The late Mesoproterozoic to early Neoproterozoic Grenvillian orogeny and the assembly of Rodinia: Turning point in the tectonic evolution of Laurentia

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Abstract

The amalgamation of Laurentia's Archean provinces ca. 1830 Ma was followed by ~700 million years of accretionary orogenesis along its active southeastern margin, marked by subduction of oceanic lithosphere, formation of arcs and backarcs, and episodic accretion. This prolonged period of active-margin processes, spanning the late Paleoproterozoic and Mesoproterozoic eras, resulted in major accretionary crustal growth and was terminated by closure of the Unimos Ocean (new name). Ocean closure was associated with rapid motion of Laurentia towards the equator and resulted in continental collision that led to profound reworking of much of the accreted Proterozoic crust during the ca. 1090-980 Ma Grenvillian orogeny. The Grenvillian orogeny resulted in the formation of a large hot long-duration orogen with a substantial orogenic plateau that underwent extensional orogenic collapse before rejuvenation and the formation of the Grenville Front tectonic zone. The Grenvillian orogeny also caused the termination and inversion of the Midcontinent Rift which, had it continued, would likely have split Laurentia into distinct continental blocks. Voluminous mafic magmatic activity in the Midcontinent Rift from ca. 1108 to 1090 Ma was contemporaneous with magmatism in the Southwestern Laurentia large igneous province. We discuss a potential link between prolonged subduction of oceanic lithosphere beneath southeast Laurentia in the Mesoproterozoic and the initiation of this voluminous mafic magmatism. In this hypothesis, subducted water in dense hydrous Mg-silicates transported to the bottom of the upper mantle could have led to hydration and increased buoyancy, resulting in upwelling, decompression melting, and intraplate magmatism. Coeval collisional orogenesis in several continents, including Amazonia and Kalahari tie the Grenvillian orogeny to the amalgamation of multiple Proterozoic continents in the supercontinent Rodinia. These orogenic events collectively constitute a major turning point in both Laurentian and global tectonics. The ensuing paleogeographic configuration, and that which followed during Rodinia's extended break-up, set the stage for Earth system evolution through the Neoproterozoic Era.

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Introduction

The suturing of Archean provinces by late Paleoproterozoic collisional orogenesis, especially the extensive ca. 1860 to 1820 Ma Trans-Hudson orogeny, led to formation of the cratonic core of internal Laurentia (Hoffman, 1988; St-Onge et al., 2009; Corrigan, 2012). Also in the Paleoproterozoic, accretionary orogenesis along Laurentia's active southeastern margin (present-day coordinates) led to the growth of external Laurentia (Fig. 1; Whitmeyer and Karlstrom, 2007). These latter orogens span Laurentia from the Grand Canyon region of Arizona in the southwest to southern Greenland in the northeast and include orogenesis contemporaneous with the Trans-Hudson orogeny (Central Plains-Penokean-Makkovik-Ketilidian; Schulz and Cannon, 2007; Garde et al., 2002; Hinchey et al. 2020), and postdating it (Yavapai and Mazatzal-Labradorian orogenies; Whitmeyer and Karlstrom, 2007; Gower et al., 2008). Active-margin tectonics and episodic accretionary orogenesis continued on Laurentia's southeastern margin into the early and mid-Mesoproterozoic (Eastern and Southern Granite-Rhyolite provinces, Picuris-Baraboo-Pinwarian orogenies), collectively resulting in large-scale lateral growth of the continent (Fig. 1). The resulting large area of Paleoproterozoic and Mesoproterozoic crust comprising external Laurentia that formed during this 700-million-year interval of active-margin tectonics has been collectively referred to as the Great Proterozoic Accretionary Orogen (Condie, 2013). This orogen corresponds to approximately one third of Laurentia's surface area and forms most of the now tectonically stable part of the USA. The youngest two of these accretionary events, which were subsequently subsumed by the Grenvillian orogeny, are the Elzevirian orogeny (ca. 1250-1220 Ma) and the Shawinigan orogeny (ca. 1190-1160 Ma; Figs. 2 and 3). Note that while the remnants of these accretionary orogens are now located in the Grenville Province, they are distinct from the subsequent collisional Grenvillian orogeny. Coeval with the later stages of the Shawinigan orogeny, there was a major pulse of anorthosite-mangerite-charnockite-granite (AMCG) magmatism that resulted in the emplacement of voluminous intrusive complexes inboard from Laurentia's eastern margin from ca. 1170 to 1150 Ma. These intrusions temporally overlapped with magmatism in the Lake Superior region that led to the emplacement of the Abitibi dikes and other mafic intrusions, as well as lamprophyre and alkaline intrusions (Fig. 3).

During an interval of apparent tectonic quiescence on Laurentia's eastern margin, the Midcontinent Rift initiated ca. 1109 (see location in Fig. 1 and timescale in Fig. 2; Swanson-Hysell et al., 2019). An early stage of widespread plateau volcanism ca. 1109 to 1105 Ma was following by a main stage of voluminous mafic magmatism that led to the accumulation of thick successions of tholeiitic basalt within the confines of the rift ca. 1097 to 1092 (Green, 1983, Swanson-Hysell et al., 2019), and the emplacement of voluminous comagmatic intrusive complexes (Paces and Miller, 1993, Swanson-Hysell et al., 2021b, Zhang et al., 2021). Extension continued within the rift to at least 1091 Ma with more localized magmatic activity continuing until ca. 1084 Ma (Fairchild et al., 2017). As magmatic activity waned, the basin transitioned to terrestrial clastic sedimentation associated with thermal subsidence (Cannon, 1992). Termination of extension and magmatism in the Midcontinent Rift was coeval with onset of the collisional Grenvillian orogeny (ca. 1090 Ma; Fig. 3; Cannon, 1994). The Grenvillian orogeny was a major mountain-building event, both in terms of the physical size of the orogen and the duration of orogenesis (ca. 1090-980 Ma). Within the Grenville orogen, the Grenvillian orogeny is associated with ductile thrusting, nappe formation, and crustal imbrication under high-grade metamorphic conditions (Rivers et al., 2012). Insight into the scale of crustal shortening within the Grenville orogen can be gained from the observation that the northwestern limit of significant Grenvillian deformation, the Grenville Front, cuts progressively across the ~1200 km-wide Great Proterozoic Accretionary orogen from southwest to northeast. As a result of this geometry, reworked Archean rocks of the Superior Province (internal Laurentia) occur within the exposed northwestern Grenville Province in Canada, whereas farther to the southwest the rocks adjacent to the Grenville Front are Mesoproterozoic and part of external Laurentia (Fig. 1).

Abundant U-Pb zircon geochronological data confirm the polymetamorphic character of many high-grade gneiss units in the Grenville Province, with zircon growth during both Paleo- to Mesoproterozoic accretionary metamorphism and in the ensuing collisional Grenvillian orogeny (e.g., Carr et al, 2000; Rivers et al., 2012). Moreover, Nd model ages support the interpretation that gneisses within the Grenville Province were derived from the continuation of units in the unreworked Paleoproterozoic to Mesoproterozoic foreland to the northwest of the Grenville Front (Fig. 1b; Martin and Dickin, 2005). These data support the interpretation that such units comprised components of the Great Proterozoic Accretionary Orogen before incorporation within the Grenville Province.

The last major contractional phase of the protracted Grenvillian orogeny, the ca. 1010 to 980 Ma Rigolet phase, led to the development of the Grenville Front and the parautochthonous belt. It was associated with propagation of the orogen towards the interior of the continent by incorporation of crust from the adjacent orogenic foreland as it was subducted beneath it (Hynes and Rivers, 2010). Northwest of the Grenville Front, Laurentia remained largely, but not entirely, undeformed. Far-field contraction during the Rigolet phase resulted in final structural in-

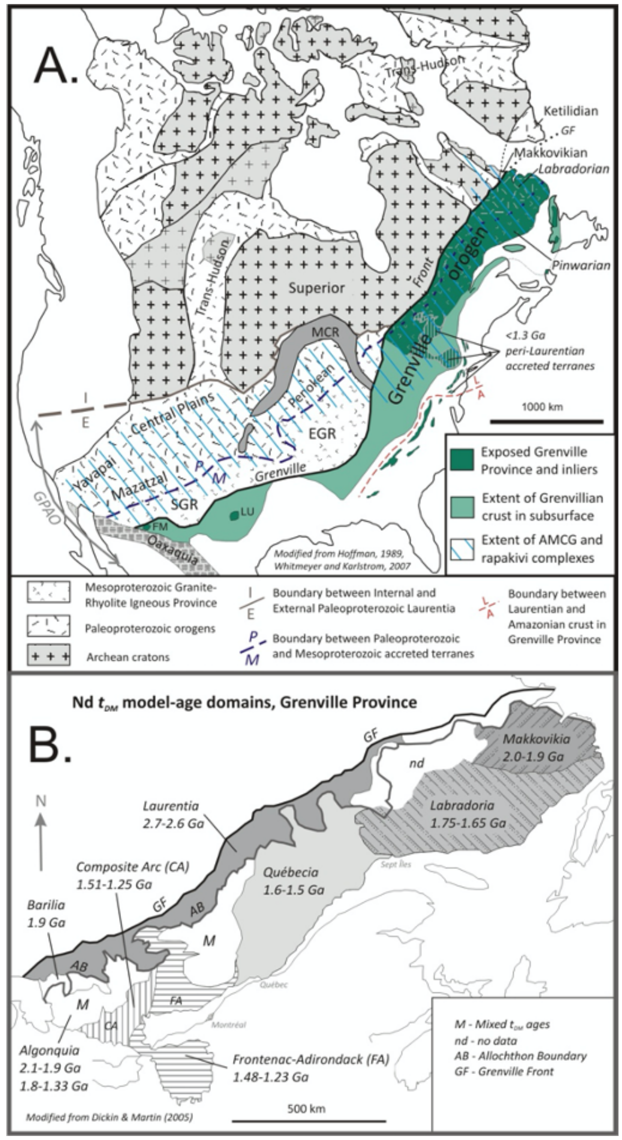

Figure 1: (A): Precambrian tectonic provinces of Laurentia, illustrating the trajectory of the Grenville Front cutting obliquely across External Laurentia in the subsurface and intersecting the boundary with Internal Laurentia in the western Grenville Province. Abbreviations: EGR, SGR, Mesoproterozoic Eastern and Southern GraniteRhyolite provinces; GF, Grenville Front; GPAO, Great Proterozoic Accretionary Orogen; MCR, Midcontinent Rift. The Labrador Orogen (age-equivalent to the Mazatzal Orogen) and Pinwarian Orogen (in part age-equivalent to the EGR), are reworked parts of the Great Proterozoic Accretionary Orogen within the Grenville Orogen. The extent of AMCG and rapakivi suites in southwestern Laurentia is after McLelland et al., 2010b). The boundary between Laurentian and allochthonous lithosphere (potentially derived from Amazonia; L/A) is based on whole-rock Pb isotope data. FM, Franklin Mountains; LU - Llano Uplift. Oaxaquia is a separate Rodinia fragment accreted to Laurentia in the Mesozoic (modified from Rivers et al., 2012; after Hoffman, 1989; Loewy et al., 2004; Whitmeyer and Karlstrom, 2007, where references to original sources are provided). (B) Map showing depleted mantle Nd model age (Nd tDM) domains of the Grenville Province (modified from Rivers et al., 2012, after Martin and Dickin, 2005).

version of the Midcontinent Rift (Hodgin et al., 2022). This deformation was superimposed on shortening that occurred within the rift earlier during the Ottawan phase of the orogeny (Cannon et al., 1993; Hodgin et al., 2022). The last stage of shortening in the Midcontinent Rift resulted in the deposition of syn-orogenic sedimentary rocks that are now in the footwall of reverse faults that uplifted rift volcanic rocks during the Rigolet phase (Hodgin et al., 2022).

Turning points

The development of the Midcontinent Rift and the subsequent collisional Grenvillian orogeny mark major turning points in Laurentia's tectonic evolution. If the timeline of tectonic events had been slightly different, Laurentia as we know it would likely not exist today. The extension and co-located magmatic activity that led to the development of the Midcontinent Rift in the continental interior (Fig. 1) was so significant that, in the absence of the Grenvillian orogeny, it could have resulted in the break-up of Laurentia. In so doing, it would have separated much of external Laurentia that had developed through the preceding Paleoproterozoic and Mesoproterozoic orogenesis from the core of internal Laurentia.

Instead, the rift underwent far-field contractional deformation as a result of Grenvillian collisional orogenesis (Cannon, 1994), and its potential as a turning-point was extinguished. The Grenvillian orogeny was preceded by rapid motion of Laurentia toward the equator where collision with conjugate continents led to the assembly of the supercontinent Rodinia (Hoffman, 1991; Swanson-Hysell et al., 2019; see paleogeographic reconstruction in Fig. 5). The collisional Grenvillian orogeny marked the end of the prolonged interval of episodic accretionary orogenesis along Laurentia's southeastern margin that extended to Baltica an enduring aspect of Laurentia's paleogeographic evolution from ca. 1830 to 1160 Ma (e.g., Karlstrom et al. 2001; Swanson-Hysell et al., 2021a). In this contribution, we refer to the long-lived ocean that closed in the lead-up to the Grenvillian orogeny as the Unimos Ocean. Cawood and Pisarevsky (2017) used the term "Mirovoi ocean" to refer to this ocean basin. However, that term was originally proposed for, and is used in the literature to refer to, the ocean that existed external to Rodinia (McMenamin and McMenamin, 1990). Unimos is the plural conjugation of the Spanish and Portuguese verb unir (to join; to unite) and therefore translates to "we have united." Given that the unification of continents into Rodinia as a result of the ocean's closure includes parts of the modern-day Spanish- and Portuguese-speaking world, we feel this name is well-suited for the ancient ocean basin.

The 200 million years following the end of the Grenvillian orogeny (from ca. 980 to 780 Ma) was an interval of tectonic stability for Laurentia given its position as the central constituent of the supercontinent Rodinia (see 1060 Ma and 775 Ma reconstructions in Fig. 5). Laurentia's emergence from Rodinia initiated with rifting associated with the ca. 778 Ma Gunbarrel large igneous province (panel 775 Ma in Fig. 5; Harlan et al., 2003) and was followed by progressive rifting of conjugate continents from its margins through the rest of the Neoproterozoic Era (Macdonald et al., this volume). In summary, the Grenvillian orogeny was a turning point not only for the evolution of Laurentia, but also of global significance in light of Laurentia's central position within Rodinia, and we investigate this tectonic history further in the text that follows.

Towards a more nuanced approach to late Mesoproterozoic tectonics

The terms "Grenvillian," "Grenville," and "Grenville-age" have been widely, and unfortunately somewhat loosely, used in the literature to refer to Mesoproterozoic orogenic events in Laurentia and elsewhere. Due to the importance of the Grenvillian orogeny to our understanding of Mesoproterozoic and Neoproterozoic global tectonics, we take advantage of this platform to make a plea for more consistent and precise terminology that we hope will stimulate and underpin more careful and critical analysis. "Grenville" and "Grenvillian" are to some degree interchangeable depending upon one's predilection for using adjectives derived from nouns versus repurposing nouns as adjectives, but conventional usages are "Grenville Province," "Grenville orogen," and "Grenvillian orogeny." In this usage, "Grenville Province" refers to the exposed geologic province in southeastern Canada and contiguous northeastern USA in which the Grenvillian orogeny was the last major tectonic event, whereas "Grenville orogen" includes both the Grenville Province and its unexposed subsurface extensions within Laurentia (colored dark and light green respectively in Fig. 1a). "Grenvillian orogeny" refers to the tectonic processes associated with ca. 1090-980 Ma orogenesis within the Grenville orogen and farther down the Laurentia margin that are inferred to have taken place in a continent-continent collisional setting (discussed in more detail below). Note that the formation ages of units within the Grenville Province range from Archean to Mesoproterozoic.

The broad and imprecise usage of Grenville/Grenvillian terminology originated at a time when the community's ability to date orogenic events was in its infancy (e.g. Collins et al., 1954). As a result, the timing and duration of the Grenvillian orogeny have fluctuated considerably among publications, with a start date as early as ca. 1.3 Ga suggested by some authors based on the presence of metamorphic rocks of that age within the southwestern Grenville Province. However, once the conceptual distinction between the collisional Grenvillian orogeny and precursor accretionary orogenies was formalized, the temporal limits of the former could be defined, and they are now usually given as ca. 1090-980 Ma, which bracket the limits of ductile Grenvillian deformation and metamorphism (Figs. 2 and 3; Rivers et al., 2012). The term "Grenvillian orogenic cycle" has been used by some authors to encompass the late Mesoproterozoic (<1.3 Ga) accretionary and collisional orogenesis in the southwestern Grenville Province. However, neither its temporal limits nor the suitability of the term 'cycle' when referring to a succession of orogenic events can be rigorously justified. Nonetheless, the term continues to appear in the literature and is probably the source of recent usage of ca. 1.3-0.9 Ga as the limits of the Grenvillian orogeny. For all these reasons, and because it is in conflict with known constraints, we do not recommend use of this term.

The Grenvillian orogeny has been divided into two orogenic phases, based on the spatial distribution and timing of ductilely deformed, high-grade regional metamorphic rocks (Rivers et al. 2012): the ca. 1090-1030 Ma Ottawan orogenic phase in allochthonous nappes and thrust sheets in the southeast (hinterland), and the ca. 1010-980 Ma Rigolet orogenic phase in the parautochthonon northwest near the Grenville Front (foreland).

Early attempts to identify conjugate margins to Laurentia (e.g., Young, 1980) subsequently led to proposals for the existence of the supercontinent Rodinia with the Grenville orogen at its heart (e.g., McMenamin and McMenamin, 1990; Dalziel, 1991; Hoffman, 1991; Moores, 1991). The centrality of the Grenvillian orogeny for the assembly of Rodinia (see 1060 Ma reconstruction in Fig. 5) makes it clear that the limits and duration of the Grenvillian orogeny in Laurentia have more than local significance. However, while the recognition of peaks in orogenic activity associated with supercontinent assembly is valuable, the continued broad global usage of the term Grenville for any orogenic event between ca. 1.3 and 0.9 Ga can be problematic insomuch as it can convolve distinct events that occurred at distinct times in distinct locations. No orogenic event is global and the spatial and temporal complexity is rich in information. Since the 1980s, the tectonic history of the Grenvillian orogeny (in its type location in the eponymous province in eastern North America), as well as other late Mesoproterozoic orogenies, have become much better constrained temporally and spatially, with the result that some published correlations are no longer tenable. For example, in the Llano inlier of southwest Laurentia (Texas; Fig. 1), collisional orogenesis ca. 1150-1120 Ma was referred to as Grenvillian by Nelis et al. (1989) and Mosher (1998). Current data constrain this orogenesis to significantly predate the Grenvillian orogeny and be closer in age to the Shawinigan orogeny. Equating the Llano orogeny with the Grenvillian orogeny, in turn, led to designation of the ca. 1100 Ma Southwestern Laurentia large igneous province as "post-Grenville" by Bright et al. (2014), despite the fact that it predates the Grenvillian orogeny in the Grenville Province. While acknowledging that it is tempting to use Grenville in a broad sense, especially in regional correlations and supercontinent reconstructions, one of the goals of this volume is to synthesize the record of orogenesis and basin development across Laurentia. We can utilize the current knowledge of the spatial and temporal complexity of late Mesoproterozoic orogenesis to develop more nuanced and informed tectonic and paleogeographic models.

Synthesizing the chronology of tectonism

The chronologic framework of metamorphic and tectonomagmatic events is central to efforts to unravel tectonic history and infer process. In this contribution, we compile rich geochronologic datasets from across Laurentia that constrain both igneous crystallization dates and metamorphic crystallization dates in the late Mesoproterozoic and early Neoproterozoic (Fig. 2). There are multiple challenges in interpreting such data. For example, isotope dilution-thermal ionization mass spectrometry (ID-TIMS) methods to develop U-Pb crystallization dates are more precise than in situ methods such as laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) or sensitive high-resolution ion microprobe (SHRIMP) that target grains within thin sections or grain mounts (Schoene, 2014). However, while grains can be imaged and selected based on morphology, ID-TIMS methods are typically not spatially resolved within a grain (note that there have been some intriguing recent efforts to laser mill subzones of zircon prior to analysis at the Boise State University Isotope Geology Laboratory [e.g., Kovacs et al., 2020], but these methods are not widely applied). Such a whole grain approach works well for igneous zircon without a significant post-crystallization metamorphic history particularly when chemical abrasion that mitigates Pb loss is integrated into analysis protocols. However, in some high-grade metamorphic systems, such as the widespread granulite-facies metamorphism of the Grenvillian orogeny, igneous zircon can be overgrown by metamorphic rims. Dating such grains through ID-TIMS can lead to dates spread between igneous and metamorphic events an issue that is particularly acute in dates developed from multigrain fractions which used to be a common method. In situ methods can lead to spatially resolved data from igneous cores and metamorphic rims. Take, for example, the Hawkeye Granite Gneiss of the Adirondack Highlands for which multigrain U-Pb TIMS upper intercept dates of 1100 ± 12 Ma, 1098 ± 4 Ma, 1095 ± 5 Ma, 1093 ± 11 Ma, and 1089 ± 6 Ma were determined (Chiarenzelli and McLelland, 1991). These dates were of particular interest as it was a rare indication of ca. 1100 Ma magmatic activity on the eastern margin of North America during the time period of Midcontinent Rift magmatic activity and has therefore been discussed in this context (McLelland et al., 2010a; Swanson-Hysell et al., 2019). However, when zircon from the Hawkeye Granite Gneiss were investigated with SHRIMP, the oscillatory-zoned igneous cores gave dates such as 1165.9 ± 5.4 Ma with the rims giving dates such as 1043 ± 5 Ma (Aleinikoff et al., 2021). These results are now interpreted to indicate that the Hawkeye granite crystallized late in the Shawinigan orogeny associated with other AMCG plutons and that zircon rims grew during the Ottawan phase of the Grenvillian orogeny (Aleinikoff et al., 2021). Rather than indicating magmatic activity on the Laurentian margin ca. 1110 Ma, this unit now fits into the established pattern of extensive plutonism ca. 1165 Ma, and minimal tectonomagmatic activity on the eastern margin of Laurentia leading up to the onset of Grenvillian orogenesis ca. 1090 Ma (Figs. 2 and 3).

While they can be essential for unraveling the chronology of complicated zircon populations, as in the Hawkeye Granite Gneiss example, in situ methods are of lower analytical precision than CA-ID-TIMS. Such low precision makes it difficult to evaluate whether grains come from single populations, which can skew calculated weighted mean dates. It also can make it difficult to assess for U-Pb concordance and evaluate the extent to which data suffer from deleterious effects such as Pb loss. Therefore, high spatial resolution dates with low analytical precision can also suffer from issues with accuracy and can lead to an artificial spread of dates. There are numerous examples where intervals of magmatism that appeared protracted in compilations of low precision dates have turned out to be of much shorter duration when investigated with higher-precision methods. This reality presents a challenge when seeking to synthesize data and interpret the duration of tectonomagmatic and tectonometamorphic events from low precision dates. Simply stating the range of dates neglects the uncertainty associated with the dates.

In this contribution, we seek to quantify durations through a resampling approach (Fig. 2). We bootstrap resample dates from the population of dates with replacement (see introduc-

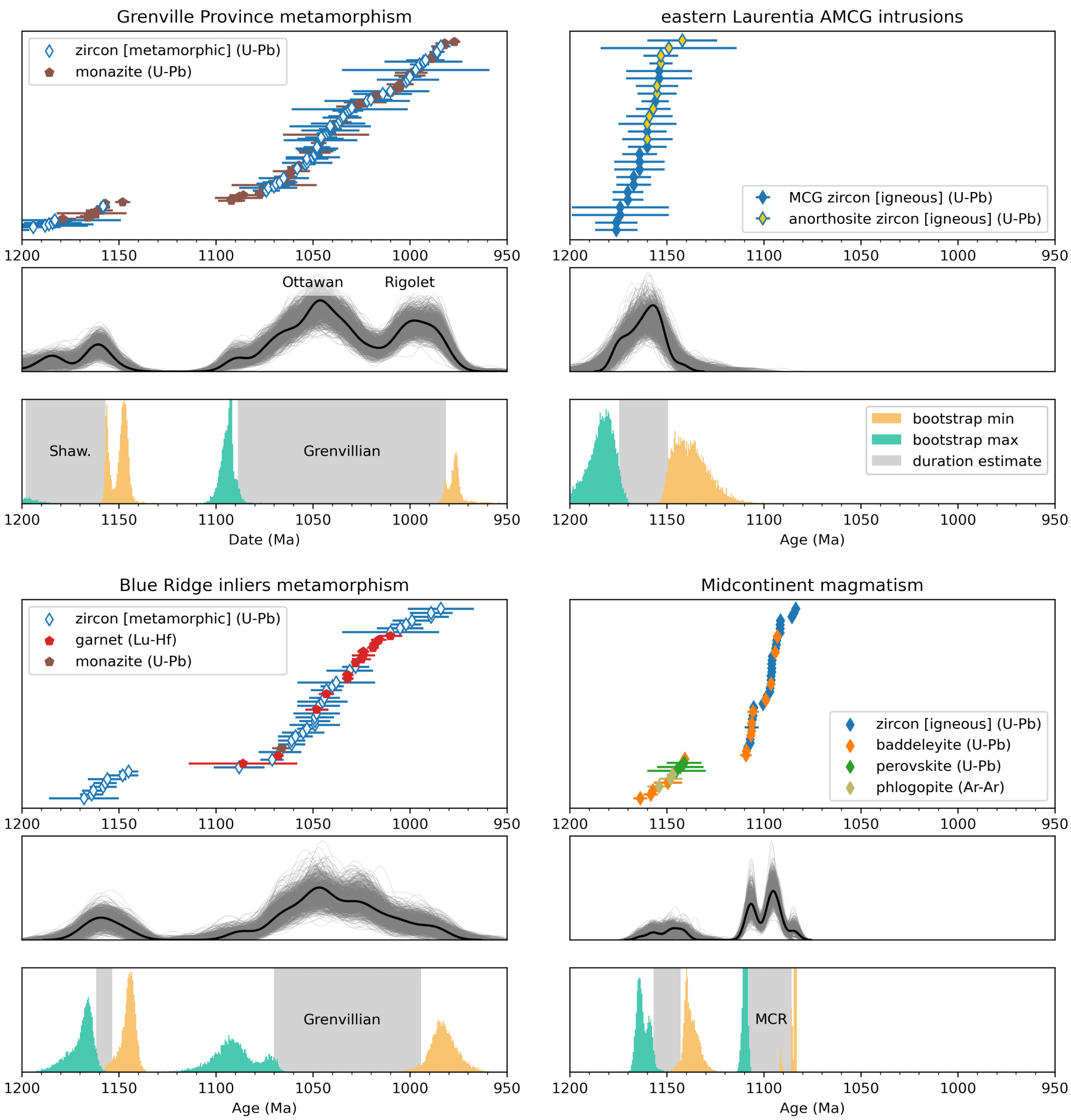

Figure 2: Compilation of geochronological data that provide insight into late Mesoproterozoic tectonics within Laurentia. The top panels in each group shows the dates with their 2 uncertainties keyed by mineral and method. The middle panel shows the kernel density estimates (continuous probability density estimate curves) for the dates in black and for bootstrap/Monte Carlo resamples of the data using the methods described in the text. The lower panel shows histograms of the maximum and minimum bounds from these distributions. The grey boxes provide estimates of the duration of the event constrained by the geochronology and robust to the resampling approach providing likely durations. These durations are: Grenville Province Shawinigan orogenesis 1198 to 1157 Ma; Grenville Province Grenvillian orogeny 1089 to 981 Ma; Blue Ridge pre-Grenvillian orogeny 1162 to 1153 Ma; Blue Ridge Grenvillian orogeny 1070 to 994 Ma; AMCG plutonism 1174 to 1149 Ma; pre-Midcontinent Rift magmatism 1157 to 1143 Ma; Midcontinent Rift magmatism 1108 to 1086 Ma. The data come from the Canadian Geochronology Knowledgebase compilation (2013) as well as additional data sets compiled in this work from the following publications: Aleinikoff et al. (2013, 2021), Bleeker et al. (2020), Chiarenzelli et al. (2011), Connelly (2006), Davis and Green (1997a), Dunning and Indares (2010), Fairchild et al. (2017), Hamilton et al. (2004), Jannin et al. (2018a, 2018b), Johnson et al. (2018, 2020), Jordan et al. (2006), Krogh et al. (1987), Labat et al. (2020), Lasalle et al. (2014), Markley et al. (2018), McCormick et al. (2017), McLelland et al., (2004), Moecher et al. (2020), Paces and Miller (1993), Peck et al. (2018), Queen et al. (1996), Regan et al., (2019), Shinevar et al. (2021), Smith et al. (2020), Southworth et al. (2010), Swanson-Hysell et al. (2019, 2020), Tollo et al. (2010, 2017), Williams et al., (2019), Wu et al. (2017). For some data sets, new weighted means were calculated for populations of dates. The data compilation as well as the Python code used for the analysis are available in a Github repository: https://github.com/Swanson-Hysell/Mesoproterozoic_Turning_Point and in this Zenodo archive ().

tion to bootstrap methods in Efron and Tibshirani, 1993). For each resampled date, we take a random draw from a Gaussian distribution where is set by the published uncertainty for that date. This resampling procedure is repeated 10,000 times and we determine the maximum and minimum dates from these resampled populations as well as visualize their overall probability density distributions (Fig. 2). This approach seeks to address the reality that outliers will skew duration estimates to be longer regardless of whether they are too old or too young, and to determine how robust durations are with respect to the population of dates. For a population of precise dates where there are multiple dates at the younger and older bounds, the overall duration will be similar across all resampled distributions (e.g. Midcontinent Rift magmatism in Fig. 2). However, for a lower precision population of data they can be quite scattered due both to outliers as well as the low precision on individual dates. Given that the goal is to evaluate how robust duration estimates are to resampling and uncertainty, we take the 5th percentile of the maximum age and the 95th percentile of the minimum age and use these as an estimate of the duration that is robust to resampling (Figs. 2 and 3). Alternatively, we can take the median of the distributions of maximum and minimum dates to provide a more lenient estimate of the timing of the magmatic or metamorphic event. Both this more conservative and this more lenient approach to estimate duration from the geochronology data are visualized in the timelines of Figure 3.

An additional challenge to interpreting the onset of metamorphic events is that metamorphic chronometers are more likely to capture peak metamorphic conditions such that dates are from a time after the initiation of orogenesis. Subsequent exhumation can be captured through thermochronometers that record cooling through their closure temperatures (e.g. Tohver et al., 2006). For example, dates from the Ottawan phase of the Grenvillian orogeny are dominantly associated with formation of substantially thickened crust in which the dates are from granulite- and eclogite-facies rocks that formed in the middle to lower crust. These dates therefore do not represent the onset of collision, but instead capture the time when the orogen became substantially shortened and thickened. Additionally, metamorphic chronometers such as zircon and monazite capture times of mineral growth in metamorphic reactions that have a shorter duration than that of the metamorphism as a whole. However, the low precision of some metamorphic chronometers can make it difficult to accurately determine the timing of the metamorphic events they represent. Despite metamorphic chronometers often being associated with peak metamorphic conditions, the oldest dates associated with the Grenvillian orogeny are monazite grains (see red pentagons in Grenville Province panel in Fig. 2). These oldest monazite grains have high yttrium concentrations and are interpreted to have crystallized during prograde metamorphism prior to the crystallization of garnet (Markley et al., 2018). An estimate of the onset of Grenvillian orogenesis using our resampling approach based on both monazite and metamorphic zircon dates gives an age of 1089 Ma, while an estimate of the onset based on the zircon dates alone would be younger at 1070 Ma. This difference supports the interpretation that the oldest Grenvillian monazite dates are capturing an earlier stage of orogenesis prior to the peak metamorphic conditions of the Ottawan phase.

Late Mesoproterozoic tectonic history of Laurentia

While this contribution is focused on the Grenvillian orogeny as a turning point in Laurentia's tectonic history, the prior tectonic history of its southeastern margin is relevant to set the stage. Here, we summarize aspects of the preceding Mesoproterozoic tectonic history of Laurentia in order to document the distinct tectonic settings prior to the Grenvillian orogeny itself.

Accretionary orogenesis prior to the Grenvillian orogeny

As introduced above, juvenile terrane and arc accretion occurred episodically along Laurentia's southeastern to eastern margin from the time of assembly of internal Laurentia during the Trans-Hudson orogeny until collisional orogenesis in the Grenvillian orogeny. This history imposes significant constraints on the tectonic and paleogeographic setting of Laurentia throughout the late Paleoproterozoic and most of the Mesoproterozoic (Karlstrom et al., 2001). In the Mesoproterozoic, tectonic activity along this margin resulted in ca. 1450 Ma orogenesis from southwest to northeast Laurentia in the Picuris-Baraboo-Pinwarian orogenies (Medaris et al., 2021). These orogenies place the ca. 1480 to 1350 Ma Granite-Rhyolite Province in an active margin setting, consistent with interpretations that it is the result of continental arc and back-arc magmatism (Bickford et al., 2015; Medaris et al., 2021). In this section, we focus on the geologic record of this margin from ca. 1300 to 1100 Ma to elucidate the tectonic history during the second half of the Mesoproterozoic prior to the onset of the Grenvillian orogeny.

1300 to 1100 Ma tectonic evolution in eastern Laurentia

The distribution and extent of 1300 Ma peri-Laurentian accreted terranes in the southwestern Grenville Province and in proximal inliers in the Appalachians is shown in Figure 1. The rocks comprising these terranes, as well as intrusive complexes on the margin, constitute the youngest phase of the Great Proterozoic Accretionary Orogeny. Our summary of the regional geology and tectonic setting in the Grenville Province is heavily influenced by Carr et al. (2000), Rivers et al. (2012), and Peck et al. (2013) where additional references are provided. Within the eastern and central Grenville Province (where they are metamorphosed and deformed) and extending farther north into what is now its foreland (where they are minimally metamorphosed), magmatism in northeastern Laurentia resulted in the emplacement of small gabbronorite plutons and NE-trending, ca. 1270-1230 Ma mafic dikes, and ca. 1250-1230 Ma mangerite and tonalite bodies (Carr et al., 2000). Extrusive volcanic units emplaced onto Laurentia include ca. 1270-1250 Ma rhyolite and spatially associated sub-volcanic granite in the western part of the Wakeham domain, ca. 1250-1230 Ma mafic flows in the Seal Lake Group, and a belt of ca. 1240-1200 Ma deformed and metamorphosed, interlayered mafic to felsic gneisses near Manicouagan Reservoir (Indares and Moukhsil, 2013). In the western Grenville Province, magmatism from ca. 1270-1240 Ma includes the 1240 Ma NW-trending Sudbury

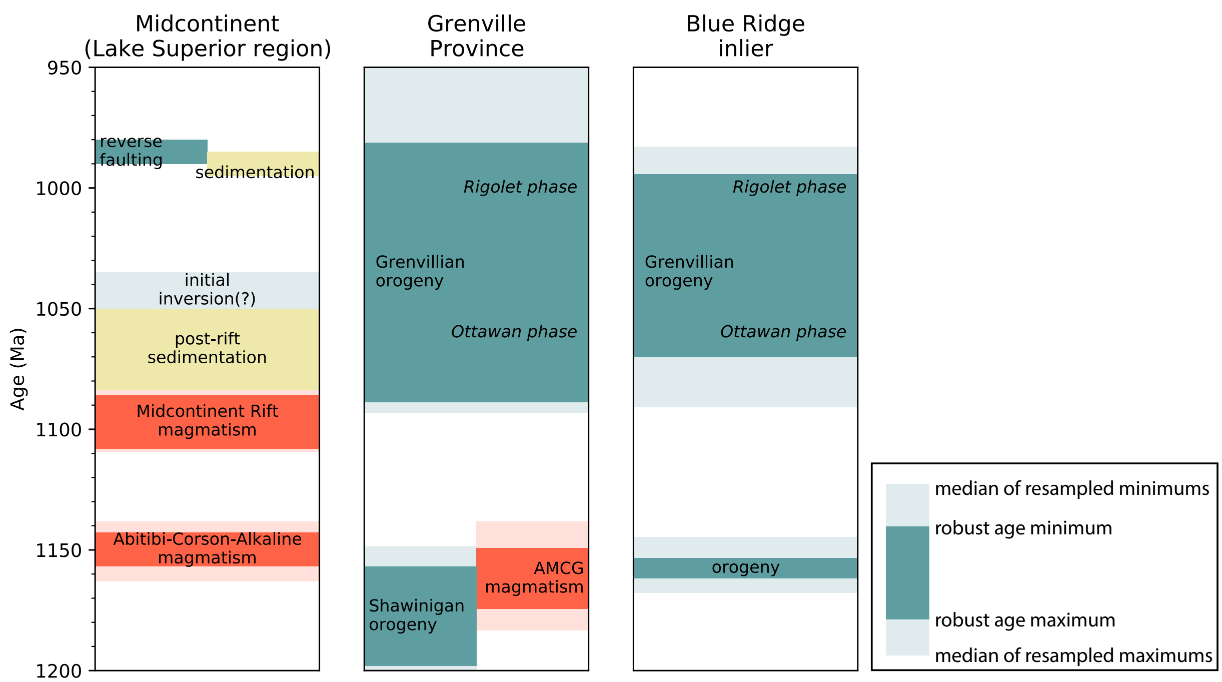

Figure 3: Simple timelines of tectonic and tectonomagmatic events in the Midcontinent-Lake Superior region, the Grenville Province, and the Mesoproterozoic Blue Ridge inlier. The times shown for orogenic events and for magmatic events are directly taken from the analysis of the geochronology data in Figure 2. The darker colors represent the bounds on the 5th percentile of the resampled maximum ages and the 95th percentile of the resampled minimum ages. This range, which is more robust to resampling, is interpreted to constrain the duration of the magmatic or orogenic interval. The fainter colors are the medians of those bounds, indicating that there are dates that imply those ages, but they are more likely to be outliers due to low precision. This compilation highlights AMCG magmatic activity being a late to post-Shawinigan phenomenon and temporally overlapping with magmatic activity in the Midcontinent. Note that the onset of Grenvillian collision orogenesis is closely temporally related to the end of Midcontinent Rift magmatism, which itself is closely associated with the end of extension.

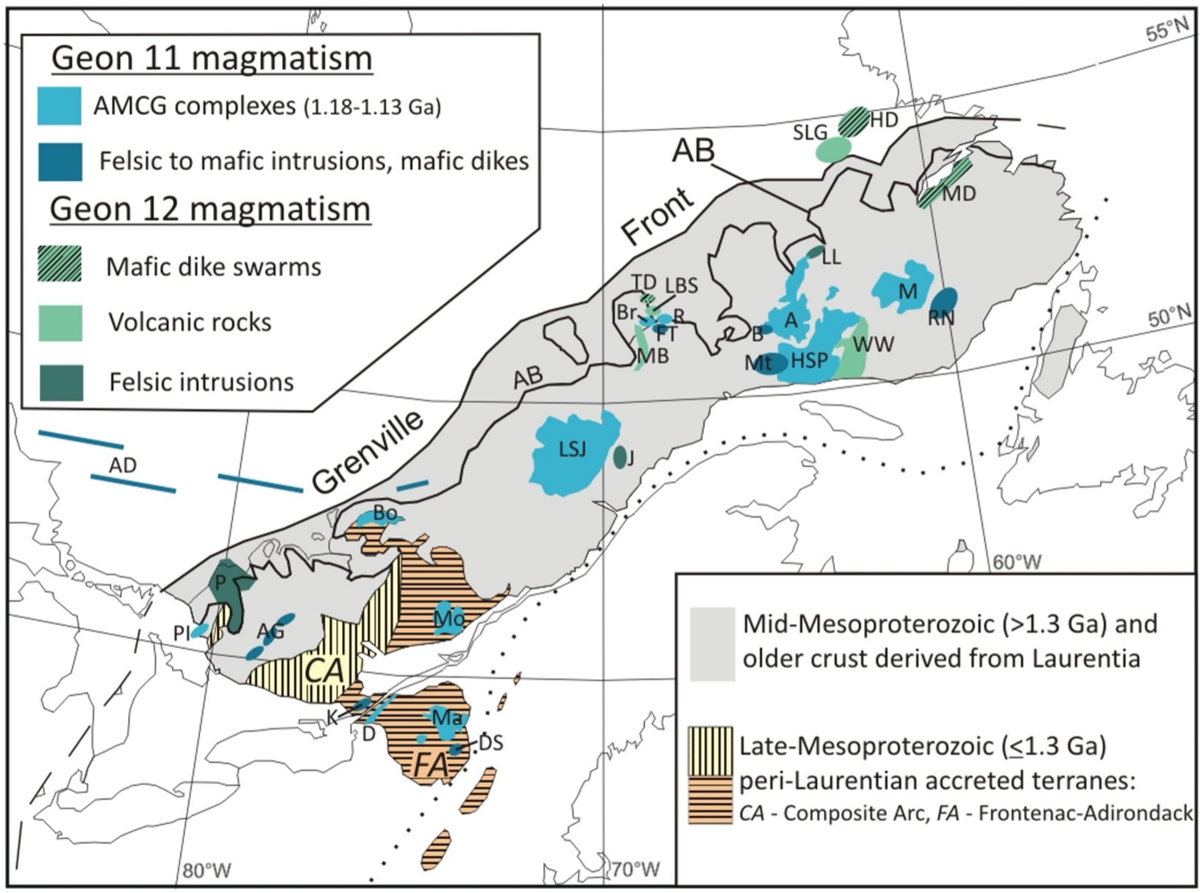

Figure 4: Sketch map of the Grenville Province and its immediate foreland, showing the Allochthon Boundary (AB), late Mesoproterozoic (<1.3 Ga) pericratonic accreted terranes, and major magmatic units emplaced during geons 12 and 11 (a geon is a 100 million year interval ; Hofmann 1990; for instance geon 12 is all ages between 1200 and 1299.9 Ma). Abbreviations: A, Atikonak-Lac Fournier anorthosite massif; AD, Abitibi dikes; AG, Algonquin gabbros; B, Baune gabbro; Bo, Bouchette anorthosite; Br, Brien anorthosite; D, Diana AMCG complex; DS, Dresden Station gabbro; FT, Fe-Ti gabbro; G, Gananoque monzogranite suite; J, Joncas mangerite; HD, Harp dikes; K, Kingston dikes; LBS, Layered bimodal sequence; LSJ, Lac St-Jean anorthosite massif; LL, Lac Long tonalite; M, Mécatina anorthosite massif (undated); Ma, Marcy, Snowy Mountain and Oregon Dome anorthosite massifs, spatially associated syenite, monzonite, granite; MB, Manicouagan extensional belt; Mo, Morin anorthosite massif; MD, Mealy dikes; Mt, Manitou monzonite-diorite-granite complex; P, includes Powassan, Sturgeon Falls, Mulock and Bonfield monzogranitic plutons, St-Charles and Mercer anorthosites; PI, Parry Island anorthosite; R, Rodot anorthosite-leucogabbro; RN, Robe noire mafic sills; SD, Sudbury dikes, SLG, Seal Lake Group; TD, Toulnustouk dikes; WW, rhyolite in western Wakeham domain. Modified after Rivers et al. (2012), with additional information from Indares and Moukhsil (2013), where ages and original references are given.

dike swarm (Dudás et al., 1994), a compositionally bimodal assemblage of several large sheet-like monzogranitic intrusions (ca. 1250-1240 Ma), and two smaller ca. 1220 Ma bodies of anorthosite/leucogabbro (Davidson and van Breemen, 2001).

At the same time, magmatism was taking place farther southeast (present coordinates) in continental-margin and pericratonic settings off Laurentia. In the Composite Arc Belt of the southern Grenville Province (Fig. 4), this magmatism included formation of the ca. 1270-1230 Ma arc and backarc (calc-alkaline to tholeiitic) Elzevir suite composed of mafic and felsic volcanic rocks and subvolcanic plutons, subordinate peralkaline intrusions, and associated marine sedimentary rocks (e.g. carbonates), and spatially associated ophiolitic lithologies.

In summary, given the widespread record of both felsic and mafic magmatism, these data collectively suggest that between ca. 1270 and 1220 Ma eastern Laurentia was in an upper plate setting and underwent minor extension perpendicular to the continental margin. The extension may have led to crustal thinning on a regional scale (e.g., Seal Lake basin, Manicouagan extension belt) as well as intrusion and extrusion of small volumes of mantle-derived mafic magmas, crustal melting, and felsic magmatism. The coeval record from the accreted terranes, which also exhibit basaltic and rhyolitic magmatism, has been interpreted in terms of arc and back-arc formation in the upper plate of an active margin and the opening of small backarc and marginal basins underlain by thinned continental (transitional) crust and oceanic crust. The modern-day Sea of Japan has been proposed as an analogue setting (Easton, 1992). Amalgamation of the components of the Composite Arc Belt in an oceanic setting occurred ca. 1250 Ma, an interpretation reinforced by the recent recognition of high-pressure metamorphic rocks formed during subduction and associated accretion in an oceanic realm (Easton, 2020), and was followed by accretion to Laurentia ca. 1220 Ma during the Elzevirian orogeny.

Active margin tectonics continued with ca. 1200 to 1180 Ma formation of a calc-alkaline arc on an offshore fragment of Laurentian crust (Chiarenzelli et al., 2010). Closure of the Trans-Adirondack backarc basin, tectonic juxtaposition of the Frontenac and Adirondack Lowlands domains, obduction of an ophiolite complex onto the Adirondack segment with its sedimentary cover, and accretion of the Adirondack Belt to Laurentia took place in the ca. 1200-1160 Ma Shawinigan orogeny (e.g., Chiarenzelli et al., 2010; Peck et al., 2013; Fig. 3). The Shawinigan orogeny resulted in crustal thickening and heating sufficient to drive partial melting ca. 1160 Ma as recorded by migmatites and constrained by zircon and monazite geochronology in the Adirondack Lowlands and Highlands (Heumann et al., 2006; Williams et al., 2019). Considered together with the accretion of Elzevirian crust ca. 1220 Ma, this arc-continent collision indicates the presence of a collage of arcs and backarcs offshore of Laurentia in the late Mesoproterozoic within the Unimos Ocean prior to the Grenvillian orogeny. An analogous modern setting could be the Southeast Asian Islands, where there is a complex assemblage of oceanic arcs and ongoing arc-continent collision along the northern margin of Australia (Hall, 2017).

Overlapping with and post-dating the later stages of Shawinigan deformation in eastern Laurentia was the widespread emplacement of dispersed mafic dike and sill swarms and small gabbroic intrusions, a suite of monzogranite plutons, and several large anorthosite-mangerite-charnockite-granite (AMCG) complexes, including mangerite and granite bodies in the absence of other AMCG components (Fig. 4). In the Adirondack Lowlands, calc-alkaline units including the 1203 ± 14 Ma bimodal Antwerp-Rossie suite (U-Pb zircon SHRIMP; Chiarenzelli et al., 2010), the alkaline to calc-alkaline 1182 ± 7 Ma Hermon granitic gneiss (U-Pb zircon SHRIMP; Heumann et al., 2006) and the 1172 ± 5 Ma Hyde School tonalitic gneiss (U-Pb zircon TIMS; Wasteneys et al., 1999) are interpreted to have formed in a magmatic arc as a result of northward subduction of oceanic crust under Laurentia preceding the Shawinigan orogeny. Calc-alkaline arc magmatism was succeeded by AMCG plutonism ca. 1170 to 1150 Ma (Figs. 2 and 3). The AMCG plutons are less deformed than older plutons in the Adirondacks, leading Chiarenzelli et al. (2010) to infer that Shawinigan deformation had ceased by ca. 1160 Ma. This inference, supported by evidence from other syn- and post-tectonic units, has led to the interpretation that contraction during the Shawinigan orogeny principally occurred between ca. 1200 and 1160 Ma, with subsequent metamorphism associated with AMCG plutonism (McLelland et al., 2010b; Peck et al., 2013).

Anorthosite-mangerite-charnockite-granite (AMCG) complexes

The AMCG complexes that were emplaced into eastern Laurentia are typical examples of these Proterozoic composite batholiths, with the anorthosite-leuconorite components forming large massifs composed of >80% plagioclase of composition ca. An50±10 mol% (e.g., Ashwal and Bybee, 2017). In Laurentia as a whole, Proterozoic AMCG and spatially associated rapakivi granite suites with emplacement ages from ca. 1600-1130 Ma occur in a broad band stretching from the southwestern USA to Labrador (Fig. 1a). These batholiths are emplaced within the Great Proterozoic Accretionary Orogen that forms external Laurentia, with the exception of the farthest northeast intrusions in eastern Labrador, and most were emplaced within 200 Myr of the time of accretion of the crust in which they occur.

The classic petrologic model for the genesis of Proterozoic AMCG suites invokes a mantle origin for the anorthosite component, lower crustal origins for the mangerite-charnockite-granite components, and a mixed mantle and lower crustal origin for volumetrically minor Fe-rich magmas such as jotunite (e.g., Ashwal, 1993, 2010). This model has been modified in light of isotopic studies that have consistently demonstrated crustal contamination of the mantle-derived parent magma of anorthosite, and mixing of mantle and crustal magmas in some of the MCG components, indicating a more complex magmatic evolution in detail (e.g., Emslie and Hegner, 1993; Bickford et al., 2010; Hegner et al., 2010; Peck et al., 2010; Ashwal and Bybee, 2017). There is a general consensus that the anorthosite develops within large bodies of mafic magma at the base of the crust (35-45 km depth) by prolonged fractionation at high temperature, producing plagioclase cumulates by flotation (Kushiro, 1980). Coeval partial melting of the overlying lower crust forms the MCG components of the complexes that also mix with and contaminate the mafic magma. The emplacement of anorthosite in the middle to upper crust is by transport of the accumulated crystal mush in melt, but the degree of crystallinity of the mixture remains an open question (Ashwal and Bybee, 2017).

The tectonic setting of Proterozoic AMCG complexes has been a long-standing enigma (e.g., see Ashwal, 2010; Ashwal and Bybee, 2017 for reviews). Formerly considered to be anorogenic, more recent studies have recognized a spatial and temporal association with active-margin or collisional tectonic settings (e.g., Corrigan and Hanmer, 1997; McLelland et al., 2010b; Ashwal and Bybee, 2017; Valentino et al., 2019), which is supported by their distribution within external Laurentia (Fig. 1). Although the setting of AMCG complexes in the Grenville Province is difficult to assess on account of the subsequent Grenvillian tectonic overprint, emplacement of two of the most intensely studied complexes, the Morin and Marcy massifs, was closely associated in time and space with accretion of the Frontenac-Adirondack belt to Laurentia during the Shawinigan orogeny (Fig. 4). In light of this temporal association, McLelland et al. (2010b) and Valentino et al. (2018) proposed that the emplacement of AMCG intrusions in the Adirondack region was a result of detachment of a slab of subducting oceanic lithosphere associated with terrane accretion during the Shawinigan orogeny. In this model, arc-continent collision jams the subduction zone leading to detachment of the downgoing lithospheric slab. Descent of this slab into the deeper mantle makes space for rising asthenosphere, which undergoes decompression melting to form a large subcrustal mafic intrusion (commonly termed a mafic or crustal underplate). Both the asthenospheric flux and the magmas derived from it create a broad thermal anomaly, inducing partial melting of the lower crust inboard from the active margin of Laurentia. This is an attractive model for the Marcy and Morin AMCG complexes, which occur in the Frontenac-Adirondack belt (Fig. 4), but any successful model must also provide an explanation for other AMCG complexes of similar age farther northeast in Laurentia outside the accreted Frontenac-Adirondack belt and the known effects of the Shawinigan orogeny, and also for the MCG intrusions lacking an anorthosite component. In the context of an active margin, there are other potential pathways for upwelling asthenosphere to reach the base of the crust, such as slab windows resulting from ridge (plate edge) subduction or post-collisional slab steepening, both of which could allow an influx of asthenosphere to the base of the mantle wedge and former trench. Moreover, the discovery that high alumina orthopyroxene megacrysts, a common feature of Proterozoic anorthosite massifs, grew from 60-100 Myr before emplacement in some of the AMCG complexes in which they occur (Bybee et al., 2014), implies a prolonged genesis for these complexes and the need for two tectonic triggers; one for the rise of asthenospheric mantle, decompression melting, and the emplacement of a thick subcrustal mafic intrusion, and a second event several tens of Myr later that caused their emplacement within the crust. Bybee et al. (2014) did not analyze high alumina orthopyroxene megacrysts from ca. 1160 Ma AMCG complexes in the Grenville Province, so there is insufficient information to usefully speculate further, but the two-trigger hypothesis provides a new avenue of research into the origins of these enigmatic intrusions, and the generation of such prodigious volumes of mafic magma inboard from the active margin of Laurentia (Figs. 4 and 5) throughout the late Paleoproterozoic and Mesoproterozoic. Regardless of the specific tectonic model, the ca. 1170 to 1150 Ma AMCG magmatism is the last recorded tectonomagmatic event along Laurentia's eastern margin prior to the onset of Grenvillian orogenesis ca. 1090 Ma (Fig. 2).

1200 to 1100 Ma tectonic evolution in southern Laurentia

The Llano uplift, a Mesoproterozoic inlier in central Texas (Fig. 1), consists of an imbricate stack of gneisses interpreted to have formed on the southern Laurentian margin. The following summary of the tectonic history of the uplift is largely drawn from Mosher et al. (1998, 2008), where additional references are provided, as well as from more recent contributions. The lithologies of the Llano uplift include ca. 1288-1232 Ma plutonic and clastic supracrustal rocks of the Valley Spring domain, interpreted as a continental arc complex and its supracrustal cover, and the structurally overlying ca. 1274-1238 Ma supracrustal and intrusive rocks of the Packsaddle domain inferred to have developed in a forearc basin setting. The Coal Creek domain, an island arc and ophiolite complex, forms the structural top of the succession. Eclogite formation at ~2.4 GPa (Carlson et al., 2007) implies subduction to ~70 km depth. The tectonic model proposed by Mosher et al. (2008) involved subduction of the Laurentian (lower) plate, shortening and imbrication of the arc, local accretion of an island arc (Coal Creek domain), followed by interpreted continent-continent collision. Relatively less deformed ca. 1120 Ma granitoid plutons constrain the cessation of penetrative deformation in the orogen (Mosher, 1998). Dalziel et al. (2000) hypothesized that the Llano orogeny resulted from collision of the Kalahari craton with Laurentia, but paleomagnetic data from Kalahari's Umkondo large igneous province and the oldest units of the Midcontinent Rift show the continents to have been separated by >30°of latitude at 1109 Ma, thereby ruling out Kalahari as the conjugate continent to Laurentia in the Llano orogeny (panel 1108 Ma in Fig. 5; Swanson-Hysell et al., 2015).

Proterozoic inliers in the Franklin Mountains near Van Horn, westernmost Texas, record a distinct tectonic evolution (Bickford et al., 2000; Fig. 1). In this area, the reconstructed stratigraphy consists of ca. 1380-1330 Ma schists of the Carrizo Mountain Group, interpreted as part of the Southern Granite-Rhyolite province which is unconformably overlain by a shallow basinal sequence with stromatolitic carbonate and interlayered mafic volcanic rocks that is followed by volcanic lithic sandstone with basaltic agglomerate and mafic and felsic volcanic rocks (ca. 1260-1240 Ma Allamoore and Tumbledown formations respectively; Bickford et al., 2000). Inversion of the basin, imbrication and overturning of the whole sequence towards the north resulted in formation of a complex fold-thrust belt with well-documented evidence for polyphase deformation (Davis and Mosher, 2015). This basinal sequence is unconformably overlain by coarse-grained siliciclastic sedimentary rocks comprising the Hazel Formation which includes conglomerate with clasts of the 1123 ± 4 Ma Red Bluff granite (Bickford et al., 2010) and has a dominant detrital zircon peak of ca. 1120 Ma (Spencer et al., 2014). Spencer et al.

(2014) suggested that the youngest grains in the Hazel Formation may be ca. 1080 Ma, but this interpretation is reliant on low precision 206Pb/238U dates obtained through LA-ICP-MS and should be considered tentative until the youngest population is investigated through CA-ID-TIMS. Nevertheless, the data from the Hazel Formation constrain it to post-date the Llano orogeny. As a result, it has been interpreted to have been deposited in a proximal foreland basin associated with orogenesis that was ongoing ca. 1050 Ma, and was thus not only contemporaneous with the Grenvillian orogeny, but also potentially spatially continuous with the Grenville orogen (Mulder et al., 2017).

Integrating the contrasting timing and kinematic evolutions for the inliers in the Llano Uplift and Franklin Mountains has proven challenging (Davis and Mosher, 2015). A fundamental issue that remains to be addressed in tectonic reconstructions for both the Llano Uplift and Franklin Mountains areas is that Laurentia is placed in a lower plate setting in both cases (Mosher et al., 2008; Davis and Mosher, 2015), but since Laurentia is inferred to have been in an upper plate setting during formation of the Southern Granite-Rhyolite province, a lower plate setting would imply a subduction flip between ca. 1300 and 1260 Ma. In this respect, the abundant presence of bimodal volcanic products in the Allamoore and Tumbledown formations could be more compatible with a backarc basin (i.e., upper plate) setting than the proposed passive margin setting. A second point concerns timing. The Llano Uplift preserves evidence for arc accretion followed by an inferred continental collision ca. 1150-1120 Ma, whereas the Franklin Mountain inliers document basin inversion associated with temporal and spatial propagation of deformation to progressively higher structural levels towards the continent at the time of the Grenvillian orogeny (Grimes and Copeland, 2004; Davis and Mosher, 2015). This record implies that tectonism in the Franklin Mountains area was initiated after collision in the Llano Uplift had ceased. In an attempt to reconcile these differences, Davis and Mosher (2015) proposed that initial contact of an exotic crustal indenter with Laurentia took place in the Llano area and was followed by clockwise rotation of the indenter towards the west, but many questions with respect to this tectonic model remain. Given that regional deformation and metamorphism in the Llano uplift predated the Ottawan phase in the Grenville Province, it could be that the Llano orogeny occurred in an accretionary setting. It is perhaps comparable with that of the Shawinigan orogeny which is of similar age, and the 'indenter' of Davis and Mosher (2015) could have been a ribbon continent (e.g. such as the AREquipa-Pampia-Antofalla [AREPA] block; Macdonald et al., this volume; panel 1140 Ma in Fig. 5). Collision of such a ribbon continent could provide a linkage between ca. 1160-1150 Ma metamorphism recorded in the Blue Ridge inlier with the Llano orogeny. Regional deformation and metamorphism in the Franklin Mountains coeval with the late Ottawan and Rigolet phases in the Grenville Province raises the possibility that this deformation resulted from terminal continental collision at the same time as the Grenvillian orogeny.

Midcontinent magmatism and Midcontinent rift development

Broadly distributed intracratonic magmatism that occurred ca. 1160-1140 Ma within the interior of Laurentia to the north and northeast of Lake Superior resulted in emplacement of lamprophyre and diabase dikes, and alkalic carbonatite complexes (Krogh et al., 1987; Queen et al., 1996; Wu et al., 2017). This magmatism included the emplacement of the Abitibi dikes, of which the 1140 ± 2 Ma Great Abitibi dike (U-Pb baddeleyite; Krogh et al., 1987) reaches widths of 250 m and is continuous for over 620 km (Ernst and Bell, 1992). Magmatism of similar age resulted in the emplacement of diabase intrusions in eastern South Dakota (1149.4 ± 7.3 Ma, U-Pb baddeleyite; McCormick et al., 2017) and mafic dikes in the subsurface in eastern Iowa (Drenth et al., 2020). The older of these intrusions are coeval with emplacement of the AMCG suites on Laurentia's eastern margin thereby expanding the footprint of igneous activity at that time (compare the Midcontinent and Grenville Province timelines in Fig. 3). Given that this magmatic activity in interior Laurentia occurred in the region of subsequent ca. 1108-1084 Ma volcanism in the Midcontinent Rift, it has been suggested that it represents a precursor stage associated with a common upwelling source (Queen et al., 1996; Piispa et al., 2018). The long temporal gap between the emplacement of these intrusions and voluminous volcanism in the Midcontinent Rift complicates a direct connection, but the earlier magmatism could have played a role in thinning and weakening the lithosphere, thereby setting the stage for upwelling magma to ascend through the lithosphere during rifting of the midcontinent.

Midcontinent rift development

Magmatism in the Midcontinent Rift began in earnest ca. 1109 Ma (Figs. 2 and 3). The Midcontinent Rift is the result of the co-location of lithospheric extension and the emplacement of a large volume of erupted lavas and associated intrusions between ca. 1109 and 1084 Ma (Cannon, 1992; Swanson-Hysell et al., 2019; Bleeker et al., 2020; Woodruff et al., 2020). The western arm of the rift extends from under Phanerozoic sedimentary cover in the Great Plains region to the Lake Superior region where rift-associated rocks are well exposed (Van Schmus and Hinze, 1985). The volume of volcanic rocks (including associated shallow level intrusions) has been estimated to be between 300 to 3000 km^3 per km of rift length, amounting to about 1.8 million km^3 for the lava flows under both Lake Superior and the western arm of the Midcontinent Rift, which comprises a rift length of approximately 1700 km. The eastern arm, southeast of the lake, is estimated to hold another 0.2 million km^3 of volcanic rocks over ~700 km of length. An additional, equivalent volume of magmatic rocks has been inferred to reside at Moho depths, first interpreted beneath Lake Superior (Tréhu et al., 1991; Miller and Nicholson, 2013), and more recently found to continue along the western arm (Zhang et al. 2016). Zhang et al. (2016) imaged this long magmatic root (also commonly referred to as an underplate) by isolating, analyzing, and tracking scattered S waves recorded by SPREE seismic stations (Wolin et al., 2015) back to the layer boundaries from where they were generated by incoming P waves from teleseismic earthquakes. This dense seismic array analysis shows a split Moho that presents as a gradual boundary in seismic data from sparser seismic networks. The combined volume of both the volcanic rocks and this magmatic root (or "underplate") are such that the Midcontinent Rift stands out as one of the most voluminous large igneous provinces in Earth history.

An initial stage of magmatic activity from ca. 1109 to 1105 Ma, known as the "early" or "plateau" stage (Miller and Vervoort, 1996; Woodruff et al., 2020), resulted in the emplacement of mafic intrusions and eruption of picritic to tholeiitic basaltic lavas across the Lake Superior region. Exposed sequences of lava flows that erupted during the early plateau stage reach a thickness of >3 km in northern Lake Superior (Hollings et al., 2007; Swanson-Hysell et al., 2014b). Following an interval of more limited volcanic activity, known as the "latent" stage (Miller and Nicholson, 2013; Swanson-Hysell et al., 2014a), the main rift stage of tectonomagmatic activity from ca. 1098 to 1091 Ma is characterized by the accumulation of thick sequences of basaltic lava flows that filled rapidly subsiding extensional basins (Woodruff et al., 2020). In the North Shore Volcanic Group of northern Minnesota, lavas from this interval are >9 km thick (Green et al., 2011) and seismic data are interpreted to indicate a stack of up to 20 km of preserved volcanic lava flows under Lake Superior (Cannon, 1992).

A particularly voluminous pulse of predominantly mafic magmatism ca. 1096 Ma led to the rapid emplacement of the Duluth Complex (one of the largest mafic intrusive complexes on Earth) within 500,000 ± 260,000 years, along with the thick comagmatic succession represented by the North Shore Volcanic Group (Swanson-Hysell et al., 2021b). A voluminous ca. 1092 Ma pulse of magmatic activity led to emplacement of the Beaver Bay Complex in northern Minnesota and coeval eruptions of the Portage Lake Volcanics on the Keweenaw Peninsula, Michigan, including the Greenstone Flow which is one of the largest known mafic lava flows on Earth (Longo, 1984; Fairchild et al., 2017; Swanson-Hysell et al., 2019; Zhang et al., 2021).

Temporally overlapping with Midcontinent Rift magmatism was the emplacement of the Southwestern Laurentia large igneous province that includes sills in central and northern Arizona and the Death Valley region of California, and the Cardenas basalts of the Grand Canyon (Bright et al., 2014). While higher precision geochronology is needed to precisely relate magmatic pulses of the Southwestern Laurentia large igneous province to those in the Midcontinent Rift, paleomagnetic and geochronologic data suggest that the bulk of the Southwestern Laurentia large igneous province was likely coeval with the main stage of Midcontinent Rift development (Harlan, 1993; Bright et al., 2014). In short, it appears that magmatism was widespread and voluminous across much of Laurentia at the time of Midcontinent Rift development.

Rift-related unconformities indicate extension continued after intrusion of the 1091.61 ± 1.2 Ma Beaver Bay Complex (CA-ID-TIMS, 206Pb/238U zircon date; 2 uncertainty includes decay constant uncertainty; Fairchild et al., 2017; Swanson-Hysell et al., 2019). Erosion of uplifted rift margins provided a source of sediment for the coarse-grained alluvial fan deposits of the Copper Harbor Conglomerate (Elmore, 1984), which contains lava flows dated to 1085.57 ± 1.3 Ma (CA-ID-TIMS, 206Pb/238U zircon date; 2 uncertainty including decay constant uncertainty; Fairchild et al., 2017). The Copper Harbor Conglomerate fines upward into lacustrine sediments of the Nonesuch Formation (Elmore et al., 1989; Stewart and Mauk, 2017; Slotznick et al., 2018), which preserves a diverse record of ca. 1075 Ma microfossils (Strother and Wellman, 2021). The Nonesuch Formation is followed by the overlying >4 km thick Freda Formation, composed predominantly of sandstone and siltstone. The Freda Formation was deposited in a low-gradient fluvial depositional environment with only minor and spatially restricted volcanic activity of the Bear Lake lavas and hypabyssal intrusions near its base (Swanson-Hysell et al., 2019). These post-rift sedimentary formations constitute the Oronto Group, for which accommodation space was generated by thermal subsidence associated with cooling following lithospheric thinning beneath the Midcontinent Rift and emplacement of a magmatic root (Cannon, 1992).

Midcontinent rift inversion

Volcanic activity and extension ended prior to complete lithospheric separation. Folding and reverse faulting in a subsequent compressional stress regime then led to structural inversion of the Midcontinent Rift (Cannon et al., 1993), including transpressional faulting in accommodation zones (Zhang et al., 2016). The largest structure associated with this contraction is the Montreal River monocline, in which a 35-km-thick package of Archean, Paleoproterozoic and Midcontinent Rift lithologies was uplifted and tilted along a major reverse fault (Cannon et al., 1993). Rb-Sr dates of biotite in the more deeply exhumed portion of the monocline have been interpreted to give thermochronometric insight into the uplift process and suggest that it occurred ca. 1050 Ma, coeval with the Ottawan phase of the Grenvillian orogeny (Cannon et al., 1993). Fluvial sandstones of the Jacobsville Formation were deposited unconformably atop these uplifted lithologies and were subsequently overthrust by Midcontinent Rift volcanic rocks along structures such as the Keweenaw Fault (Hinze et al., 1990; Cannon, 1994; Manson and Halls, 1994). A CA-ID-TIMS U-Pb date of 992.51 ± 0.64 Ma on detrital zircon from the Jacobsville Formation provides the maximum depositional age for the unit that, together with a low-precision U-Pb date of 985.5 ± 35.8 Ma on calcite from the Keweenaw Fault breccia, constrain this final stage of Midcontinent Rift inversion to have occurred during the Rigolet stage of the Grenvillian orogeny (Hodgin et al., 2022). The inferred WNW-ESE shortening direction associated with the Grenvillian orogeny (both Ottawan and Rigolet phases) aligns with the principal compressional stress direction inferred by Zhang et al. (2016) from along-rift variations in seismically imaged crustal structure. The thickness of preserved post-rift sedimentary rocks and the depth of the magmatic root vary with the orientation of the rift, showing greater uplift of the central rift graben along the NNE-SSW portions of the rift and less uplift where the rift is oriented in other directions, which also applies to Lake Superior portion (Tréhu et al., 1991). The regions of less uplift are associated with lower Bouguer gravity anomalies and appear to coincide with regions also affected by strike-slip faulting, such as the Belle Plaine Fault Zone (Zhang et al., 2016). This along-rift variation of contractional vs. transpressional behavior corresponding to rift orientation is consistent with the expected azimuth of the principal compressive stress during Grenvillian orogenesis. Similar observations have been made on kinematic slip indicators on the Keweenaw Fault itself, which reveal combinations of strike slip and reverse dip slip motion as would be expected from far-field Grenvillian stress fields (Mueller, 2021). In summary, the data on the Keweenaw Fault definitively relate the final contractional inversion of the Midcontinent Rift to the Rigolet phase of the Grenvillian orogeny (Hodgin et al., 2022), with data on other structures suggestive of earlier contraction during the Ottawan phase of the orogeny as well (Fig. 3).

Other intracratonic basins

In addition to subsidence enabling sedimentation coeval with the Grenvillian orogeny in the Midcontinent Rift region, there was basin development during the Ottawan phase of the orogeny in Arctic Canada from Victoria Island to Baffin Island (ca. 1087 ± 6 Ma sedimentation on Baffin Island; Greenman et al., 2021). Turner et al. (2016) interpreted the Bylot Basins of Baffin Island and northern Greenland to have formed as the result of local extension resulting from tension at a high angle to the contraction of the Ottawan phase (an impactogen in the terminology of Sengör, 1976). Re-Os depositional ages reveal that coeval sedimentation was ongoing even farther from the orogen in the Amundsen basin ca. 1067 ± 14 Ma (Rainbird et al., 2020). Greenman et al. (2021) speculated that thermal anomalies under Laurentia expressed as the Midcontinent Rift and the Southwestern Laurentia large igneous province could have played a role in facilitating lithospheric extension and subsidence across these basins.

Grenvillian orogenesis

The Grenvillian orogeny resulted in the formation of a large hot long-duration orogen that was the site of significantly thickened crust under an orogenic plateau (c.f., the Himalaya-Tibet orogen). Although much of the Grenville orogen consists of previously deformed and metamorphosed rocks, both the regional continuity of structures and U-Pb geochronological data indicate that its generally high-grade, commonly gneissic signature is in large part a result of the intense Grenvillian reworking. Geochronological data reveal that the Grenvillian orogeny occurred in two distinct pulses of crustal shortening/thickening and heating, the ca. 1090-1020 Ma Ottawan phase in the orogenic hinterland, and the ca. 1010-980 Ma Rigolet phase closer to the Grenville Front and orogenic foreland (Figs. 2, 3 and 4). The Ottawan phase principally affected units situated in the hanging wall of the Allochthon Boundary (Fig. 4), a gently SE-dipping, granulite-facies shear zone that forms the base of a stack of ductile thrust sheets and fold nappes, each a few kilometers thick. These structures (termed domains in map view) exhibit the effects of intense ductile deformation under eclogite-, granulite-, or amphibolite-facies metamorphic conditions, and have been separated on the basis of their peak Ottawan pressures into high-pressure (≥1.4 GPa), medium-pressure (mostly ca. 1.0-1.2 GPa), and low-pressure (ca. 0.6-0.7 GPa) belts (Rivers, 2008; Fig. 4). Geochronologic evidence for the Ottawan phase has been reported from along the length of the interior Grenville Province and from inliers in the Appalachians (Fig. 2), and the NW-directed stacking of domains is consistent with the massive crustal shortening implied by the Grenville Front cutting obliquely across external Laurentia (Fig. 1). That is to say, the thrust sheets and nappes are far-travelled allochthons derived from outboard parts of eastern Laurentia, collectively constituting an allochthonous belt. The presence of eclogite- and high-pressure granulite-facies assemblages has been interpreted to provide evidence for the development of double-thickness crust (~70 km) and the formation of an orogenic plateau during the Ottawan phase (e.g., Indares, 1993, 1995; Rivers et al., 2002, 2012).

Regional metamorphic rocks that experienced deformation and metamorphism during the Rigolet phase are situated close to the foreland and developed in a parautochthonous fold-thrust belt setting with an inverted metamorphic gradient in the hanging wall of the Grenville Front (e.g., van Gool et al., 2008; Jannin et al., 2018). The grade of Rigolet metamorphism ranges from greenschist to eclogite facies. Rocks with Rigolet fabrics occur along the length of the Grenville Province, but do not occur in the Grenville hinterland or the inliers in the Appalachians on account of their restricted location proximal to the orogenic front. Moreover, in contrast to the allochthonous domains with Ottawan metamorphism in the hinterland, those with Rigolet metamorphism in the parautochthonous belt exhibit lithological linkages with the foreland to the northwest and less dramatic shortening.

Comparison of Ottawan and Rigolet assemblages and P-T estimates has led to an interpretation that the Ottawan assemblages developed under a higher geothermal gradient (Rivers et al., 2012). This interpretation is commensurate with Ottawan metamorphism occurring in the thermal core of the orogen, as defined by an 'interior magmatic belt' marking the limits of syn-Grenvillian mantle- and crust-derived intrusions emplaced during both the Ottawan and Rigolet phases of the Grenvillian orogeny (e.g., Rivers et al., 2012; Rivers, 2021).

Ottawan high-pressure metamorphism

The high-pressure granulite- and eclogite-facies assemblages in the Grenville Province have mostly been observed in small gabbroic bodies, mapped as deformed dikes or small intrusions, surrounded by granitoid gneisses that lack an obvious high-pressure signature. Classical geothermobarometry for these high-pressure rocks from the Ottawan high-pressure belt in central Quebec yielded P-T estimates of ca. 1.2-1.5 GPa / 800-850 °C, that were interpreted to indicate that the assemblages developed at 40-50 km depth in the lower parts of hot thickened crust under an orogenic plateau, before exhumation into the granulite-facies middle crust (e.g., Indares, 1993, 1995; Indares and Rivers, 1995; Indares and Dunning, 1997). However, a more recent study of eclogite-facies assemblages from the high-pressure belt in Ontario by Cao et al. (2021), using phase equilibria modelling methods, has yielded two sets of P-T conditions, ca. 1.7 GPa / 680 °C for the peak eclogite-facies assemblage, and 1.3 GPa / 920 °C for the mid-crustal granulite-facies overprint. These results, which are more precise, are more compatible with eclogite formation in a subduction zone setting than at the base of double-thickness crust, suggesting that earlier P-T estimates by classical geothermometry may not have adequately distinguished the peak pressure eclogite-facies assemblage from the granulite-facies overprint that developed during/after exhumation into the middle crust. Although more work is needed to validate this conclusion, the new data suggest that subduction of continental crust with mafic dikes and enclaves to upper mantle depths of 50-60 km prior to its exhumation into the orogenic middle crust was likely an important tectonic process beneath the Ottawan orogenic plateau.

High temperature of the Ottawan middle and lower crust

As with peak pressure estimates, the estimation of peak Ottawan temperature conditions in mid-crustal granulite-facies gneisses by phase equilibria modelling has resulted in higher peak temperatures than by earlier classical thermobarometric methods (which mostly yielded estimates of 750-800 °C). For example, many temperatures estimates of ≥850 °C have been determined (e.g., Indares et al., 2008; LaSalle et al., 2014; Patrick and Indares, 2016), and more recently some estimates have been ≥900 °C (e.g., Davis et al., 2020; Shinevar et al., 2021), thereby qualifying as ultra-high-temperature (UHT) metamorphism.

These results suggest that the phase equilibria modelling approach is better able to see through the widespread post-peak diffusional resetting in high-grade assemblages, thereby retrieving temperatures closer to peak conditions. The revised peak-T estimates have important implications for the viscosity of the middle and lower crust during the Ottawan phase, considering they are significantly above both the hydrous and anhydrous solidi of most felsic lithologies. Due to the widespread and pervasive migmatitic character of most Ottawan granulite-facies gneisses, and the conclusion of Rosenberg and Handy (2005) that the viscosity of partially molten granite drops significantly at ~7% liquid by volume, it is reasonable to conclude that the middle and lower crust under the orogenic plateau would have been rheologically weaker than the non-migmatitic upper crust. This interpretation is significant from a tectonic perspective because a hot Moho and weak lower and middle crust are among the preconditions for extensional orogenic collapse predicted by numerical modelling (e.g., Rey et al., 2009; Brun et al., 2018).

Ottawan orogenic collapse

In addition to the Ottawan high-, medium-, and low-pressure belts, there are domains in the hanging wall of the Allochthon Boundary that escaped significant Ottawan ductile strain, and in which the peak-Ottawan temperature was below the Ar-Ar closure temperature of hornblende (~500 °C; Schneider et al., 2013). These observations suggest that these domains formed part of the upper orogenic crust (Fig. 4), which was termed the Ottawan orogenic lid by Rivers (2008). Segments of the orogenic lid are juxtaposed against mid-crustal, granulite-facies domains along post-peak, normal-sense ductile shear zones in the hanging wall of the Allochthon Boundary, providing a signal of the profound post-peak extensional collapse of the orogen (e.g., Streepey et al., 2004; Rivers, 2008, 2012). In particular, three large metamorphic core complexes, in which the granulite-facies metamorphic cores have diameters of 150 to >400 km, have been identified in the western Grenville Province, collectively supporting the inference of regional extensional collapse of double thickness crust under an orogenic plateau (Rivers, 2012; Schneider et al., 2013; Rivers and Schwerdtner, 2015; Soucy La Roche et al., 2015; Schwerdtner et al., 2016; Dufréchou, 2017; Regan et al., 2019; Baird, 2020). Collapse is interpreted to have taken place by extensional flow of the rheologically weak middle and lower crust late in the Ottawan Phase of the orogeny (ca. 1050-1020 Ma), giving rise to the sub-horizontal, high-strain layering in the metamorphic cores. The best constrained estimates for the time of collapse are based on U-Pb dating of monazite integrated with trace element modelling of REE+Y (rare earth element + yttrium) compositions of coexisting monazite and garnet (e.g., Markley et al., 2018; Regan et al., 2019). These ages imply that collapse was initiated some 40 Myr after the onset of Ottawan high-grade metamorphism in the middle crust, significantly predating thrusting and crustal shortening in the parautochthonous belt during the Rigolet phase.

Rigolet phase and development of the Grenville Front

Within the hinterland of the Grenville Province, the crustal-scale thrust stack in the hanging wall of the Allochthon Boundary that developed during the Ottawan phase of the Grenvillian orogeny implies important crustal shortening and thickening by stacking of far-traveled thrust slices derived from the continental margin to the southeast (Rivers et al., 1989; Carr et al., 2000; see position of Allochthon Boundary in Fig. 4). During the Rigolet phase of Grenvillian orogeny, on the other hand, Laurentian crust from the foreland was subducted towards the southeast under the Allochthon Boundary, and Rigolet deformation and metamorphism propagated in the opposite direction, such that the youngest contractional structures are located in the northwest of the orogen (Hynes and Rivers, 2010). The northwestern limit of ductile deformation and associated metamorphism of the Rigolet phase is the Grenville Front, a reverse-sense structure that is well defined along the length of the Grenville Province from the Labrador Sea to Lake Huron in Ontario (see its position in Fig. 1).

Ottawan ages are also recorded in high-grade rocks from the Adirondack Highlands (e.g., Regan et al., 2019) and Grenvillian inliers in the Appalachians (e.g., New Jersey Highlands; Volkert and Aleinikoff, 2021; Blue Ridge; Johnson et al., 2018, 2020; Fig 2). The similarity of the timing and intensity of Ottawan high-grade metamorphism throughout the eastern to southeastern margin of Laurentia indicates the region formed part of a coherent orogen undergoing simultaneous deformation and metamorphism. While tectonic and metamorphic evidence of Grenvillian deformation extends far south into the USA in inliers, its western limit is covered by Paleozoic sedimentary rocks.

Insight into the position of the Grenville Front under younger cover has been obtained from geophysical and drill core data. Data from drill cores have long revealed a contrast in metamorphic grade through central Ohio (Bass, 1960) and U-Pb geochronology of metamorphic zircon from drill cores has confirmed the age of metamorphism as Grenvillian (zircon rims with U-Pb date of 1018 ± 19 Ma; Moecher et al., 2018). Seismic reflection surveys, such as COCORP and GLIMPCE, have imaged narrow, east-dipping ductile shear zones within the crust that separate horizontally layered undeformed Proterozoic rocks to the west from deformed rocks east of the E-dipping shear zones. Corroborated by drill holes and gravity and magnetic anomalies, the E-dipping deformation fronts in these seismic lines have been interpreted as a system of thrust faults that mark the Grenville Front (Pratt et al., 1989; Hauser, 1993). The presence of the E-dipping shear zone in central Ohio has been independently confirmed by EarthScope recordings of seismic waves from teleseismic earthquakes at seismometers of MAGIC (Long et al., 2019). Long et al. (2019) isolated S waves scattered by P waves approaching the stations through the underlying crust, to map the depths of discontinuities in elastic properties of crustal rocks. The polarity of the scattered waves confirms the anisotropic nature of the dipping boundary, as expected for a major shear zone associated with contractional deformation.

Discussion

Midcontinent Rift development and cessation

The Midcontinent Rift is interpreted to have been well on the way to complete lithospheric separation that would have formed a new ocean basin if extension and volcanism had not ceased (Cannon et al., 1989). Cannon (1994) proposed that cessation and inversion of the Midcontinent Rift can be attributed to the Grenvillian orogeny. That is, if it were not for the Grenvillian orogeny, much of southeast Laurentia that had become part of the continent through prolonged accretionary orogenesis during the Paleoproterozoic and Mesoproterozoic Eras would have rifted off to become an independent continent.

The chronology of the Grenvillian orogeny has improved since Cannon's hypothesis, as has the chronostratigraphy of the Midcontinent Rift. The best available temporal constraint for the youngest extension in the rift is a rift-related unconformity that developed ca. 1091 Ma between the Beaver Bay Complex and the Schroeder-Lutsen basalts (Green et al., 2011; Swanson-Hysell et al., 2019) which likely developed near the end of active extension. This age of youngest extension is very close to the best available geochronologic constraints for the onset of the Ottawan phase of Grenvillian orogenesis (Fig. 2); specifically, there are a few monazite dates from high-grade rocks as old as ca. 1090 Ma (e.g. Corrigan et al., 2000; Markley et al., 2018), and more ca. 1070 Ma monazite and zircon rim dates (Fig. 3), constraining substantial shortening, crustal thickening and heating by that time. These data associate the timing of cessation of extension within the Midcontinent Rift with the onset of Grenvillian orogenesis.

An alternative hypothesis for the cessation of extension in the Midcontinent Rift has been proposed. In this model, successful rifting of a conjugate continent from the eastern margin of Laurentia was associated with the end of extension in the continent interior (Stein et al., 2014). However, this hypothesis cannot be reconciled with the robust geologic record of convergent tectonism along the margin of Laurentia. From the Grenville Province southward to the Blue Ridge inliers, the record of high-grade metamorphism and crustal thickeningconvergent mountain-buildingcannot be reconciled with the opening of a new ocean basin. Rather, the geochronological constraints support the hypothesis of Cannon and Hinze (1992) that the cessation of rifting was the result of far-field Grenvillian compression.

The subsequent history of the Midcontinent Rift following the end of extension and magmatic activity is multiphase, as briefly noted previously. Post-rift sedimentary rocks record an interval of continued subsidence followed by convergent tectonism that uplifted portions of the Midcontinent Rift and underlying Paleoproterozoic rocks along major thrust faults, potentially during the later portion of the Ottawan phase of the Grenvillian orogeny (Cannon et al., 1994). Unconformably overlying these uplifted rocks are clastic sedimentary rocks that were likely deposited a basin associate with lithospheric flexure during the Rigolet phase (Hodgin et al., 2022). Towards the end of the Rigolet phase at 980 Ma, as Grenvillian deformation propagated farther towards the interior of the continent, final shortening within the Midcontinent Rift occurred, as rift volcanic rocks were thrust over these sediments (Hodgin et al., 2022).

Deep connections between Mesoproterozoic subduction and intracontinental magmatism?

The multi-phased emplacement of large volumes of igneous rocks within and along the Midcontinent Rift indicates prodigious generation of melt and thus the former presence of significant thermal anomalies from mantle upwellings. An advantage of studying the onset of rifting in a billion-year-old rift is that thermal anomalies, which typically dominate active rifting environments, have dissipated. Their absence allowed Zhang et al. (2016) to seismically image the extensive fossil magmatic root at Moho depths (commonly called an "underplate") along a 600-km stretch of the western arm of the Midcontinent Rift. Their result documents that the magmatic root extends well beyond the Lake Superior region, where it has long been known and discussed (Tréhu et al., 1991; Miller and Nicholson, 2013). The finding of Zhang et al. (2016) was based on analysis following application of the receiver function method to teleseismic seismograms from EarthScope's SPREE array of seismic stations (Wolin et al., 2015), and their results were broadly corroborated by Chichester et al. (2018). Delay times of teleseismic P waves recorded by SPREE were also measured and used to tomographically image three-dimensional spatial variations in mantle properties (Bollmann et al., 2019), and a study of teleseismic SKS waves has revealed spatial variations in the intensity and orientation of anisotropy in the subcrustal mantle (Frederiksen et al., 2021). Both studies show that variations in anisotropy align no more strongly with the Midcontinent Rift than with geologic units of older ages, suggesting that heterogeneity in the mantle lithosphere is a combination of inherited structure and signatures from cooling, re-equilibration, and healing over the past billion years, with the most compelling rift signatures preserved in and just below the crust. The magmatic root at Moho depths is substantial in volume, comparable to the estimated volume of near-surface igneous rocks of 1.8 million km^3.

The lack of prominent anomalies in the mantle lithosphere associated with the Midcontinent Rift suggests that mafic magmatism affected a wider region of the lithosphere despite predominantly reaching the Earth's surface within the rift. This interpretation is consistent with the Southwestern Laurentia large igneous province and the Midcontinent Rift being sourced from a mantle upwelling that underwent lateral flow or was of considerable lateral extent. In this context, U-Pb thermochronologic data on middle to lower crustal xenoliths ~500 km north of Lake Superior, indicating the presence of an anomalous ca. 1.1 Ga sublithospheric heat source under that part of Laurentian lithosphere (Edwards and Blackburn, 2018), may provide further support for broad upwelling. As noted previously, magmatic activity in the Midcontinent Rift consists of the early plateau stage ca. 1108-1105 Ma and the main rift stage ca. 1097-1092 Ma, collectively resulting in voluminous mafic flows and intrusions. Both stages exhibit the rapid and voluminous magmatism characteristic of a large igneous province that is typically attributed to decompression melting of hot fertile upwelling mantle plumes sourced from the deep mantle (Miller and Nicholson, 2013). There were pulses of especially rapid magmatism, particularly that of the Duluth Complex, which is one of the largest mafic intrusive complexes known on Earth (Paces and Miller, 1993; Swanson-Hysell et al., 2021b), and was emplaced ca. 1096 Ma in <1 Myr. This rapid magmatic pulse occurred not only 10 million years after initial magmatism, but also after >20°of latitudinal plate motion as Laurentia moved rapidly towards the equator, thereby potentially posing difficulties in applying the plume model. This reality led to a hypothesis for the pulse of main stage volcanic activity in the Midcontinent Rift is that it is associated with mantle return flow following a slab avalanche (Swanson-Hysell et al. 2019). Such a slab avalanche could have enhance slab pull and contributed to Laurentia's rapid motion. However, in the context of considering a deep seated plume, any upwelling thermal anomaly that resulted in main stage magmatism need not have risen directly under the Midcontinent Rift. Rather it could have flowed laterally upon encountering a laterally inhomogeneous Laurentian lithosphere via "upside-down drainage" (terminology of Sleep, 1997), with melt migrating to the surface at the locally thinned lithosphere of the Midcontinent Rift (Swanson-Hysell et al., 2021). A possible way to explain these pulses of magmatic activity using the plume model is that they are the result of multiple mantle plumes generated from along a lower mantle plume generation zone rather than a from a single plume in a fixed location (Burke et al., 2008). In this scenario, the first plume caused heating and lithospheric thinning in, and to the north of, the Lake Superior region, with the second initially arriving elsewhere under Laurentia (potentially forming the Southwestern Laurentia large igneous province) as the continent was displaced towards the equator, but in this case the plume head then flowed laterally to the previously thinned lithosphere of the rift (Swanson-Hysell et al., 2021b).

While upwelling deep-seated mantle plumes, with lateral flow to the Midcontinent Rift, provide a possible hypothesis to explain the thermal anomaly, there are also other possibilities. The seismically imaged lithospheric structure along the western arm of the Midcontinent Rift, combined with the paleogeographic history, provides support for the possibility of a deep mantle connection between the long-lived Mesoproterozoic subduction along Laurentia's eastern margin (present coordinates) and later intracontinental magmatism.

Deep water cycling

Subduction of oceanic lithosphere into the upper mantle provides mineral-bound water to the mantle wedge through a series of dehydration reactions (Schmidt and Poli, 1998). However, a fraction of this water is estimated to survive and subduct considerably deeper than 150 km (Thompson, 1992; Rüpke et al., 2006). Prolonged subduction could bring sufficient water past the mantle wedge to the bottom of the upper mantle, where it would accumulate in the transition zone (ca. 410-660 km depth) in the nominally anhydrous olivine polymorphs ringwoodite and wadsleyite, until their buoyancy brought them slowly back to the surface in an elongated upwelling or series of upwellings. The upwelling(s) would weaken the lithosphere of the overlying continent, far (~1000+ km) away from the original subduction zone. Being slightly hydrous the upwelling would also generate abundant melt when ascending below and eventually through the weakened and stretched lithosphere. This deep water cycle hypothesis was proposed by Van der Lee et al. (2008), who inferred these processes to be weakening present-day continental lithosphere beneath the east coast of modern North America as a result of prolonged Mesozoic and Cenozoic subduction of the Farallon plate off the west coast. Variations of this mechanism have been interpreted to be effective by many authors for initiating subduction (e.g., Richard and Bercovici, 2009; Zhao and Ohtani, 2009; Faccenna et al., 2010; Nakagawa and Iwamori, 2017; Chen and Faccenda, 2019; see review by Gerya, 2011) or for inducing intraplate volcanism (Zhao, 2004; Mather et al., 2020).

According to the deep water cycle hypothesis, much of the water that is subducted past the mantle wedge is carried by dense high-pressure-low-temperature hydrous magnesium silicates (so-called alphabet phases, e.g., post-antigorite phase A, phase E, superhydrous phase B, and phase D), which ultimately break down when the slab reaches the transition zone or lower mantle, depending on its temperature (Frost and Fei, 1998; Komabayashi and Omori, 2004). When this occurs, the water released enters the stable phases wadsleyite and ringwoodite that are present in the surrounding mantle. Although nominally anhydrous, the crystal structures of wadsleyite and ringwoodite can contain up to 2-3% hydroxyl (OH') by weight. Hydration of these mineral lowers their densities (Chang et al., 2015; Buchen et al., 2018), generating a slight relative buoyancy that could initiate upwelling. Olivine, their low-pressure polymorph in the upper mantle above the transition zone, can only contain up to several hundred ppm OH' in its crystal structure, its presence nevertheless making it more susceptible to partial melting. Van der Lee et al. (2008) estimated that this deep water cycle, involving subduction of water into the transition zone, its accumulation there and the resultant rheological weakening, followed by buoyant rise to the base of the overlying lithosphere, would take 200 to 300 Myr. For a relatively warm slab, in which the dense hydrous magnesium silicates break down near the top of the transition zone, the cycle could be as fast as 125 Myr, which makes ongoing subduction in the late Mesoproterozoic prior to the Elzevirian and Shawinigan orogenies a plausible timeframe for delivery of the water to the transition zone, and initiation of the widespread upwelling that eventually generated the Midcontinent Rift thermal anomalies.

Applying this deep water cycle hypothesis to intracontinental magmatism in the Midcontinent Rift suggests a connection to the preceding long history of Mesoproterozoic subduction. An attractive aspect of this hypothesis is that an elongated slab-induced upwelling from the bottom of the upper mantle could explain the voluminous magmatism along the entire rift length and beyond, including the eastern arm of the rift, the Southwestern Laurentia large igneous province, and precursors in Quebec (the Abitibi dikes), eastern South Dakota, and NE Iowa, . Moreover, because such mantle upwellings are composed of slightly hydrated mantle mineralogy, their solidus temperature would be lower than normal, providing an additional driver for the voluminous decompression melting. The estimated duration of the deep water cycle suggests that subduction during the mid-Mesoproterozoic associated with the Eastern and Southern Granite-Rhyolite provinces, and Picuris-Baraboo-Pinwarian orogenies, and/or in the late-Mesoproterozoic associated with the Elzevirian and Shawinigan orogenies, could provide plausible timeframes for delivery of the water to the transition zone, and initiation of the widespread upwelling that eventually generated the thermal anomalies leading to the Midcontinent Rift.

Once development of the Midcontinent Rift had initiated, Laurentia rapidly moved southwards, away from the mantle in which pre-Shawinigan oceanic lithosphere subducted. However, in its journey to a lower latitudes, Laurentia could potentially have moved over the mantle where pre-Elzevirian oceanic lithosphere had subducted previously, also at lower latitudes. Associated, potentially elongated, upwellings through the above mechanism are a possible source of the mantle anomalies that the resulted in prodigious Midcontinent Rift magmatism.

Uncertainties remain with respect to this hypothesis. For example, it is neither entirely clear how hydroxyl transfers from superhydrous phase B or phase D in the slab to ringwoodite or wadsleyite distributed within the ambient transition zone, nor how the water that is eventually released by the upwelling via sub-lithospheric partial melting finds its way to the cold strong core of the lithosphere, where it is needed to weaken it. Additionally, while some ultramafic to mafic Midcontinent Rift intrusions are constrained to have had volatile-rich parent magmas (Miller and Nicholson, 2013), it is unclear whether the presence of volatiles is consistent with the bulk of the magmatic activity, including the generation of cumulate plagioclase and formation of anorthosite in some magma chambers. Future investigation into the volatile continent of plagioclase could be valuable, such as was done for lunar anorthosites where it provided evidence for a wet early Moon in contrast with classical anhydrous interpretations (Hui et al., 2013). Another uncertainty is associated with what occurs when such an upwelling crosses the wadsleyite to olivine phase change boundary at 410 km, given that the water storage capacity of olivine is much less than that of wadsleyite (Ohtani et al., 2001). Karato et al. (2006) proposed that when the water content of upwelling wadsleyite exceeds the water storage capacity of olivine, most of the water will then be trapped in a high density melt at 410 km. However, water content estimates for a transition zone locally hydrated by prolonged subduction are below the saturation limits (Van der Lee at al., 2008; Mao et al., 2012). Additionally, the water contents of the upwelling do not need to be above these saturation limits to achieve mass balance with the amount of water that is estimated to have been subducted. For example, a 100-km thick upwelling with about 0.6 weight % of OH in olivine polymorphs would, need an 8000-km wide oceanic plate to subduct if as much as 20% of the subducted water reaches the transition zone. A smaller fraction of deeply subducting water would reduce the amount of OH in the associated subsequent upwelling to be considerably below saturation limits.

Distinguishing the collisional Grenvillian orogeny from earlier accretionary events

Throughout the text, we have made a conceptual distinction between the collisional Grenvillian orogeny and earlier accretionary orogenic events. There is ambiguity in applying such a conceptual framework to the geologic record in that both accretionary and collisional orogenesis are the result of subduction of oceanic lithosphere leading to collision, deformation, metamorphism, and associated tectonic processes. Our usage of the term accretionary orogenesis refers to the tectonic collision of relatively small terranessuch as pericratonic arcs, allochthonous exotic island arcs and ribbon continentswith Laurentia. Collisional orogenesis on the other hand refers to an orogeny resulting from the collision of large blocks of continental lithosphere. There is a significant paleogeographic difference between the two categories. Following accretionary orogenesis, there will still be an ocean basin along the continent margin, whereas a collisional orogeny will result in the margin becoming a continental interior. To frame the contrast in terms of subduction, in accretionary orogenesis the locus of subduction remains in the same ocean, but redevelops on the other side of the accreted terrane. In contrast, following collisional orogenesis and closure of an ocean basin, subduction must redevelop elsewhere in the world as the plates readjust globally to the absence of a subduction pathway. The Grenvillian orogeny is widely interpreted as a collisional orogeny that involved collision of large conjugate continental blocks (e.g. Hoffman et al., 1991; Li et al., 2008). However, an alternative paleogeographic reconstruction of the Grenvillian orogeny as accretionary, and juxtaposed with an ocean basin rather than a continent, was explored by Evans (2009).

Here we summarize the geological evidence that the Grenvillian orogeny was the result of collisional, rather than accretionary, orogenesis:

(i) Cessation of calc-alkaline arc magmatism in the upper plate, signaling the end of subduction of oceanic crust: In the southwestern Grenville orogen, where the constraints are tightest, continental-arc magmatism on the upper plate (Laurentia) ceased ca. 1200 Ma (e.g., Corrigan and Hanmer, 1997), and was followed by emplacement of the AMCG suite inboard from the continental margin prior to the Grenvillian orogeny. In the offshore peri-Laurentian terranes, calc-alkaline magmatism ceased at about the same time, with inversion of the Elzevir and Trans-Adirondack backarc basins ca. 1220 and 1200 Ga respectively (Carr et al., 2000; Chiarenzelli et al., 2010, 2011; Peck et al., 2013).

(ii) Structural continuity along the length of the orogen: In contrast to accretionary structures that are of restricted areal extent in the Grenville orogen (e.g., Composite Arc and Frontenac-Adirondack belts; Fig. 1), the gently SE-dipping Allochthon Boundary formed during the Ottawan phase, and the Grenville Front formed during the Rigolet phase, are not only continuous at the erosion surface along the 2000 km length of the Grenville Province, but have also been imaged by geophysical methods beyond its confines beneath Phanerozoic cover.

(iii) Crustal-scale structures: In contrast to the boundaries of accretionary domains in the Grenville Province that appear to be relatively shallow crustal features based on metamorphic criteria (see later point), both the Allochthon Boundary and Grenville Front carry eclogite and high-pressure granulite facies rocks in their hanging walls, indicating they transected the thickened orogenic crust and penetrated the lithospheric mantle. For example, as noted previously, recent estimates of the peak pressure-temperature conditions of eclogite fragments in continental crust, which characterize part of the Allochthon Boundary, have yielded values of ca. 17 kbar / 670 °C (Cao et al., 2021), suggesting subduction of the continental margin to depths of ca. 50-60 km. These conditions are indicative of a collisional orogenic setting, and continental subduction is similarly implied by the presence of eclogite proximal to the Grenville Front.

(iv) Rheologically weak middle crust in large collisional orogens: In contrast to pre-Grenvillian accretionary domains in which granulite-facies gneisses are generally not conspicuously highly deformed, those in the hanging wall of the Allochthon Boundary are commonly intensely strained, forming continuously banded gneisses, indicating that they were rheologically weak. These rocks, which have yielded pressure-temperature estimates of ca. 10±2 kbar and 850±100 °C from along the length of the Grenville Province, are widely interpreted to represent the ductile middle portion of double-thickness crust that underwent extensional collapse under an extensive orogenic plateau stretching the length of the Grenville Province (e.g., Rivers, 2012).

(v) Collapse of a large orogenic plateau: Although small orogenic plateaux can develop in continental margin arcs, the orogen-wide extent of the collapsed former plateau that has been identified in the Grenville Province is Tibetan in scale and more compatible with a collisional setting.

(vi) Contrast in peak pressure conditions between accretionary and collisional metamorphism: Accretionary metamorphic events preceding the Grenvillian orogeny, although in some cases attaining granulite-facies conditions, have yielded significantly lower estimates of the peak pressure. For instance, estimates of 6-8 kbar for granulites formed during Pinwarian accretion (ca. 1.5-1.45 Ga) in the western Grenville Province compared to 11-12 kbar for mid-crustal Ottawan assemblages from the same area (Ketchum et al., 1994), and 6-7 kbar for granulites formed during the accretionary Shawinigan Orogeny (ca. 1.19-1.14 Ma) in the Adirondack Lowlands compared to 7-9 kbar for Ottawan metamorphism in the adjacent Adirondack Highlands (Bohlen et al., 1985).

In summary, although no single criterion in the rock record provides a robust and unambiguous signal to distinguish accretionary from collisional orogeny, in aggregate the criteria above form a compelling argument that the Grenvillian orogeny was a result of continent-continent collision. This interpretation supports paleogeographic models in which there was closure of an ocean basin and collision of conjugate continents along Laurentia's margin resulting in the assembly of Rodinia ca. 1090 Ma.

Laurentia's role in the assembly of Rodinia

The record of tectonism indicates that Laurentia had a long-lived active southeast margin throughout the Mesoproterozoic up to and including the ca. 1190 to 1160 Ma Shawinigan orogeny (Fig. 5). For the Shawinigan orogeny, Peck et al. (2013) have described the crustal evolution resulting from the development of several offshore arcs and back arcs and their subsequent accretion to Laurentia (Figs. 2 and 3). This evidence, together with the identification of widespread late-Paleoproterozoic and Mesoproterozoic continental-arc rocks developed on Laurentia, is consistent with subduction dominantly towards the northwest (present-day coordinates) beneath Laurentia during formation of the Great Proterozoic Accretionary Orogen. The presence of an active margin on Laurentia until termination of Shawinigan orogenesis precludes proposals that invoke a major conjugate continental block, such as Amazonia, immediately offshore of Laurentia ca. 1200 to 1160 Ma (as in Elming et al., 2009). Rather, the geology and paleogeography demand an ocean to the southeast of Laurentia (the Unimos Ocean) such that a continental arc could develop on its southeast margin and oceanic arcs could develop farther offshore prior to accretion to that margin during the Shawinigan orogeny (1140 Ma panel in Fig. 5).

Concerning the subduction geometry during the Grenvillian orogeny, the classic interpretation is that Laurentia was the lower plate (Hynes and Rivers, 2010). This interpretation is consistent with seismic evidence for southeast-dipping boundaries within Laurentian crust (Green et al., 1988), and the robust geologic linkage of this seismic imaging at depth to the exposed crustal-scale Grenville Front tectonic zone at the surface in the northwestern Grenville Province. The interpretation of Laurentian lithosphere as the lower plate during collisional orogenesis has been adopted in numerical models of Grenvillian orogenesis, which principally purport to explain crustal thickening and lower crustal flow during the Ottawan phase (e.g., Jamieson et al., 2007, 2010). However, linking the seismic observations to subduction during the Ottawan phase is not straightforward. A significant challenge to interpretation of the geophysical data is that the Rigolet phase of the Grenvillian orogeny was initiated ~80 Myr after the onset of high-grade Ottawan metamorphism and following an interval of extensional orogenic collapse, and it is the Rigolet structures that were imaged in the crust and linked to surface data in the Grenville Front tectonic zone by Green et al. (1988). The long interval between Ottawan crustal thickening and the development of Rigolet stacking in the northwest of the orogen means that the present-day deep-crustal architecture is strongly shaped by the effects of both extensional collapse (in the orogenic hinterland), and contraction during the Rigolet orogenic phase (in the northwestern parautochthonous part of the orogen adjacent to the foreland). Alternatively stated, the southeast-directed subduction of Laurentian continental crust under the Grenville orogen in the Grenville Front tectonic zone (Green et al., 1988) is a Rigolet structure. Maity and Rivers (2020) interpreted this Rigolet crustal structure to be the secondary subduction direction in the Grenville orogen, and noted a comparison with the initiation of secondary subduction of Eurasian crust (Tarim block) in the Himalaya-Tibet orogen some 50 Myr after the collision with India. The vergence of primary subduction during the Ottawan phase is obscure, not only on account of later structural overprinting as discussed, but also because much of the orogen was rifted away in the Neoproterozoic. Consequently, we address whether the data constraining the broader paleogeographic context of Laurentia can provide insight into the primary polarity of subduction.

Paleogeographic constraints on subduction polarity

In conjunction with the geologic data, there is a particularly rich record of robust paleomagnetic poles for Laurentia in the late Mesoproterozoic to constrain paleogeographic models. Paleomagnetic data from ca. 1180 to 1160 Ma intrusions in Greenland, the ca. 1140 Ma Abitibi diabase dikes and lamprophyre dikes of the Lake Superior region, and the earliest ca. 1108 Ma lavas and intrusions of the Midcontinent Rift all constrain Laurentia to have been at high latitudes during and after the time of Shawinigan orogenesis (Lake Superior region at ~60°N; Evans et al., 2021; Swanson-Hysell, 2021; 1140 Ma reconstruction in Fig. 5). The relatively low latitudinal velocity of Laurentia during this period prior to development of the Midcontinent Rift is in stark contrast to the record of paleomagnetic poles from the Midcontinent Rift in the ensuing ~25 Myr interval from ca. 1108 to 1084 Ma. These poles form a path known as the Keweenawan Track that constrains the latitudinal motion of Laurentia to have exceeded 25 cm/yr (Swanson-Hysell et al., 2019) faster than the maximum velocity of ~17 cm/yr attained by India as it sped from the southern hemisphere towards Eurasia prior to the onset of Himalayan orogenesis (van Hinsbergen et al., 2011). Although some of this motion could be attributed to true polar wander (Evans, 2003), Euler pole inversions including true polar wander yield rates of plate motion that still exceed 17 cm/yr (Swanson-Hysell et al., 2019). Such inversions incorporate paleomagnetic pole positions and ages, as well as their uncertainties, to determine positions and rotation rates of one or multiple Euler poles that have the highest probability of fit to the data. The paleomagnetic pole path is particularly well-explained by two Euler pole inversions in which the most rapid motion (~25 cm/yr) occurs from 1108 to 1096 Ma, with a subsequent change in direction and reduction in velocity from 1096 to 1080 Ma. Given that all the geochronologic estimates for the onset of the Grenvillian orogeny are from high-grade metamorphic rocks and hence must postdate collision by several Myr, it is probable that the period of most rapid motion immediately preceded the onset of Grenvillian orogenesis in the upper crust. We suggest that such rapid motion is consistent with a contribution of slab pull due to subduction of Unimos oceanic lithosphere during final closure of the Unimos Ocean as Laurentia collided with a conjugate continent or continents.

The records of paleomagnetic poles for continents hypothesized to have been the conjugate colliders are much sparser than those of Laurentia. Available poles from Amazonia ca. 1200 and 1150 Ma imply distinct motion relative to Laurentia prior to Rodinia assembly (e.g., Evans, 2013), but these are not robust poles that can quantitatively test the position of Amazonia within Rodinia. Considering the record from the Kalahari craton, the high-quality ca. 1109 Ma Umkondo paleomagnetic pole constrains the craton to have been straddling the equator when Laurentia was at moderately high latitudes (1110 Ma time slice in Fig. 5; Swanson-Hysell et al., 2015). Reconstructing the Kalahari craton as a conjugate plate to Laurentia, with the Namaqua-Natal belt as the conjugate to a portion of the Grenville orogen (Jacobs et al., 1993), would have the Kalahari craton remain relatively stationary as Laurentia moved rapidly towards the equator leading to collision (which is ongoing in the 1060 Ma timeslice in Fig. 5). In comparison, India's rapid motion was similarly driven by slab pull (potentially of multiple slabs; Jagoutz et al., 2015) of the subducting Tethys oceanic lithosphere towards Eurasia. Substantial slab pull was considered to provide the only feasible mechanism for such rapid plate motions by Pusok and Stegman (2020) in their recent modeling study and discussion of the case of India. This history of Laurentian plate motion thus strongly supports the inference that Laurentia arrived at the conjugate plate connected to a slab of down-going oceanic lithosphere at the time of initiation of the Grenvillian orogeny.

Paleogeographic model

We implement the rapid southerly motion of Laurentia in the paleogeographic model (Fig. 5) that is constrained by the paleomagnetic pole database (Swanson-Hysell, 2021). As noted, the record of arc volcanism as well as the collision of arcs and backarc basins during the Elzevirian and Shawinigan orogenies precludes there having been a conjugate continent on Laurentia's eastern margin (which would have been its southern margin in the late Mesoproterozoic) in the ca. 1140 Ma time-slice. In this context, the model of slab detachment during inversion / closure of the Trans-Adirondack basin ca. 1200 Ma, and its replacement by rising asthenosphere that eventually resulted in AMCG emplacement ca. 1170 Ma (e.g., McLelland et al., 2010b; Valentino et al., 2019), could also have provided the tectonic set-up for initiation of Laurentia's transition from an upper plate to a lower plate setting. This transition could explain the gap in metamorphic and igneous activity from ca. 1140-1090 Ma on Laurentia's eastern margin (Fig. 2), which is striking relative to the rest of the record, and would be consistent with the interpretation that the margin was not active from the end of Shawinigan orogenesis until the onset of Grenvillian collision (e.g., Regan et al., 2019). However, there are challenges with this model on account of its limitation to two dimensions normal to a single short segment of the Laurentian margin: firstly the Trans-Adirondack basin and Shawinigan orogeny deformation are limited to the Frontenac-Adirondack belt, whereas the ca. 1170 Ma AMCG complexes extend well beyond its confines (Fig. 4); and secondly, and perhaps more importantly in the present context, the inferred change of Laurentia's position from an upper to a lower plate setting would also have to have occurred along its southeast margin as a whole, not just within the Frontenac-Adirondack belt. Therefore, the trigger for any change in subduction polarity must have been something that affected the margin as a whole. We are not aware of other data that can further constrain this discussion at this time, but the possibilities of a double trigger for AMCG formation and emplacement, and ridge subduction, both discussed previously, may be research avenues worth pursuing.

The late Mesoproterozoic Sunsás orogen of Amazonia has long been proposed as a conjugate to the Grenville orogen in Laurentia (Hoffman, 1991; Cawood and Pisarevsky, 2017). In contrast to eastern Laurentia, there is evidence in Amazonia for accretionary orogenesis in the ca. 1160 to 1090 Ma time period leading up to the Sunsás orogeny (Nedel et al., 2020, 2021; Quadros

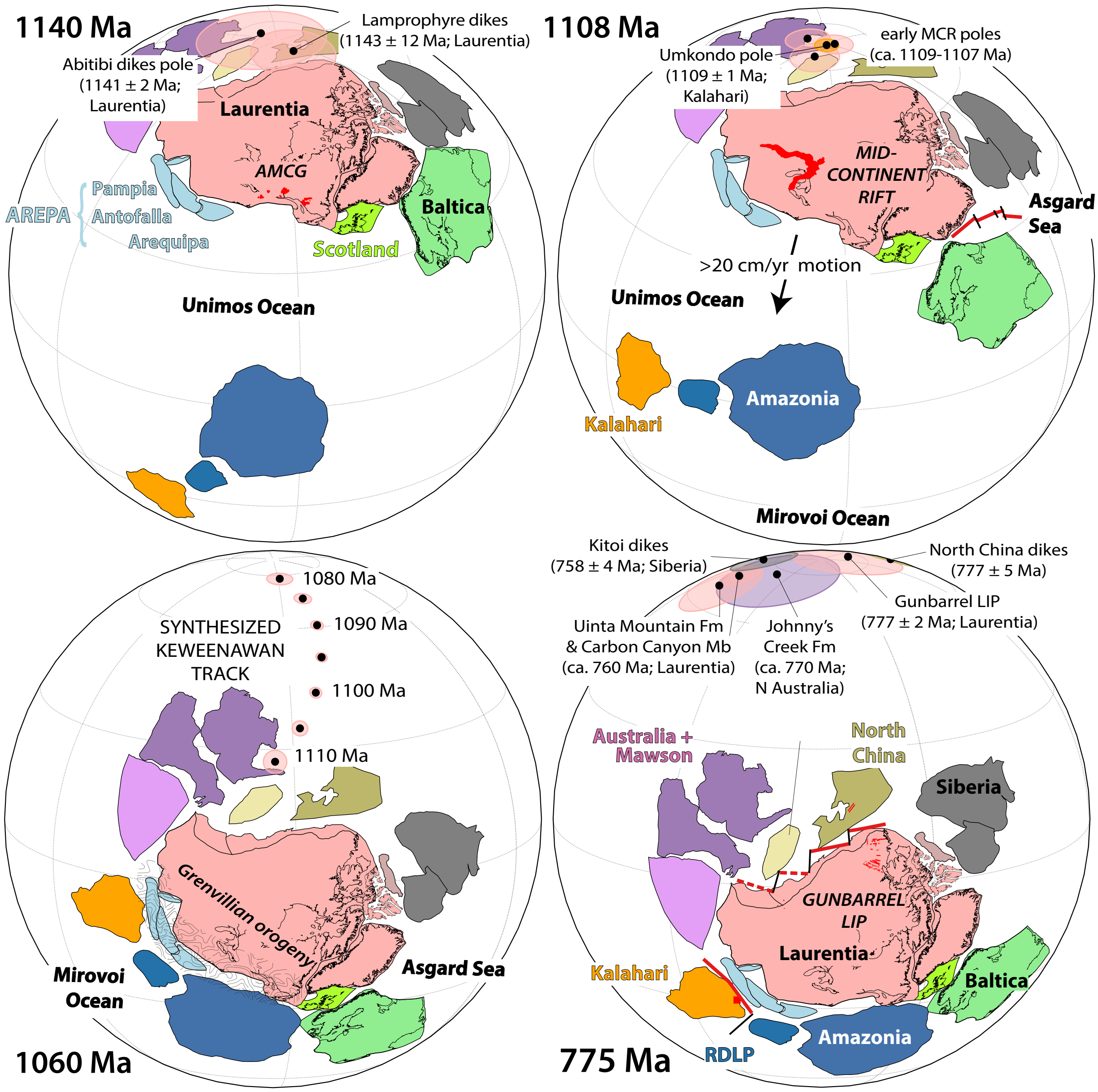

Figure 5: Paleogeographic reconstruction of Laurentia and adjacent Proterozoic continents in the late Mesoproterozoic and early Neoproterozoic at different time slices. Laurentia's position is constrained by paleomagnetic poles shown on the reconstructions. In the 1140 Ma time slice, the ca. 1170 to 1150 Ma AMCG complexes are shown (red). Baltica is shown in the NENA configuration which is supported paleomagnetically from 1750 to at least 1270 Ma and potentially to 1122 Ma (Evans and Pisarevsky, 2008; Salminen et al., 2009; Swanson-Hysell et al., 2021a) before rifting away from East Greenland to open the Asgard Sea (Cawood et al., 2010; Cawood and Pisarevsky, 2017). The AREquipa-Pampia-Antofalla (AREPA) ribbon continent (see discussion in Macdonald et al., this volume) arrived prior to or during the Grenvillian orogeny and may have collided ca. 1140 Ma as shown, resulting in the Llano orogeny and orogenesis recorded in the Blue Ridge inliers. Paleomagnetic poles constrain Amazonia and Kalahari to have been separate from Laurentia prior to the Grenvillian orogeny when they could have been on a conjugate plate. At 1108 Ma during the early plateau phase of the Midcontinent Rift when Laurentia was at high latitudes, the Kalahari craton is constrained to have been straddling the equator by the paleomagnetic poles for the Umkondo large igneous province (Swanson-Hysell et al., 2015). A synthesis of the Keweenawan Track resulting from an Euler pole inversion (Swanson-Hysell et al., 2019) is shown in the 1060 Ma timeslice. This path records the rapid motion of Laurentia towards the equator between ca. 1108 and 1080 Ma during the time period when the Unimos Ocean was being consumed prior to the collisional orogenesis associated Grenvillian orogeny. The assembled Rodinia persisted until initial rifting ca. 775 Ma with episodic rifting continuing until ca. 530 Ma. This history is summarized in Figure 3 of Macdonald et al. (this volume). The code and Euler pole parameters used to generate this model are available here: https://github.com/Swanson-Hysell/Mesoproterozoic_Turning_Point

et al., 2020). For instance, Quadros et al. (2020) interpreted geologic and geochronologic data from the Nova Brasilândia belt inboard of the southwestern margin of the Amazonia craton to indicate arc magmatism and accretionary orogenesis associated with arc and terrane collisions ca. 1137 to 1106 Ma. A subordinate peak of metamorphic ages coeval with a major peak of ca. 1050 Ma monazite dates from the Sunsás belt on the craton margin indicates metamorphic reworking of the recently accreted Nova Brasilândia belt inboard of the margin during the collisional Sunsás orogeny at the margin (Quadros et al., 2020). In turn, this model supports the interpretation that the Grenville orogen and the Sunsás orogen were conjugates during the Ottawan phase (Nedel et al., 2021). These data are consistent with subduction under Amazonia (Quadros et al., 2020), with Amazonia as the upper plate and Laurentia as part of the lower subducting plate as in the preferred interpretation of Tohver et al. (2006). In contrast to the Grenville Province, where there is a record of widespread resetting of high-temperature thermochronometers during the Grenvillian orogeny, Tohver et al. (2006) demonstrated there is a mix of pre-, syn-, and post-collisional resetting in southwest Amazonia that they interpreted to be a result of Amazonian crust being colder and stronger, compatible with an upper plate setting. Note that this arrangement would imply that primary (leading up to and during the Ottawan phase) and secondary (during the Rigolet phase) subduction of Laurentia were both in the same direction (towards the southeast in present coordinates), in contrast to the opposing directions of primary and secondary subduction in the Himalaya-Tibet orogen.

Pb isotope data from the southern Mesoproterozoic inliers in SE Laurentia have been interpreted to indicate that the inliers are a remnant of Amazonian lithosphere (Fig. 1; Fisher et al., 2010), and other terranes such as Arequipa have a similar signature (Loewy et al., 2004). While Arequipa may have been derived from Amazonia, it had a distinct history, at least in the Neoproterozoic, since it may be separated from Amazonia by Cambrian orogenic belts (Hodgin et al., 2021a). Given the subsequent constraints on Neoproterozoic rifting, we reconstruct Amazonia farther north on the margin (present-day coordinates) within Rodinia and place the AREquipa-Pampia-Antofalla ribbon continent farther south (Fig. 5; Macdonald et al., this volume).

The rapid motion of Laurentia between ca. 1108 to 1080 Ma can be seen in the synthesized Keweenawan apparent polar wander path shown in the 1060 Ma time slice of Fig. 5, where the poles get progressively farther away from the continent (implying that the continent was moving away from the pole; Swanson-Hysell et al., 2019). This motion resulted in the distinctly different positions of the continent in the ca. 1108 and 1060 Ma timeslices that are shown for the reconstruction.

In the reconstruction, Laurentia is conjoined with Siberia (following Evans et al., 2016), North China (following Ding et al., 2021) and Australia+East Antarctica (following Swanson-Hysell et al., 2012). We implement the model that, throughout the late Paleoproterozoic and the majority of the Mesoproterozoic, Baltica was in a configuration where there was a tight fit between northern Norway and the Kola Peninsula of Russia with the east margin of Greenland (Gower et al., 1990). This northern Europe and North America (NENA) configuration is well-supported by paleomagnetic pole comparisons from ca. 1780 to 1270 Ma (Evans and Pisarevsky, 2008; Swanson-Hysell et al., 2021) and could extend until 1120 Ma (Salminen et al., 2009). We implement the model that Baltica rotated away from this margin to open the Asgard Sea (Cawood et al., 2010; Cawood and Pisarevsky, 2017), and occupied a position relative to Laurentia in which it would remain until break-up was initiated by the Central Iapetan Magmatic Province ca. 615 Ma (Macdonald et al., 2021). All these cratonic blocks are envisioned to have been conjoined with Laurentia as it rapidly journeyed to the equator where they collided with Kalahari and Amazonia forming conjugate late Mesoproterozoic orogens. The onset of the Ottawan stage of the Grenvillian-Sunsás orogeny thus marks the assembly of Rodinia ca. 1090 Ma. However, the protracted nature of the Grenvillian collision means that it was not until the end of the Rigolet phase of the orogeny ca. 980 Ma that Rodinia was stable without significant ongoing differential internal motions across the orogen. While other continents peripheral to or separate from Rodinia, such as South China, would continue to have active tectonism throughout the 1000 to 720 Ma Tonian Period of the Neoproterozoic (Cawood et al. 2018, Park et al., 2021), Laurentia would remain in the stable interior of Rodinia for 200 million years. Laurentia's tranquil interlude in the early Neoproterozoic would end with the Gunbarrel large igneous province and the initiation of rifting ca. 780 Ma (Macdonald et al., 2021). It would take another 200 million years for Laurentia to emerge from Rodinia as conjugate continents progressively rifted off its margins.

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