{-35}	Park et al. (1973)
Laurentia-Trans-Hudson orogen	Deschambault Pegmatites	B	256.7	54.9	276.0	67.5	7.7	1766^{+5}_{-5}	Symons et al. (2000)
Laurentia-Trans-Hudson orogen	Jan Lake Granite	B	257.2	54.9	264.3	24.3	16.9	1758^{+1}_{-1}	Gala et al. (1995)
Laurentia	Cleaver Dykes	A	242.0	67.5	276.7	19.4	6.1	1741^{+5}_{-5}	Irving (2004)
Laurentia-Greenland	Melville Bugt diabase dykes	B	303.0	74.6	273.8	5.0	8.7	1633^{+5}_{-5}	Halls et al. (2011)
Laurentia	Western Channel Diabase	A	242.2	66.4	245.0	9.0	6.6	1590^{+3}_{-3}	Irving and Park (1972)

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terrane	unit name	Nordic rating	site lon (°)	site lat (°)	plon (°)	plat (°)	A_{95} (°)	age (Ma)	pole reference
Laurentia	St.Francois Mountains Acidic Rocks	A	269.5	37.5	219.0	-13.2	6.1	1476^{+16}_{-16}	Meert and Stuckey (2002)
Laurentia	Michikamau Intrusion	A	296.0	54.5	217.5	-1.5	4.7	1460^{+5}_{-5}	Emslie et al. (1976)
Laurentia	Spokane Formation	A	246.8	48.2	215.5	-24.8	4.7	1458^{+13}_{-13}	Elston et al. (2002)
Laurentia	Snowslip Formation	A	245.9	47.9	210.2	-24.9	3.5	1450^{+14}_{-14}	Elston et al. (2002)
Laurentia	Tobacco Root dykes	B	247.6	47.4	216.1	8.7	10.5	1448^{+49}_{-49}	Harlan et al. (2008)
Laurentia	Purcell Lava	A	245.1	49.4	215.6	-23.6	4.8	1443^{+7}_{-7}	Elston et al. (2002)
Laurentia	Rocky Mountain intrusions	B	253.8	40.3	217.4	-11.9	9.7	1430^{+15}_{-15}	Nordic workshop calculation based on data of Harlan et al. (1994); Harlan and Geissman (1998)
Laurentia	Mistastin Pluton	B	296.3	55.6	201.5	-1.0	7.6	1425^{+25}_{-25}	Fahrig and Jones (1976)
Laurentia	McNamara Formation	A	246.4	46.9	208.3	-13.5	6.7	1401^{+6}_{-6}	Elston et al. (2002)
Laurentia	Pilcher, Garnet Range and Libby Formations	A	246.4	46.7	215.3	-19.2	7.7	1385^{+23}_{-23}	Elston et al. (2002)
Laurentia-Greenland	Zig-Zag Dal Basalts	B	334.8	81.2	242.8	12.0	3.8	1382^{+2}_{-2}	Marcussen and Abrahamsen (1983)
Laurentia-Greenland	Midsommersoe Dolerite	B	333.4	81.6	242.0	6.9	5.1	1382^{+2}_{-2}	Marcussen and Abrahamsen (1983)
Laurentia-Greenland	Victoria Fjord dolerite dykes	B	315.3	81.5	231.7	10.3	4.3	1382^{+2}_{-2}	Abrahamsen and Van Der Voo (1987)

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terrane	unit name	Nordic rating	site lon (°)	site lat (°)	plon (°)	plat (°)	A_{95} (°)	age (Ma)	pole reference
Laurentia	Nain Anorthosite	B	298.2	56.5	206.7	11.7	2.2	1305^{+15}_{-15}	Murthy (1978)
Laurentia-Greenland	North Qoroq intrusives	B	314.6	61.1	202.6	13.2	8.3	1275^{+1}_{-1}	Piper (1992)
Laurentia-Greenland	Kungnat Ring Dyke	B	311.7	61.2	198.7	3.4	3.2	1275^{+2}_{-2}	Piper and Stearn (1977)
Laurentia	Mackenzie dykes grand mean	A	250.0	65.0	190.0	4.0	5.0	1267^{+2}_{-2}	Buchan et al. (2000)
Laurentia-Greenland	West Gardar Dolerite Dykes	B	311.7	61.2	201.7	8.7	6.6	1244^{+8}_{-8}	Piper and Stearn (1977)
Laurentia-Greenland	West Gardar Lamprophyre Dykes	B	311.7	61.2	206.4	3.2	7.2	1238^{+11}_{-11}	Piper and Stearn (1977)
Laurentia	Sudbury Dykes Combined	A	278.6	46.3	192.8	-2.5	2.5	1237^{+5}_{-5}	Palmer et al. (1977)
Laurentia-Scotland	Stoer Group	B	354.5	58.0	238.4	37.2	7.7	1199^{+70}_{-70}	Nordic workshop calculation
Laurentia-Greenland	Narssaq Gabbro	B	313.8	60.9	225.4	31.6	9.7	1184^{+5}_{-5}	Piper (1977)
Laurentia-Greenland	Hviddal Giant Dyke	B	313.7	60.9	215.3	33.2	9.6	1184^{+5}_{-5}	Piper (1977)
Laurentia-Greenland	South Qoroq Intr.	A	314.6	61.1	215.9	41.8	13.1	1163^{+2}_{-2}	Piper (1992)
Laurentia-Greenland	Giant Gabbro Dykes	B	313.7	60.9	226.1	42.3	9.4	1163^{+2}_{-2}	Piper (1977)
Laurentia-Greenland	NE-SW Trending dykes	B	314.6	61.1	230.8	33.4	5.7	1160^{+5}_{-5}	Piper (1992)
Laurentia	Ontario lamprophyre dykes	NR	273.3	48.8	223.3	58.0	9.2	1143^{+10}_{-10}	Piispa et al. (2018)

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terrane	unit name	Nordic rating	site lon (°)	site lat (°)	plon (°)	plat (°)	A_{95} (°)	age (Ma)	pole reference
Laurentia	Abitibi Dykes	A	279.0	48.0	215.5	48.8	14.1	1141^{+2}_{-2}	Ernst and Buchan (1993)
Laurentia	Nipigon sills and lavas	A	270.9	49.1	217.8	47.2	4.0	1109^{+2}_{-2}	Nordic workshop calculation based on data of Palmer (1970); Robertson and Fahrig (1971); Pesonen (1979); Pesonen and Halls (1979); Middleton et al. (2004); Borradaile and Middleton (2006)
Laurentia	Lowermost Mamainse Point volcanics -R1	A	275.3	47.1	227.0	49.5	5.3	1109^{+2}_{-3}	Swanson-Hysell et al. (2014a)
Laurentia	Lower Osler volcanics -R	A	272.3	48.8	218.6	40.9	4.8	1108^{+3}_{-3}	Swanson-Hysell et al. (2014b)
Laurentia	Middle Osler volcanics -R	A	272.4	48.8	211.3	42.7	8.2	1107^{+4}_{-4}	Swanson-Hysell et al. (2014b)
Laurentia	Upper Osler volcanics -R	A	272.4	48.7	203.4	42.3	3.7	1105^{+1}_{-1}	Halls (1974); Swanson-Hysell et al. (2014b, 2019)
Laurentia	Lower Mamainse Point volcanics -R2	A	275.3	47.1	205.2	37.5	4.5	1105^{+3}_{-4}	Swanson-Hysell et al. (2014a)
Laurentia	Mamainse Point volcanics -C (lower N, upper R)	A	275.3	47.1	189.7	36.1	4.9	1101^{+1}_{-1}	Swanson-Hysell et al. (2014a)
Laurentia	North Shore lavas - N	A	268.7	46.3	181.7	31.1	2.1	1097^{+3}_{-3}	Tauxe and Kodama (2009); Swanson-Hysell et al. (2019)

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terrane	unit name	Nordic rating	site lon (°)	site lat (°)	plon (°)	plat (°)	A_{95} (°)	age (Ma)	pole reference
Laurentia	Portage Lake Volcanics	A	271.2	47.0	182.5	27.5	2.3	1095^{+3}_{-3}	Books (1972); Hnat et al. (2006) as calculated in Swanson-Hysell et al. (2019)
Laurentia	Chengwatana Volcanics	B	267.3	45.4	186.1	30.9	8.2	1095^{+2}_{-2}	Kean et al. (1997)
Laurentia	Uppermost Mamainse Point volcanics -N	A	275.3	47.1	183.2	31.2	2.5	1094^{+6}_{-4}	Swanson-Hysell et al. (2014a)
Laurentia	Cardenas Basalts and Intrusions	B	248.1	36.1	185.0	32.0	8.0	1091^{+5}_{-5}	Weil et al. (2003)
Laurentia	Schroeder Lutsen Basalts	A	269.1	47.5	187.8	27.1	3.0	1090^{+2}_{-7}	Fairchild et al. (2017)
Laurentia	Central Arizona diabases -N	A	249.2	33.7	175.3	15.7	7.0	1088^{+11}_{-11}	Donadini et al. (2011)
Laurentia	Lake Shore Traps	A	271.9	47.6	186.4	23.1	4.0	1086^{+1}_{-1}	Kulakov et al. (2013)
Laurentia	Michipicoten Island Formation	A	274.3	47.7	174.7	17.0	4.4	1084^{+1}_{-1}	Fairchild et al. (2017)
Laurentia	Nonesuch Shale	B	271.5	47.0	178.1	7.6	5.5	1080^{+4}_{-10}	Henry et al. (1977)
Laurentia	Freda Sandstone	B	271.5	47.0	179.0	2.2	4.2	1070^{+14}_{-10}	Henry et al. (1977)
Laurentia	Haliburton Intrusions	B	281.4	45.0	141.9	-32.6	6.3	1015^{+15}_{-15}	Warnock et al. (2000)
Laurentia-Scotland	Torridon Group	B	354.3	57.9	220.9	-17.7	7.1	925^{+145}_{-145}	Nordic workshop calculation
Laurentia-Svalbard	Lower Grusdievbreen Formation	B	18.0	79.0	204.9	19.6	10.9	831^{+20}_{-20}	Maloof et al. (2006)

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terrane	unit name	Nordic rating	site lon (°)	site lat (°)	plon (°)	plat (°)	A_{95} (°)	age (Ma)	pole reference
Laurentia-Svalbard	Upper Grusdievbreen Formation	B	18.2	78.9	252.6	-1.1	6.2	800^{+11}_{-11}	Maloof et al. (2006)
Laurentia	Gunbarrel dykes	B	248.7	44.8	138.2	9.1	12.0	778^{+2}_{-2}	Calculation from Eyster et al. (2019) based on data of Harlan (1993); Harlan et al. (1997)
Laurentia-Svalbard	Svanbergfjellet Formation	B	18.0	78.5	226.8	25.9	5.8	770^{+19}_{-40}	Maloof et al. (2006)
Laurentia	Uinta Mountain Group	B	250.7	40.8	161.3	0.8	4.7	760^{+6}_{-10}	Weil et al. (2006)
Laurentia	Carbon Canyon	NR	248.2	36.1	166.0	-0.5	9.7	757^{+7}_{-7}	Weil et al. (2004) as calculated in Eyster et al. (2019)
Laurentia	Carbon Butte/Awatubi	NR	248.5	35.2	163.8	14.2	3.5	751^{+8}_{-8}	Eyster et al. (2019)
Laurentia	Franklin event grand mean	A	275.4	73.0	162.1	6.7	3.0	724^{+3}_{-3}	Denyszyn et al. (2009a)
Laurentia	Long Range Dykes	B	303.3	53.7	355.3	19.0	17.4	615^{+2}_{-2}	Murthy et al. (1992)
Laurentia	Baie des Moutons complex	B	301.0	50.8	321.5	-34.2	15.4	583^{+2}_{-2}	McCausland et al. (2011)
Laurentia	Baie des Moutons complex	B	301.0	50.8	332.7	42.6	12.0	583^{+2}_{-2}	McCausland et al. (2011)
Laurentia	Callander Alkaline Complex	B	280.6	46.2	301.4	46.3	6.0	575^{+5}_{-5}	Symons and Chiasson (1991)
Laurentia	Catoctin Basalts	B	281.8	38.5	296.7	42.0	17.5	572^{+5}_{-5}	Meert et al. (1994)

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terrane	unit name	Nordic rating	site lon (°)	site lat (°)	plon (°)	plat (°)	A_{95} (°)	age (Ma)	pole reference
Laurentia	Sept-Iles layered intrusion	B	293.5	50.2	321.0	-20.0	6.7	565^{+4}_{-4}	Tanczyk et al. (1987)