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Mapping Neodymium Model Ages of the Quebecia Terrane Near Saguenay, Quebec

Serena Formenti[1], Alan Dickin[2]

1. McMaster University, Integrated Science, Class of 2021

2. McMaster University, Professor Emeritus

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SUMMARY

The geological evolution of the Grenville Province, an area of southeastern Ontario and Quebec, remains a subject of confusion among geologists. Mountain building events have deformed the original features, formed more than 2 billion years ago, making the geology of the area challenging to understand. This study maps the distribution of crustal formation ages within a section of the Grenville Province near the town of Saguenay, Quebec. This provides insight into the crustal provenance of the geological units present, and hence the settings in which they formed. Four geological samples were analyzed to determine the age at which the rocks formed by using the ratio of the radioactive element, neodymium, to its decay product, samarium. The samples analyzed indicate formation approximately 1.5-1.6 billion years ago, which is young in comparison to other portions of the Grenville Province. Mapping the distribution of these ages in conjunction with ages derived from previous studies further constrains geological boundaries within the Grenville Province, delineating the detailed structure of this complicated terrane and the possible settings in which it was formed.

ABSTRACT

The geological evolution of the Grenville Province remains a subject of confusion among geologists. Orogenic events have deformed the original features, making the geology of the area challenging to delineate. This study maps the distribution of crustal formation ages within the Quebecia terrane of the Grenville Province. This provides insight into the crustal provenance of the geological units present. Previous research suggested the presence of slivers of Paleoproterozoic crust (>1.65 Ga) within Pinwarian crust (1.5 Ga). Four geological samples were analyzed from the southern side of the Saguenay graben, where the Paleoproterozoic crustal slivers were thought to extend. Analysis through TDM model ages derived from Sm-Nd radiogenic dating aimed to identify the boundaries of these slivers. Determining the model age distribution within the terrane allows for further delineation of the geological history of the region. The samples analyzed in this study yielded Pinwarian TDM model ages, indicating that slivers of old crust are not present within the study area. These results provide further constraints in the detailed structure of the Quebecia composite arc belt and the geological events preserved within the Grenville Province.

Keywords: Quebecia, model age, accreted arc model, samarium-neodymium dating

INTRODUCTION

Geological Setting

The Grenville geological province is located throughout southeastern Ontario and Quebec, and into the United States, covering over a million square kilometres.[1] Since its formation, the area has been subjected to various mountain building events, known as orogenic events, causing extreme deformation of the original geological units.[1] Among them was the extensive Grenville Orogeny, lasting 1.1 billion years (Ga), that has rendered the geological history of the area extremely challenging to delineate by essentially creating a complicated jigsaw of geological pieces.[1] Previous literature has aimed to determine the geological evolution of the Grenville Province, mainly through reconnaissance sampling and radiogenic dating of rock samples across the area.[1,2] This research has identified sections within the Grenville Province, characterized by geological age and separation by significant geological faults, thrusts and areas of magmatic mixing, as summarized in **Figure 1**.[1,2] In general, the geological units of the Grenville Province, each composed of rock originating from the same geological event with the same lithological properties, decrease in age from the north-western edge to the southeastern edge.[1]

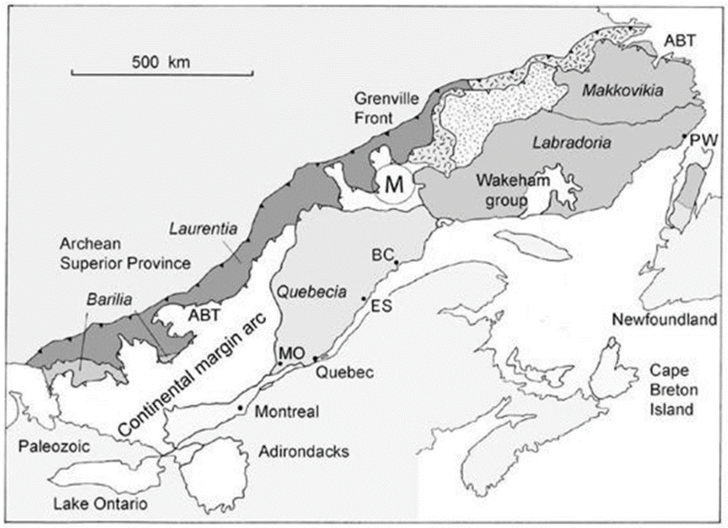

Figure 1. A geological summary map of the Grenville Province and its associated terranes, where M = Manicouagan impact, MO = Montauban, ES = Escoumins, BC = Baie Comeau, PW = Pinware, ABT = Allochthon Boundary Thrust.[3] Obtained from Vautour and Dickin (2019).

One of the most important ways of understanding the geological evolution of the Grenville Province is by using the original age of the crust.[2] Over time and exposure to heat and pressure, such as that brought on by the Grenville Orogeny, rocks are metamorphosed, creating new rocks from preexisting rocks. Determining the original age of the rocks allows geologists to consider the initial processes by which the area formed.[2,4] By defining the ages of the crust, one can identify the timeline of different geological events that formed the region.[4,5] Combining this information with other evidence, including geochemical signatures, lithologies and geological processes pertaining to what is now North America, the geological evolution can be defined.[2]

Previous neodymium (Nd) isotope mapping has defined terranes within the Grenville Province characterized by crustal formation ages.[2] The Quebecia terrane was named and characterized by Dickin (2000) as a Pinwarian-aged terrane with an average crustal formation age of approximately 1.55 Ga.[2] Further research of the current composition of the terrane, with respect to model ages derived from Nd-isotope signatures, aims to reconstruct the geological events that formed this terrane.[3] This paper aims to summarize key literature pertaining to the geological analysis of the Grenville Province, specifically the Quebecia terrane located in the southeastern part of Quebec. In addition, the paper aims to further define the crustal formation ages within Quebecia through the analysis of four crustal samples.

The use of the Nd model ages, derived from the radiogenic decay of Samarium-147 (^{147}Sm) into ^{143}Nd, is a powerful means of determining crustal formation ages of complex geological terranes, in which the original crustal material has been metamorphosed.[4] Empirical models are used to link the composition of the mantle, the source of crustal-forming material, and therefore that of the crust, with approximate ages of extraction from the subsurface. This is possible due to the immobility of rare earth elements (REE) including Nd and Sm.[4] The immobility prevents deviation of the crustal rock sample by post-formation metamorphism and sedimentation events, allowing for the use of a model based on the composition of Earth's mantle from which crust is initially derived.[2,3] This is a key consideration in determining the geological evolution of the crust in the Grenville Province, which has been subjected to various metamorphic events since extraction from the mantle.[1]

The concept of model ages is described by McCulloch and Wasserburg (1978) based on the chondritic uniform reservoir (CHUR) model of DePaolo and Wasserburg (1976).[6,7] These ages are referred to as model ages because they are derived from an empirical model rather than the composition of the mantle.[4] Model ages based on Nd-isotope signatures can be used to describe crustal formation ages by considering the decay of ^{147}Sm into ^{143}Nd with reference to a stable isotope, ^{144}Nd, which remains constant throughout time.[4] As shown in **Figure 2**, the ratio of ^{143}Nd/^{144}Nd increases throughout time as ^{147}Sm decays, resulting in a defined relationship between the crustal formation age and the isotope ratio, as indicated by the bulk Earth evolution line.[6]

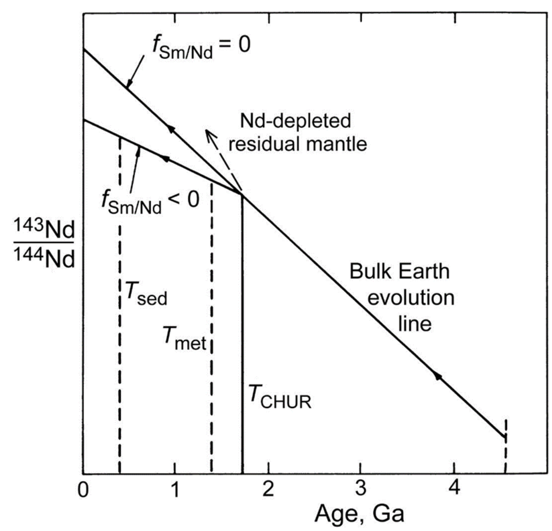

Figure 2. The ratio of ^{143}Nd/^{144}Nd increases with time as ^{147}Sm decays to ^{143}Nd. Sedimentary (T_{sed}) and metamorphic (T_{met}) events do not affect this dating method due to the relative immobility of Sm and Nd.[6] Obtained from McCulloch and Wasserburg (1978).

The CHUR model represents the mantle as a uniform reservoir from which crust is formed.[6] A further variable, ϵ_{Nd}, denotes one part per 10 000 that the $^{143}Nd/^{144}Nd$ ratio of a given sample deviates from that of the CHUR model, as calculated by Equation 1. This value is used to describe variation from the empirical model, which can be used in further analysis.[4,7]

$$(1) \qquad \epsilon_{Nd} = \left(\frac{(143Nd/144Nd)_{sample\ (t)}}{143Nd/144Nd_{CHUR(t)}} - 1 \right) * 10^4$$

The Depleted Mantle Model

In a study by DePaolo (1981), deviation from the CHUR model of samples analyzed from Colorado was noted to be significant and could be represented by a quadratic relationship.[4,7] These data were attributed to the depleted mantle model, which suggests that the mantle, as a reservoir, is in fact not uniform over the geological timescale.[5] This occurs as the mantle is depleted of its crust-forming elements, thereby deviating from the CHUR model which assumes that the reservoir is a closed system throughout the geological timescale.[4,7] Deviation from the model results from incompatible elements, meaning that they are less compatible in melting processes and are depleted from the mantle during crustal formation events at a greater rate than more compatible elements.[4] With respect to determining model ages via the Sm-Nd method, Nd is less compatible than Sm, such that the $^{143}Nd/^{144}Nd$ ratio decreases over time as the mantle is depleted of ^{144}N. This enriches the crust in Nd, and lessens the amount of Nd available in the mantle for future crust-building events.[5] Hence, the CHUR model tends to underestimate the crustal formation age.[4] Instead, crustal formation ages should be calculated relative to the depleted mantle model, producing depleted mantle model ages (TDM), as shown by **Figure 3**.[5]

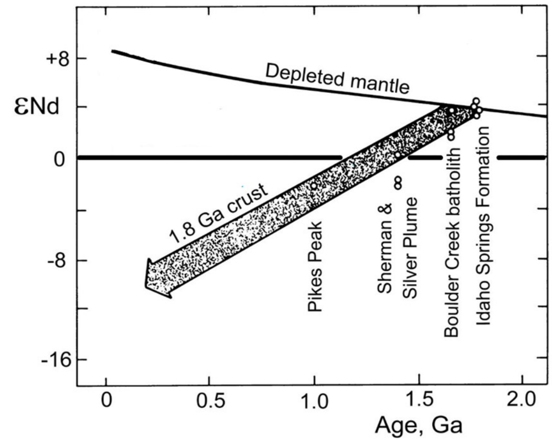

Figure 3. Plot of ϵ_{Nd} values against time from DePaolo (1981) depicting the structure of the depleted mantle model in conjunction with study samples from Colorado, named on the graph.[5] The depleted mantle model, labelled on the graph, is representative of crust forming from a mantle reservoir that changes in composition over time. This deviates from the CHUR model, as represented by the line $\epsilon_{Nd}= 0$.[5,7] The study samples from DePaolo (1981) fall on the large arrow, intersecting the depleted mantle model at an age of 1.8 Ga, indicating the original crustal age of the samples before metamorphism.[5] The left side of the graph denotes present day, in which the depleted mantle model deviates most from the CHUR model, as it is when the mantle has depleted the most.[4] Adapted from DePaolo (1981).

The depleted mantle model is represented by Equation 2, where T is the age in Ga.[5]

$$(2) \qquad \epsilon_{Nd}(T) = 0.25T^2 - 3T + 8.5$$

This empirical model arguably predicts model ages more accurately as the model accounts for changes in mantle composition over the geological timescale.[5]

The Quebecia Terrane

From a study by Dickin and Higgens (1992), gneisses in central Quebec were identified to have an average age of 1.53 ± 0.07 Ga by means of the Nd-Sm method.[8] The area was interpreted as a relatively homogeneous Mesoproterozoic arc, accreted to the Laurentia terrane, shown in **Figure 1**.[8] Similarly, Dickin (2000) used new Nd-isotope data in combination with previously published and unpublished data to further classify the crustal formation ages and their constraints within the Grenville Province, including those pertaining to Quebecia.[2] These data indicated that the terrane extends from Sept Iles to Trois Rivières, with an average crustal formation age derived from the depleted mantle model of 1.55 Ga.[2] This extends the constraints of the terrane defined in Dickin and Higgens (1992) and is in agreement with the average crustal formation age of the terrane being defined primarily as juvenile Pinwarian.[4,8]

It is notable that analysis of this nature is often paired with uranium-lead (U-Pb) dating methods, which can produce snapshots of absolute rock ages that are not based on an empirical model.[9] U-Pb dates represent a minimum age of crustal formation by dating the age of the most recent igneous crystallization event, rather than the original age of crustal formation.[9] This method is, therefore, less suitable for determining crustal formation ages in the Grenville Province due to post-formational metamorphism events that have since occurred.[9] Nonetheless, U-Pb dates are useful as they can accompany model ages derived from Nd-isotope signatures to validate the accuracy of model ages and further the understanding of the Grenville Province.[5] Comparing model ages to U-Pb ages confirms the accuracy of the depleted mantle model, thereby validating ages. Juvenile rocks that have not undergone metamorphism will have similar U-Pb ages and TDM model ages.[2] This was used by Vautour and Dickin (2019) to demonstrate the homogeneity and juvenile crustal formation ages observed throughout Quebecia.[3] The TDM model ages were suggested to be fairly accurate, as shown in **Table 1**.[3] Furthering the understanding of the Grenville province refers to using U-Pb dating to date magmatic events linked to arc accretion, in which crustal fragments experienced recrystallization. With this, it is notable that the average crustal formation age determined in Dickin (2000) is 100 million years (Ma) younger than the oldest U-Pb ages within the terrane.[2] This is suggestive of metamorphism occurring after crustal formation, possibly as a result of the accretion of Quebecia to Laurentia as U-Pb ages reset with significant melting events.[2]

Table 1. The oldest U-Pb ages within Quebecia agree, within error, to the average TDM ages presented in Dickin and Higgens (1992) and Dickin (2000), indicating that the Quebecia terrane consists primarily of juvenile Pinwarian-age crust.[2,3,8]

U-Pb Age (Ma)	Source	Age Location	TDM age from Dickin and Higgens (1992) (Ma)	TDM age from Dickin (2000) (Ma)
1506 ± 13	Hebert & van Breemen (2004)	Cap de la Mer amphibolite, Saguenay	1530 ± 70	1550*
1502 ± 6	Groulier et al. (2018)	Tadoussac granodiorite, Tadoussac		
1492 ± 3	Groulier et al. (2018)	Moulin-a-Baude dacitic tuff, Escoumins		

*No error available for data point. Adapted from Vautour and Dickin (2019).

rentia.[2]

With more in-depth reconnaissance sampling, the homogeneity of the Quebecia terrane was examined, ultimately concluding that Quebecia is far less coherent as a single unit than previously thought.[8] The primary evidence suggesting some aspects of heterogeneity in Quebecia was identified by Dickin and Higgens (1992). Samples with Paleoproterozoic (>1.65 Ga) Sm-Nd isochron ages were found along the Manicouagan River, as shown in **Figure 4**.[8]

Further evidence from isotope signatures, petrology, trace element geochemistry, and yttrium concentration data from Dickin (2000) establishes the terrane as an oceanic arc accreted to Laurentia.[2] Model ages lie within error of one another throughout sample areas, which is indicative of the terrane being extracted from the mantle in a single crust-forming event.[2] The samples were also found to have more silica-rich and alkali-poor compositions in comparison to other terranes of the Grenville Province. This is consistent with Quebecia having originated from an oceanic crust, which is typically more silica-rich, supporting the theory of Quebecia being an accreted oceanic arc.[2] Finally, yttrium concentrations show similar ranges across the terrane, further indicating homogeneity within Quebecia and adding evidence for an oceanic arc origin.[2] However, it is notable that the northwest margin of the terrane has a large range of Nd isotope signatures, suggesting contamination at the margin by other bodies of crust as a result of accretion to Lau-

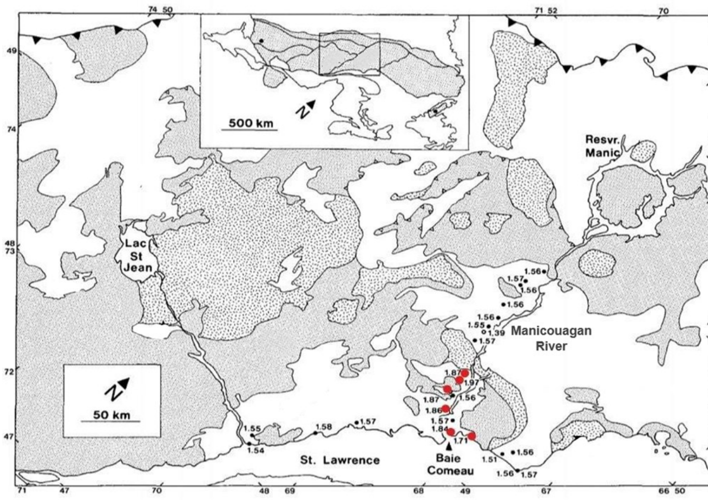

Figure 4. Map of geological units (shown as different textures) from Dickin and Higgens (1992) with Sm-Nd isochron ages of study samples along the Manicouagan River. The red

points denote samples of interest that yielded Paleoproterozoic (>1.65 Ga) crustal formation ages in comparison to the surrounding Pinwarian-aged (~1.5 Ga) crust.[8] Adapted from Dickin and Higgins (1992).

A subsequent study by Vautour (2015) further examined the organization of Quebecia, supporting the complexity of the terrane identified by Dickin and Higgens (1992), and concluded that the terrane should be treated more accurately as a composite arc belt.[10] Nd-isotope signatures examined in this study revealed the presence of older Paleoproterozoic model ages thought to possibly be slivers of older crust that were rifted away from Laurentia.[10]

The slivers of older crust within Quebecia were closely examined by Vautour and Dickin (2019), which defined the extent of two principle slivers referred to as the Labrieville and Loup Marin blocks, as shown in **Figure 5**.[3] The origins of these blocks of older crust are not fully understood, although Vautour and Dickin (2019) suggest the accretion of juvenile oceanic arc crust with attached slivers of Paleoproterozoic crust throughout the terrane.[3]

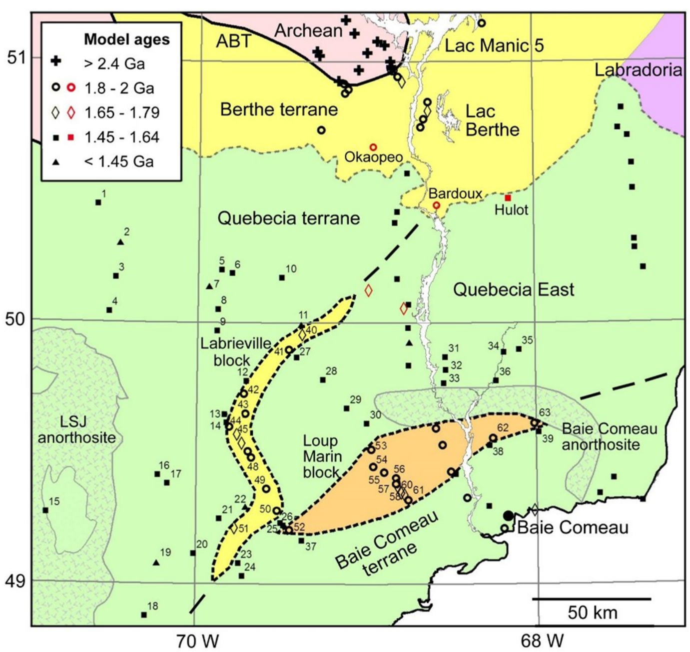

Figure 5. Model ages of the Quebecia terrane from Vautour and Dickin (2019), defining current knowledge on the extent of the Paleoproterozoic Labrieville and Loup Marin blocks within the main Pinwarian crust of the terrane. The Loup Marin block includes the regions of older crust identified in Dickin and Higgens (1992), as shown in Figure 4.[3] Obtained from Vautour and Dickin (2019).

By separating the Quebecia terrane into geological units with respect to model ages from Nd-isotope signatures, it is clear that the terrane is composed of several components.[3,8] This is consistent with it originating from Pinwarian-aged oceanic arcs accreted together with slivers of Paleoproterozoic crust.[3]

The Saguenay Study Area

Prior to this research, evidence for the extension of the main Paleoproterozoic slivers into the study area south of the Saguenay graben was identified in unpublished research by Hynes (2010).[11] This study identified crust with Paleoproterozoic TDM model ages north of the Saguenay river. Combined with previous studies and U-Pb ages, in addition to the extensive deformation characteristic throughout the Grenville Province, the extent and resolution of this section of Paleoproterozoic crust require further investigation.[11] The crust identified in this study could be an extension of the Labrieville or Loup Marin blocks, ultimately being attributed to the composite arc belt model of Vautour (2015) and Vautour and Dickin (2019), which provide an explanation for the heterogeneity throughout Quebecia.[3,10,11]

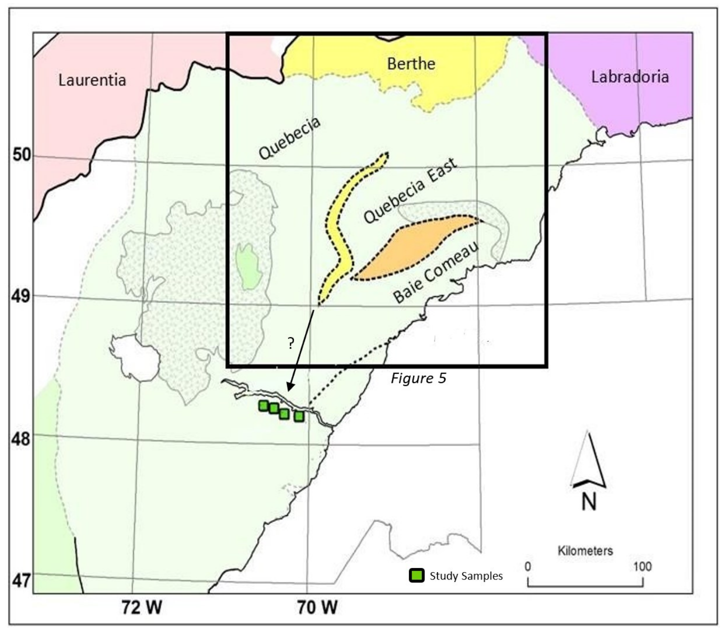

Figure 6. Study samples, shown as green squares, within the dominantly Pinwarian (green) Quebecia terrane. The samples were selected to investigate the possible constraints of the Labrieville (yellow) and Loup Marin (orange) blocks by examining a possible continuation of the blocks, as shown by the black arrow.

METHODS

Four samples were collected from the southern side of the Saguenay graben where the Paleoproterozoic crustal fragments were thought to possibly be present, as shown in **Figure 6**. Samples were selected to be as homogeneous as possible, excluding those with evidence for sedimentary origins. This was done to yield the most suitable crustal formation model ages without mixing from younger mantle components or irrelevant sediments deposited after crustal formation. Rock samples were then prepared and analyzed between October 2019 and March 2020 at McMaster University using the following methods established by Holmden and Dickin (1995).[12]

Rock Crushing

Each sample, approximately one kilogram in size, was broken down in the lab using several pieces of equipment.

Hydraulic Jaw Splitter

A hydraulic jaw splitter allowed for the removal of impurities, including igneous veins and weathered surfaces, to obtain a uniform sample. Another purpose of this step was to form pieces small enough to be put in the jaw crusher.

Jaw Splitter

Small pieces of the sample were placed one at a time inside a jaw crusher, which broke them up into gravel-sized pieces.

Shatterbox

The gravel-sized pieces of the sample were first split into smaller amounts using a table splitter, from which about half of the sample was used. The sample was transferred into a tungsten carbide disk mill which was then placed inside a shatterbox. The first 30 seconds allowed the disk mill to grind the sample into a uniform powder, and the following 60 seconds further fined the powder enough to be dissolved.

Cation and Rare Earth Element (REE) Chromatography

Dissolving and Evaporating

Following being crushed into a fine powder, samples were precisely weighed and recorded before being prepared for analysis. Analysis took place in a clean lab using two different column chromatography procedures outlined below. Rock sample powder was added to a Teflon bomb followed by 1 mL of 3 M nitric acid (HNO_3) and 15 mL of hydrofluoric acid (HF) in order to begin the first step of dissolution. HF solutions were put into Teflon jackets and placed in an oven for four days. After removal from the oven, lids were removed, and solution was evaporated on a hot plate. After evaporation, 7 mL of HNO_3 was added to the bombs and evaporated again on the hot plate. Finally, 6 M HCl was added to the bombs and placed back in the oven.

Splitting and Spiking

Once fully dissolved, samples were diluted with 15 mL of deionized water, shaken, and split by taking approximately 5 mL of sample and transferring it to a smaller bomb, which was spiked using a ^{150}Nd-^{149}Sm solution. Each solution was then evaporated under heat lamps before undergoing separation in cation and REE columns.

Cation Exchange Chromatography

Samples were re-dissolved in 2 mL of 0.3 M HCl and added to test tubes, which were mixed in a centrifuge for 10 minutes. After mixing thoroughly, 1 mL of each sample was loaded onto the cation columns. This was followed by the addition of 1 mL and 2 mL of 3 M HNO_3. Columns were then eluted with 13 mL of HNO_3. Finally, 7 mL of each solution was collected and solutions were evaporated under heat lamps.

REE Chromatography

Samples were diluted with 0.4 M HCl and loaded into the REE columns. Columns were eluted with 1 mL, then 2 mL, and then 7 mL of 0.4 M HCl. Samples with the spike containing Nd were eluted with 12 mL of 0.4 M HCl before being collected, followed by the same columns containing samarium being eluted with 11 mL of 1 M HCl added before being collected. The remaining samples were eluted with 8 mL of 0.4 M HCl before being collected. Finally, the separated samples were evaporated under heat lamps.

Mass Spectrometry

Each sample was split into three solutions, one containing Sm, one containing Nd and the last containing the ratio of ^{143}Nd/^{144}Nd. Each Teflon bomb containing the final solid was mixed with 80 µL of a dilute phosphoric acid solution and were loaded onto double filament beads for analysis on a VG Isomass 354 Mass Spectrometer. Data collected from each sample can be found in **Table 2**. The resulting TDM model ages were calculated using a computer algorithm and were recorded and uploaded to an ArcGIS map to then be interpreted alongside previous data.

These data were combined with data from previous studies to further define the constraints of Paleoproterozoic crustal slivers within Quebecia using ArcMap.

RESULTS

The samples analyzed in this study yielded results that were consistent with the dominant distribution of Pinwarian-aged crust throughout the Quebecia terrane. The TDM model ages of crustal formation fell between 1.51 and 1.60 Ga, as shown in **Table 2**. In conjunction with previous data, these ages are representative of a juvenile terrane composed of accreted oceanic arcs.

Table 2. Sample data and calculated model ages.

Sample Identification	Y Coordinate (NAD 83)	X Coordinate (NAD 83)	Nd (ppm)	Sm (ppm)	$\frac{^{147}Sm}{^{144}Nd}$	$\frac{^{143}Nd}{^{144}Nd}$	TDM (Ga)
SG42	5339195	417130	7.2	1.15	0.0973	0.511869	1.53
SG44	5341035	404150	24.3	5.17	0.1287	0.512193	1.52
SG47	5345740	395100	82.3	16.47	0.1210	0.512124	1.51
SG48	5348020	385855	14.6	3.00	0.1243	0.512101	1.60

DISCUSSION

Combining these data with previous data further maps the model age signatures within Quebecia. The samples analyzed in this study further defined the extent of the Pinwarian crust, indicating that the Paleoproterozoic slivers do not extend in the study area south of the Saguenay graben. This information is nonetheless important in helping define the constraints of older crustal fragments in order to better understand their origin and the geological evolution of the area. This is seen largely through interpretations of the Labrieville and Loup Marin blocks, shown in **Figure 5**.[3]

It is important to establish that the model age signatures throughout Quebecia indicate that it is an accreted terrane composed of oceanic-derived crust. The sharp boundaries between crustal fragments of different ages are indicative of accretion of different units of crust within Quebecia.[3] Additionally, the fairly elongate Labrieville and Loup Marin blocks, thought to be associated with crustal accretion, are indicative of accretion towards Laurentia in the northwest. Geochemical signatures discussed in Dickin (2000) and Vautour and Dickin (2019) suggest oceanic provenance for the crust of Quebecia.[2,3] The complex geological dispersion throughout Quebecia that lead to the composite arc model is currently explained by theories describing the possible provenance of the Labieville and Loup Marin blocks.[3,10]

One theory suggests the Sumatra region of Southeast Asia, shown in **Figure 7**, as an analogue for the tectonic processes that lead to the formation of Quebecia, describing the complicated assembly of terranes.[3] Sumatra is divided into two elongate terranes, known as Sumatra East and West, which are similar in size to Quebecia and Quebecia East.[3] These terranes are separated by the Medial Sumatra Tectonic Zone (MSTZ), characterized by highly deformed metamorphic rocks thought to be the shear zone along which West Sumatra moved approximately 1000 km westwards relative to East Sumatra. This shear zone can be compared to the Labrieville block that separates Quebecia and Quebecia East.[3]

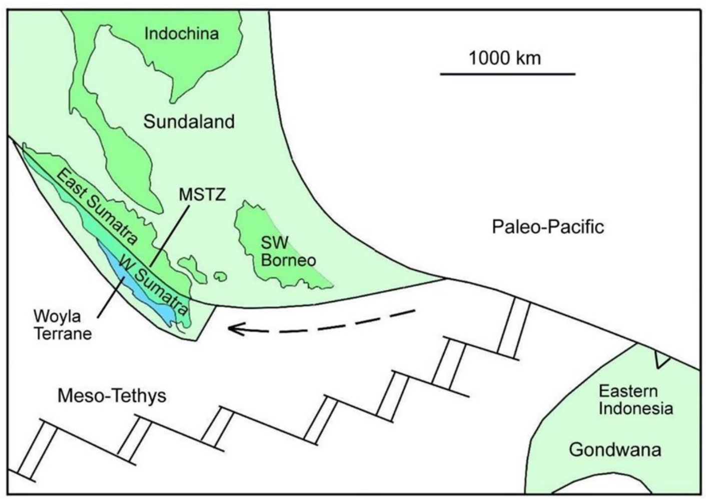

Figure 7. Map showing the westward movement of West Sumatra relative to East Sumatra.[3] Obtained from Vautour and Dickin (2019).

Comparing these two regions, Vautour and Dickin (2019) suggested that Quebecia East can be described as a significantly displaced Pinwarian terrane rifted away from its original location with the attached Labrieville block.[3] Based on this theory, the origin of the Labrieville block should be nearby, within the Grenville Province, as a terrane with a Paleoproterozoic crustal formation age. The geographically nearest terrane with the appropriate crustal formation age is the Berthe terrane, shown in **Figure 6**. With regards to age and location, this is a plausible source for the Labrieville block; however, there is no evidence suggesting that the current positioning of the Labradoria terrane is not approximately the same as it was during the Mesoproterozoic era, making the westward movement of the Labrieville block from the Berthe terrane unlikely given the post-Pinwarian accretion age of Quebecia noted by Dickin (2000).[2,3] Alternatively, the crust could have originated from the Barilia terrane, currently located on the far western side of the Canadian portion of the Grenville Province, as shown in **Figure 1**. This was investigated by Vautour and Dickin (2019) by the plot shown in **Figure 8**.[3] This plot shows the TDM model ages of different units in the Grenville Province alongside the Labrieville and Loup Marin blocks. As seen in the plot, Barilia is the only terrane with similar TDM model ages to the two Paleoproterozoic slivers, suggesting a potential origin. Moreover, the plot indicates that Labradoria has younger TDM model ages compared to the Paleoproterozoic slivers, suggesting they did not originate from Labradoria as previously discussed.[3]

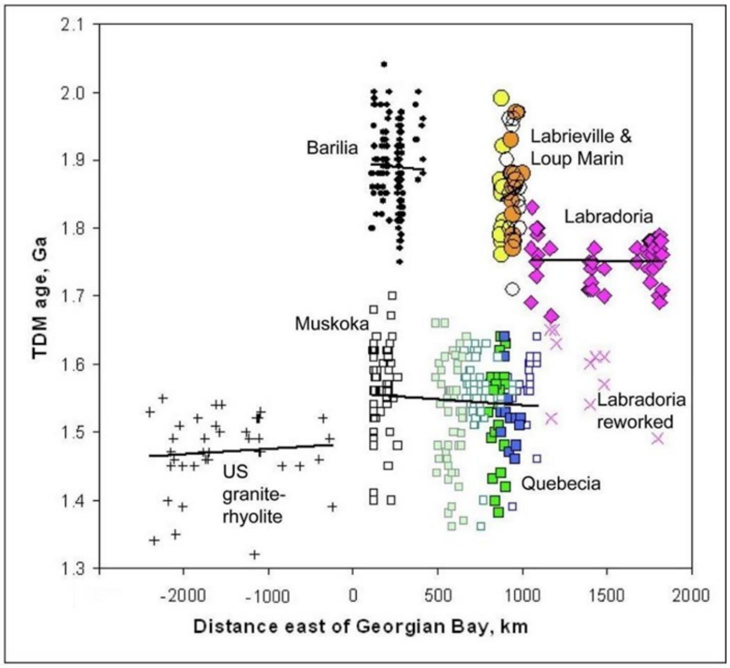

Figure 8. TDM model ages from various studies plotted with respect to the east-west distance across the Grenville Province, where black lines represent regressions within certain units.[3] Obtained from Vautour and Dickin (2019).

From this, it is suggested by Vautour and Dickin (2019) that Quebecia East was originally accreted to the far western portion of the continental margin and was later rifted away, eventually moving eastward to its current location in Quebec.[3] Similarly, the Baie Comeau terrane with the attached Loup Marin block, shown in **Figure 5**, was thought to have originated from a similar process in which the younger terrane was attached to the Paleoproterozoic sliver and was rifted away from the source. However, unpublished data discussed in Vautour and Dickin (2019) indicate a significant level of heterogeneity in the Baie Comeau terrane with respect to isotope signatures in comparison to Quebecia and Quebecia East, indicating that the Baie Comeau terrane may have a different provenance.[3] The current suggestion put forth by Vautour and Dickin (2019) is that it is transported eastwards from an ensialic arc to its current location.[3]

CONCLUSION

The literature pertaining to the Quebecia terrane continues to build from previous studies in order to define the geological events, and hence the provenance, of the terrane. Current literature supports Quebecia as a composite arc belt originating from accreted oceanic arcs with attached slivers of Paleoproterozoic crust.[3,10] The terrane can be further divided based on these slivers into three principle blocks termed Quebecia, Quebecia East and the Baie Comeau.[3] Research is required to fully understand the geological history of the area, the origins of Paleoproterozoic slivers of crust within the terrane, and to increase the resolution of the units identified.

These conclusions are drawn from the identification of old model ages along the Manicouagan river by Dickin and Higgens (1992) in addition to the constraints of the terrane investigated by Dickin (2000) and Vautour and Dickin (2019).[2,3,8] Metamorphism resulting from the Grenville Orogeny renders the use of Nd-isotope signatures and model ages useful to estimate crustal formation ages, as identified by Dickin (2000), Groulier et al. (2018) and Vautour and Dickin (2019).[2,3,13] Delineating the geological history of this terrane requires insight into crustal formation ages rather than igneous crystallization ages determined by U-Pb geochronology.[4,9] However, a combination of crustal formation ages from Sm-Nd dating methods and U-Pb ages related to periods of magmatic activity is useful to form a more complete picture of the combination of formation and accretion events recorded within Quebecia.[3,4,9]

The samples analyzed in this study all yielded Pinwarian TDM models ages. This helps to further define the constraints of previously identified Paleoproterozoic crustal slivers within the Quebecia Terrane. The older crust identified in Hynes (2010) was shown to not continue on the south side of the Saguenay river, allowing the current state of knowledge to be improved and the resolution of the TDM model ages in the Saguenay study area to be increased.[11]

Selecting future regions for analysis by similar means is dependent on previously obtained crustal formation ages to identify areas of interest and uncertainty that require further analysis. As the sampling area did not show TDM model ages consistent with the continuation of the Paleoproterozoic slivers, as suggested in

Figure 6, further research could investigate alternative constraints for these blocks, such as that proposed in **Figure 9**.

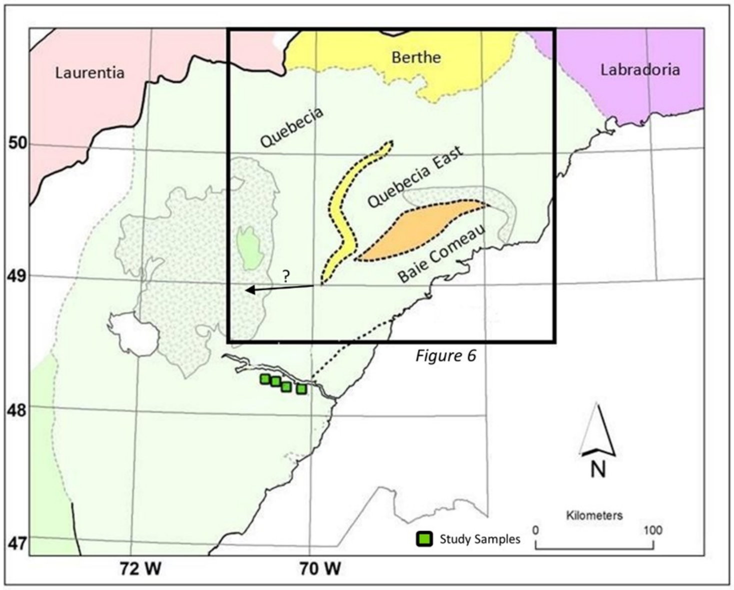

Figure 9. **A proposed future study area to further define the constraints of the Labrieville block.**

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