Nd-Isotope Mapping of the Grenville Province in Southern Labrador

Nd-Isotope Mapping of the Grenville Province in Southern Labrador

By

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ABSTRACT

New Nd isotopic data is presented, with previously published Nd model ages, to create a crustal formation age map that demonstrates the extent of crustal terranes of different ages within the Grenville Province in southeastern Labrador. An unpublished Nd data set from C. Gower was used for comparison with the data from this study. The previous U-Pb data has provided ages that define the geological history of southeast Labrador through four major orogenic events: the Makkovik orogeny (1860-1790 Ma), the Labradorian orogeny (1710-1600 Ma), the Pinwarian (1520-1460 Ma) and the Grenville orogeny (1085-985 Ma) (Gower, 2008). However, the high-grade metamorphism as a result of the Grenville orogeny has obscured the true age of the crustal material that formed the Grenville Province. The crustal formation ages determined through Nd analysis can distinguish boundaries between crustal terranes, even in areas with a complex geological history.

Previous Nd isotopic data included both the Grenville Province to the south, and the Paleoproterozoic Makkovik Province to the north, and demonstrated that older Nd values were located farther south than previously established but were unsuccessful in determining a crustal terrane boundary.

The data from this study provided depleted Mantle model (T_{DM}) age ranges that overlapped from the Hawke River, Lake Melville and Mealy Mountains terranes which suggested that they are representative of one crustal block, which was renamed the Cartwright terrane. This terrane presented an age range of 1.87-1.94 Ga, which may reflect mixing between Pre-Labradorian and Labradorian magmatism. The data from Gower which included the Groswater Bay terrane, displayed a similar age range of 1.90 to 1.97 Ga, also indicating a single crustal source. In contrast, the Pinware terrane falls into two categories in which the northerly portion has Nd signatures similar to those of the Cartwright terrane, and the southern portion has ages indicating a juvenile Labradorian source. A mean Nd model age of 1.77 Ga was recorded for this data set as well as the data from Gower. Therefore the Pinware terrane was divided into north and south domains based on a proposed suture boundary between Gilbert River and Red Bay.

The data presented suggests that the original edge of the Makkovik continental margin passed just north of Red Bay and trends westwards into the interior of southern Labrador. I expect that relatively homogeneous Nd isotope signatures are located to the south of this boundary, whereas heterogeneous signatures are expected to the north.

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I would like to thank Dr. Alan Dickin for his continual support and valued expertise with the subject matter. His passion for exploring the mysteries of the Grenville Province never ceases to amaze or inspire me. I would also like to thank my lab mates over the past two years who have supplied me with a never ending supply of encouragement, especially Esther Moore, who assisted me in my ongoing quest to understand GIS. A thank you also goes out to my friends, for understanding that my inability to socialize at times was not a reflection of my lack of interest, but a commitment to my studies and my family.

I need to express my sincere gratitude to my parents, Scott, and his parents, who made it possible for me to attend school while still trying to be a mom. I also want to thank J, for giving me a quiet place to write, and for keeping me sane during the last two months.

This is for Emma and Evan who are my inspiration for learning, and the reason for pursuing my dreams.

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Chapter 1: Geologic Background

Introduction

The Grenville Province is a Mid-Proterozoic orogenic belt that is the youngest geologic province situated in the Canadian Shield. The province is a result of the accretion of arc terranes to the edge of the active continental margin of Laurentia between 1.9-1.0 Ga. The culmination of this geological history was the Grenvillian collisional orogeny that took place from 1.085-0.985 Ga, and whose metamorphic influence defines the extent of the Grenville Province.

The geological evolution of southeast Labrador, within the Grenville Province, represents a significant period during the formation of the North American shield. Since the whole of the Grenville Province has been subject to multiple orogenies, and the resulting metamorphism has obscured the evidence of individual events, it is important to try to establish the events that shaped this region. The geological history of southeast Labrador is specifically defined by four major orogenic events that occurred in this area. These orogenic events were the Makkovik orogeny (1860-1790 Ma), the Labradorian orogeny (1710-1600 Ma), the Pinwarian (1520-1460 Ma) and the Grenville orogeny (1085-985 Ma) (Gower, 2008).The first three orogenies were accretionary, providing newly formed continental crust, and subsequently reworking the pre-existing crust. The Grenvillian orogeny was collisonal, which resulted in less significant additions of juvenile crust, but produced extensive metamorphism of the entire region. This extensive metamorphism obscures the crystallization ages of the previous orogenic collisions, making it complicated to decipher the geologic history.

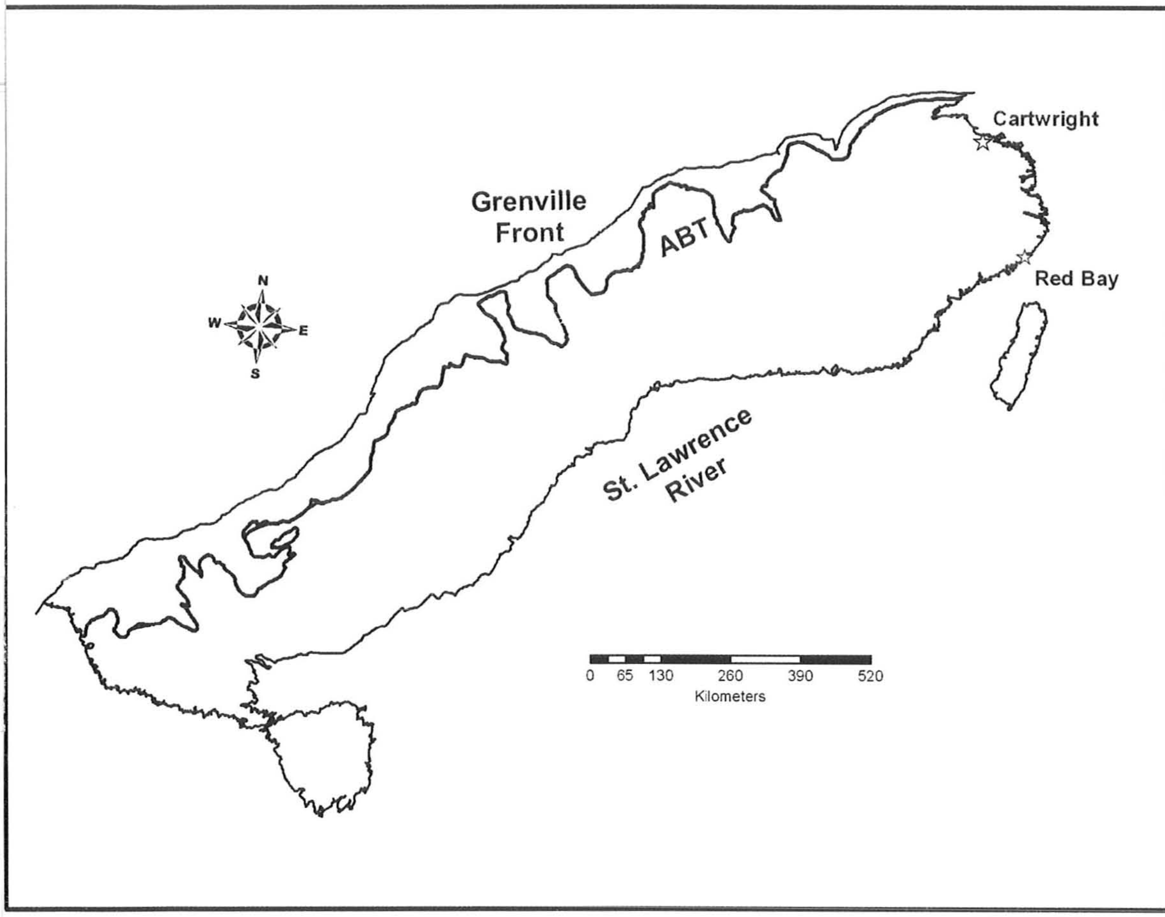

Figure 1.1 Image of the Grenville Province. The location of the study area is within southeast Labrador, between the cities of Cartwright and Red Bay.

The Grenville Province in southern Labrador has been divided into successive lithotectonic terranes with unique nomenclature, ending at the Grenville front (the northern extent of the geologic Province). These terranes are the results of the Grenville orogeny, and are not to be confused with the pre-Grenvillian history of the continental margin. These lithotectonic terranes are: The Groswater Bay, Hawke River, Lake Melville, Mealy Mountains, and the Pinware Terrane.

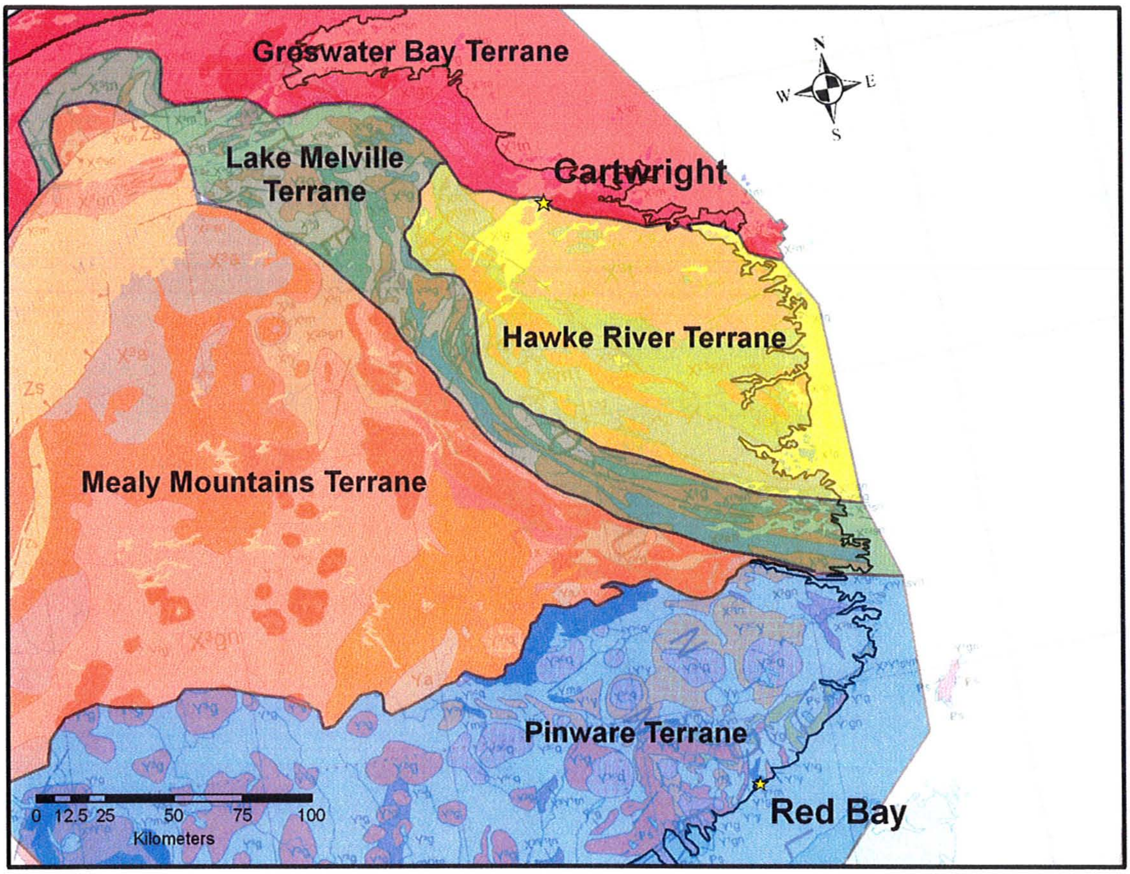

Figure 1.2 Nomenclature for Grenvillian lithotectonic terranes is illustrated: **Groswater Bay Terrane, Hawke River Terrane, Lake Melville Terrane, Mealy Mountains Terrane, and the Pinware Terrane.**

To reconstruct the pre-Grenvillian geologic events that occurred in southeast Labrador, a crustal formation age map can be used to demonstrate the extent of crustal terranes of different ages. Crustal formation mapping determines when crust was extracted from the mantle, and allows individual events to be established. Nd isotopic dating can be used to determine the age when the protolith of the sampled gneiss was removed from the mantle, thereby allowing a crustal terrane boundary to be defined. The Nd model age dating technique is an ideal method to map crustal formation ages, since Nd can remain chemically immobile during orogenic processes (Dickin, 2005). This method is extremely functional in the Grenville, where much of the province has undergone high-grade metamorphism. The crustal formation ages determined through Nd analysis can distinguish boundaries between crustal terranes, and assist in identifying the pre-Grenvillian history of southeast Labrador.

Previous research in eastern Labrador has led to a scattered database of Nd isotopic data that include both the Grenville Province to the south, and the Paleoproterozoic Makkovik Province to the north. A few Sm-Nd isotopic values have also been presented for the eastern Grenville Province by Prevec et al. (1990), Scharer (1991), and Dickin (2000). These studies demonstrated that older Nd values were located south of the Grenville Front, although a clear definition of where the crustal terrane boundary was located was not understood. Using the preceding Nd database for eastern Labrador, as well as new data accumulated for the region previously not investigated, the enlarged Nd data set will allow for a more comprehensive view of the geologic history for this area.

Regional geology

Periods of crustal growth and crustal reworking are usually accompanied by igneous intrusion, which can be dated by the U-Pb method. Therefore, in order to properly interpret Nd isotope data in a region with complex geological history, it is necessary to summarize this history, as understood from igneous crystallization ages.

The Makkovik Orogeny

To comprehend the early development of the southern margin of Laurentia, the investigation must begin beyond the northern limits of the Grenville Province. The Makkovik Province is part of a Paleoproterozoic accretionary orogen that correlates with the Ketilidian mobile belt that is located in southern Greenland, and is thought to have begun its development around 2.0 Ga, as a Pacific-type active continental margin (Figure 1.3) (Ketchum et al., 2002). U-Pb ages that have previously been reported for the Makkovik Province, record the evolution of the growth of the craton, prior to, during and post Makkovikian orogeny.

The Province is broken down into three domains based on lithological variations or tectonic events. These domains (located from the northwest to the southeast) are: the Kaipokok, the Ailik, and the Cape Harrison (Figure 1.4). The northern most domain, the Kaipokok, is considered to be comprised of mostly Archean crust that has its origins from the Nain Province to the north. It is overlain by both volcanic and sedimentary strata, and is recognized as the foreland zone for the Makkovik Province (Ketchum et al., 2001). This is in contrast to the Ailik and Cape Harrison domains which are comprised of Paleoproterozoic supracrustal and plutonic rocks.

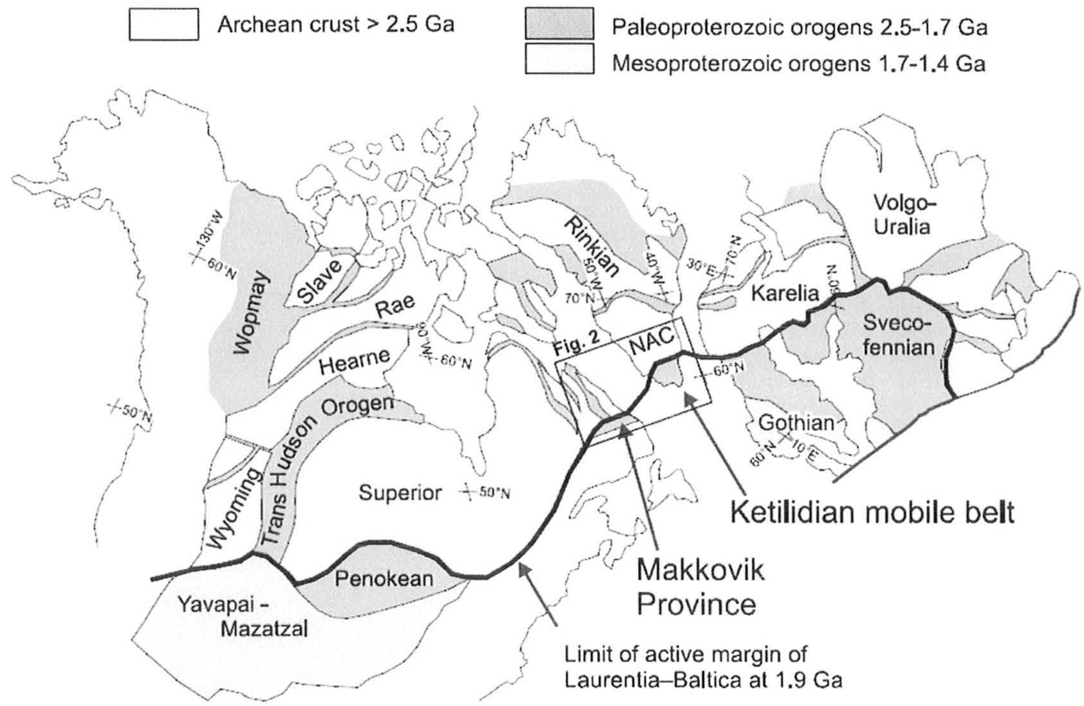

Figure 1.3 Map of Laurentia and Baltica. Selected area indicates the region identified as the Makkovikian-Ketilidian orogenic belt, and the dark line represents the location of the active margin at 1.9 Ga. (Ketchum et al., 2002)

U-Pb ages for the Makkovik Province support the structural evidence for a distinct boundary between the Kaipokok domain, and the Ailik and Cape Harrison domains. An age of 2813 $\pm^{16}_{13}$ Ma is recorded for reworked Archean gneiss in the Kaipokok domain, where as granitoid plutons within the region reflect younger intrusions whose dates are within the 1895-1870 Ma age range (Figure 1.4). Conversely, Archean ages are not seen in the Ailik and Cape Harrison domains. The structural evidence of this distinction is seen through a region of high-strain shear zones which are named the Kaipokok Bay Shear Zone (Figure 1.4) (Ketchum et al., 2002)

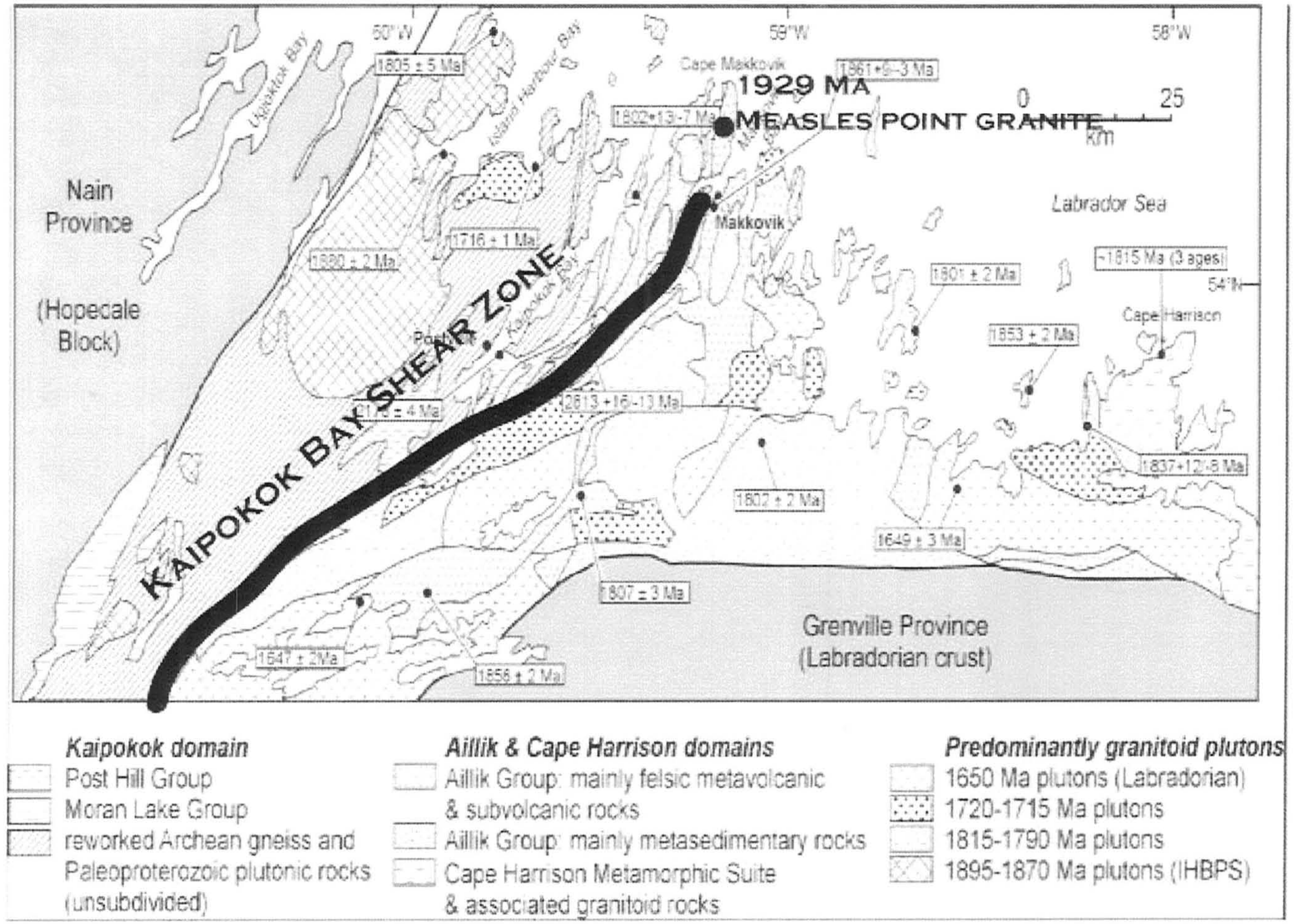

Figure 1.4 U-Pb ages reported for the major lithologic and lithotectonic units of the Makkovik Province. After Ketchum et al., 2002.

Investigating the Nd evidence within the Makkovik Province, studies done by Kerr and Fryer (1993, 1994) indicate that significant amounts of juvenile mantle derived crust were added to the Archean craton during 1800-1720 Ga, clearly defining a crustal terrane boundary between the juvenile Proterozoic, and the Archean. This is also demonstrated by offshore drilling data (Kerr and Wardle, 1997) that confirms the transition between "juvenile Proterozoic crust in the southeast to ancient Archean crust in the northwest". The Nd data support the U-Pb ages that indicate the presence of Archean rocks in the Kaipokok domain, and the boundary between the Kaipokok and the Proterozoic Ailik and Cape Harrison domains.

Unlike the Kaipokok domain, the Ailik and Cape Harrison domains are not derived from an Archean source, but have Paleoproterozoic origins. These domains are considered to represent juvenile arc (Ailik domain) and rifted arc material (Cape Harrison domain) that were accreted to the Nain craton during the Makkovikian orogeny (Ketchum et al, 2001). Syn and post orogenic plutons are abundant through the Ailik domain and are predominant in the Cape Harrison domain.

Ketchum et al., (2002), developed a tectonic model illustrating the development of the Ailik and Cape Harrison groups as they were accreted to the Archean rocks of the Kaipokok domain. The model is clearly outlined in six phases of development, as illustrated in figure 1.5.

Prior to 2.013 Ga, an island arc complex was formed offshore of the continental margin, and foredeep sedimentation had begun along the passive margin. This is documented by detrital zircons from the Post Hill foredeep sediments which provide an age range of 2.15-2.0 Ga. The island arc was then accreted to the craton by 1.895-1.870 Ga, which resulted in a switch to cratonward subduction, and initiated continental arc plutonism. At 1.860-1.850 Ga, the Ailik Group (metasediments and metavolcanics) were deposited in a retro arc foreland basin. By 1.815-1.800 Ga, the Cape Harrison Metamorphic Suite had been generated. Ketchum et al., (2002) suggests that this terrane could be a secondary arc that would have been accreted to the margin. This theory is based on the composition of arc-like rocks that make up the Cape Harrison Metamorphic Suite. They also propose that the accretion of this arc may have caused a tectonic inversion of the Ailik basin. In the last two steps, at 1.80 Ga, and 1.74-1.70 Ga, we see the introduction of syn to post collisional granitoid plutonism, and then subsequent A-type granitoid plutonism, indicating that subduction has terminated. Evidence of active subduction is recorded for this time period to the southeast (Culshaw et al., 2000a).

Although this tectonic model uses U-Pb dates to constrain its ages, there are several assumptions that have been made. The model postulates that an approaching arc occurs sometime after 2.013 Ga, there is no documented crust of 2.15-2.0 Ga within the Makkovik Province. The only event that is documented for this time period (prior to 1900 Ma), is the U-Pb zircon age of $1929 \pm {}^{10}{}_{9}$ by Sinclair et al., 2002, for the Measles Point Granite (Figure 1.4).

Although the tectonic model of Ketchum et al., (2002) is not completely supported by the known published U-Pb ages, the evidence from both the U-Pb data of Ketchum et al, (2002), and Sinclair et al., (2002), and the Nd evidence by Kerr and Fryer (1993, 1994), and Kerr and Wardle (1997), agree that the development of the Makkovik Province includes both an Archean component to the north, and a Proterozoic source in the south.

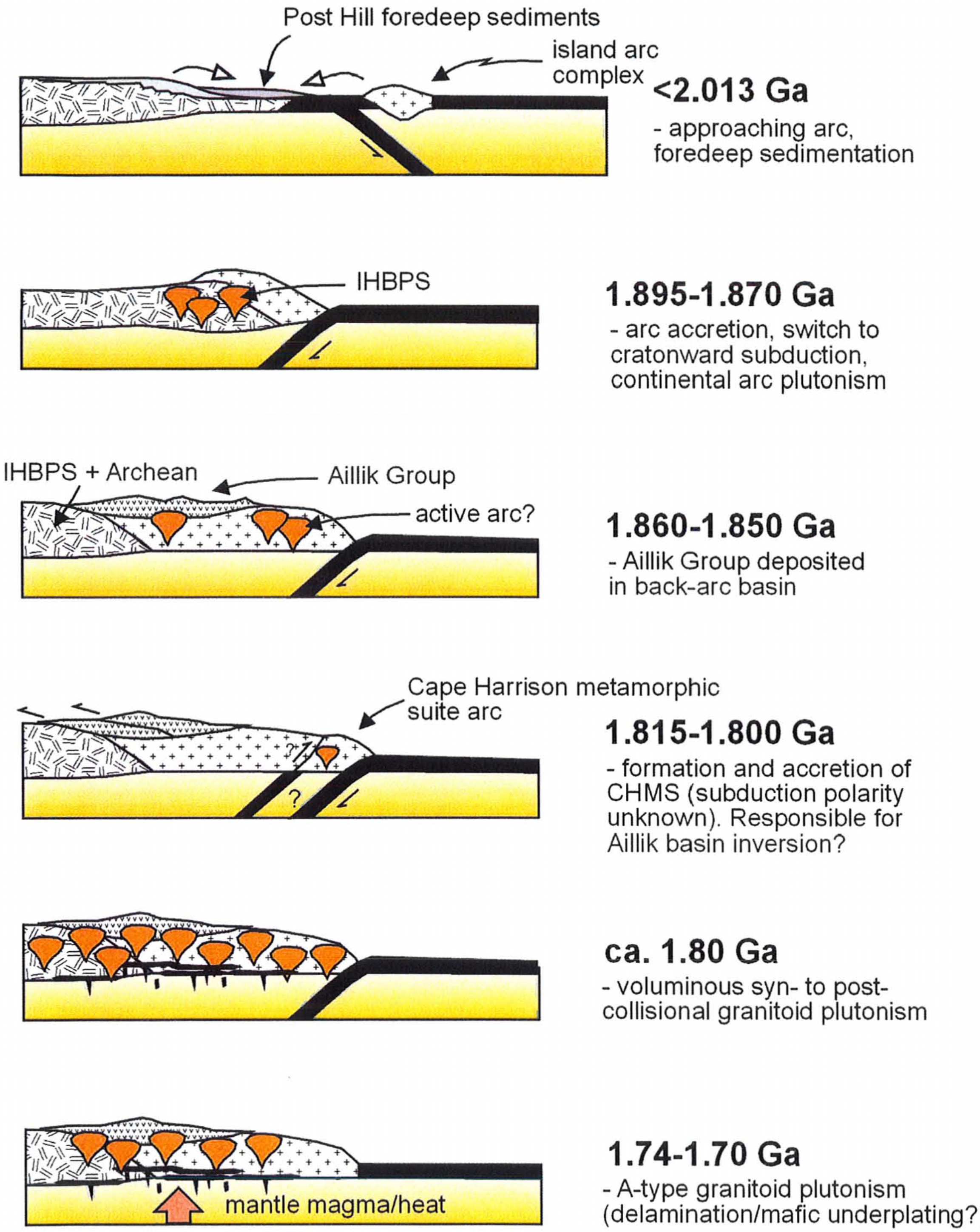

Figure 1.5 Orogenic model of the crustal development for the Makkovik Province, with age constraints based on the current U-Pb data. Transpressional shear zones are not included in this diagram. IHBPS = Island Harbour Bay Plutonic Suite (Ketchum et al., 2002)

The Labradorian Orogeny

It has been previously explained that southern Labrador was affected by the Makkovikian, Labradorian, Pinwarian and Grenvillian orogenies. While the region has been identified as part of the Grenville Province based on the extent of Grenvillian metamorphism, understanding the effects of the three previous orogenies has been the focus of many geochronologists. Since the history of the Makkovik orogeny was assumed to be confined to the north in the Makkovik Province, the main objective of many researchers was to establish the spatial extent of the Labradorian orogeny.

As early as 1986, U-Pb ages for the Labradorian orogeny were established by Scharer et al. and in 1988 by Scharer and Gower, to extend across the complete width of the southern Labrador region.

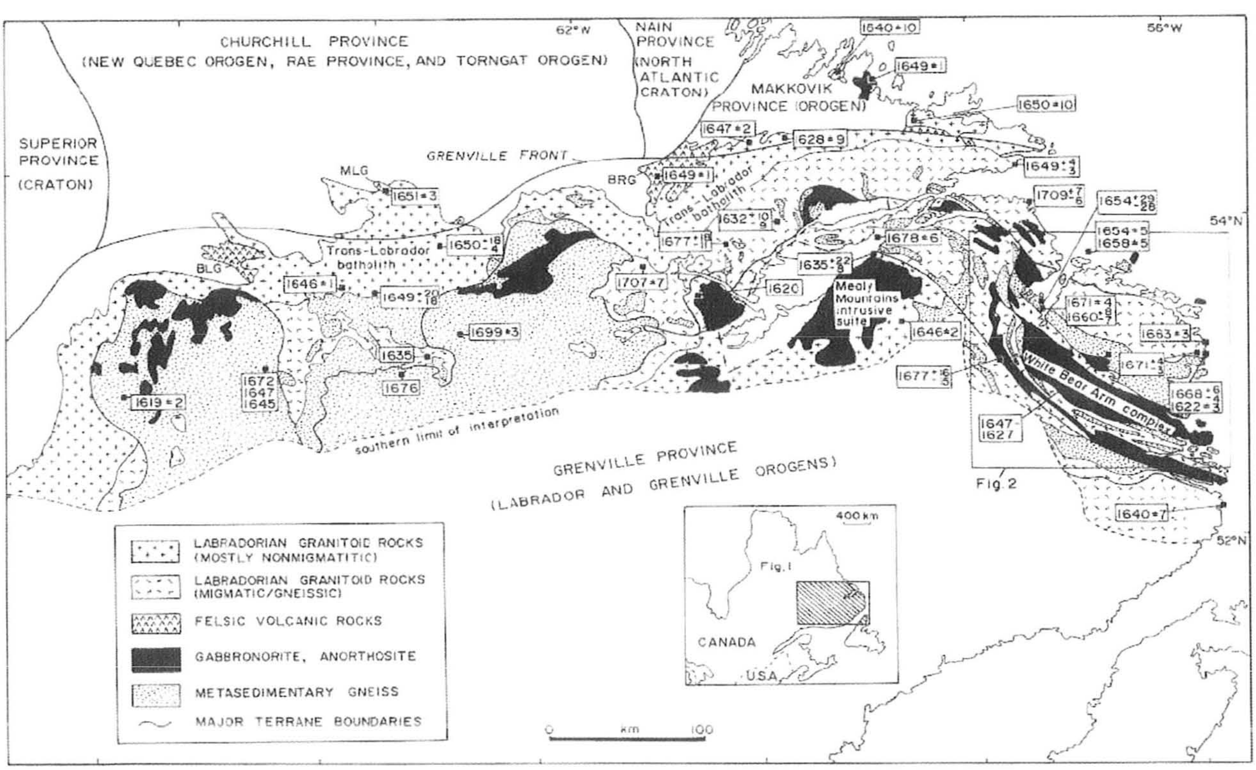

Figure 1.6 U-Pb data illustrating the distribution of Labradorian crust in the eastern Grenville Province. (Gower et al., 1992)

With this data, the orogenic period was then confined between 1710 and 1620 Ma. This evidence was also confirmed by later studies done by Kamo et al, (1996), who studied the Hawke River and Groswater Bay terranes in detail (Figure 1.7), concluding that a major migmatizing event occurred in 1665 ±3 Ma, indicating that the effects of Labradorian plutonism occurred as far north as the Trans-Labrador Batholith (south of the Grenville front, located within the Groswater Bay terrane). Kamo et al., (1996) interpreted this evidence to indicate that the Groswater Bay and Hawke River terrane were "a single crustal entity linked to pre-Labradorian Laurentia from 1663 Ma onwards" (Kamo et al, 1996). To the south, U-Pb analysis by Wasteneys et al., (1997), confirmed the presence of Labradorian age crust throughout a large extent of the Pinware terrane, and assisted in corroborating that Labradorian age crust was present across the extent of the southern Labrador region.

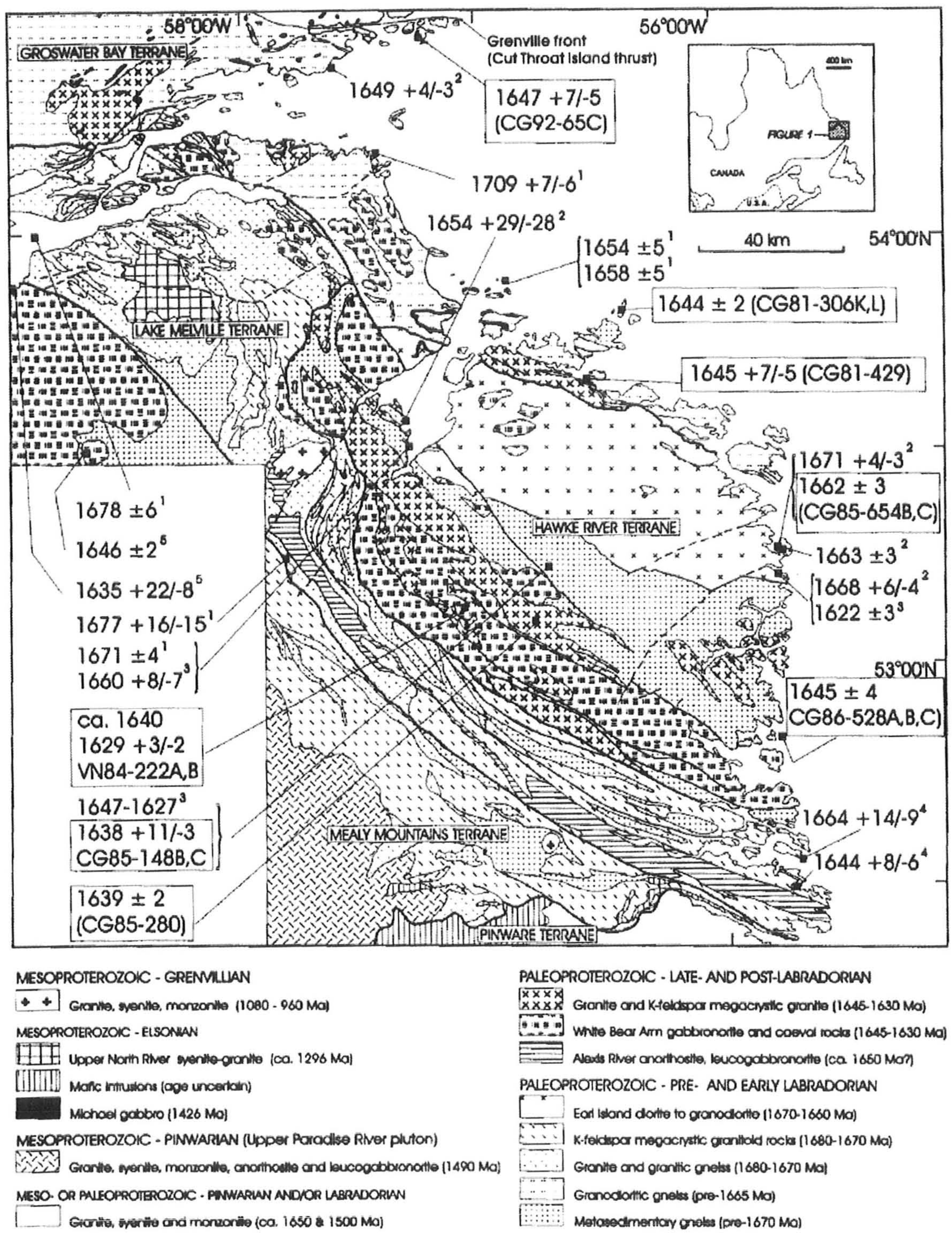

Figure 1.7 U-Pb values for samples from Kamo et al., 1996, within the Groswater Bay and Hawke River terranes, and the regional geology of the eastern Grenville Province. (Kamo et al., 1996)

In 2002, Gower and Krogh proposed a tectonic model for the evolution of the Labradorian orogeny, based on previous U-Pb ages collected across the Grenville Province. The tectonic model is broken into five stages of development, ranging from 1680 Ma to 1600 Ma (Figure 1.8).

At approximately 1680 Ma, a Pre-Labradorian arc had already been formed and was undergoing calc-alkaline magmatism, located to the south of the Laurentian margin. This arc then collided with the craton between 1665 and 1655 Ma, based on the high grade metamorphism recorded during this time. This collision initiated the Trans-Labrador batholith magmatism (1654-1646 Ma), which Gower and Krogh (2002) propose is the result of melting due to crustal thickening. They also suggest that southward dipping subduction also halted at this time.

By 1630 Ma, trimodal mafic-anorthositic-monzogranitic magmatism formed the rocks that were the later products of crustal thickening. Lastly, by approximately 1600 Ma, the crust became stable, and sediment began to accumulate when subduction had halted.

Using Gower and Krogh's tectonic model, combined with the geographical age distribution (Figure 1.7) of Labradorian crust, and other previous U-Pb studies by Kamo et al., (1996), and Wasteneys et al., (1997), geochronologists began to define the extent of the effects of the Labradorian orogeny throughout the southeast Labrador region.

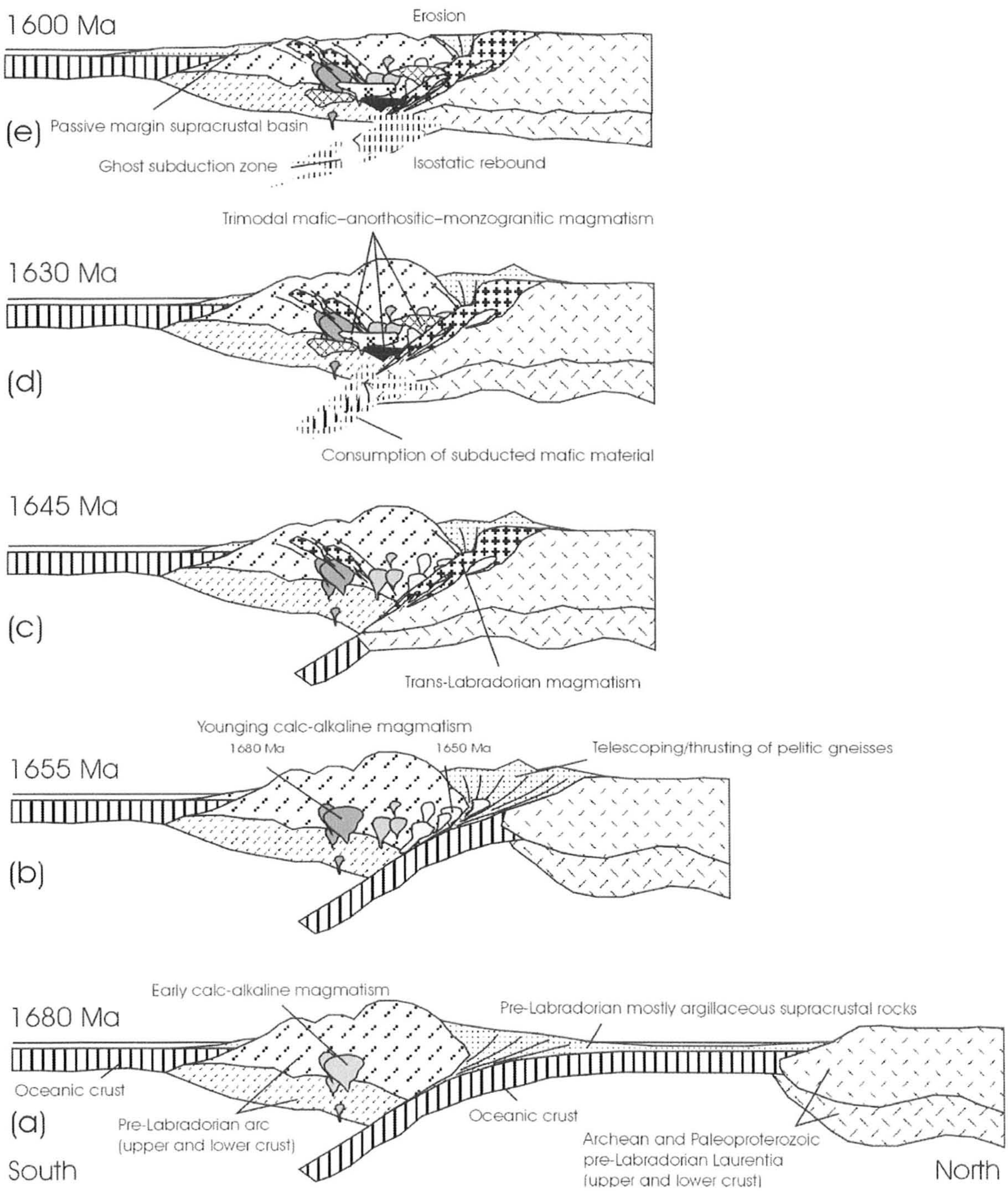

Figure 1.8 Gower and Krogh's tectonic model for the evolution of the Pre-Labradorian and Labradorian orogeny within the eastern Grenville Province. (Gower and Krogh, 2002)

The Extent of Pre-Labradorian Crust in the Grenville Province

Although there was now a general consensus among geochronologists that the entire southern Labrador region had been affected by the Labradorian orogeny, the extent of Pre-Labradorian crust within the Grenville Province was unclear. Although there were some earlier U-Pb and Sm-Nd data that suggested the presence of older age derived crust within the eastern Grenville Province, Gower and Krogh, (2001) stated that previous studies had failed to present conclusive evidence for any "appreciable volume of old crustal material".

A study using Nd analysis by Scharer, (1991), presented model ages indicating the possibility of Pre-Labradorian origin in rocks taken from the Groswater Bay terrane. Scharer reported his Nd-analysis data alongside U-Pb ages to act as a constraint, but interpreted his Sm-Nd data to be identical to the U-Pb data, suggesting that the rocks were the same isochron age of 1.72±0.066 Ga. Scharer's theory that the data were consistent with juvenile crust formation of the Labradorian age is questionable due to extreme outliers in the data set. Nd model ages of 1900 Ma and higher were removed from the conclusions based on the theory that the crust came from an abnormal source, chondritic in nature, and was, therefore, not a depleted mantle source, but gave no evidence to support this in his research. If the 1900 Ma and older data points were included, Scharer would have needed to consider a crustal source other than the Labradorian orogeny for the northern portion of the Grenville Province

The presence of Pre-Labradorian ages within the Grenville Province was also established by U-Pb analysis by Philippe et al., (1993), and Wasteneys et al., (1997). Philippe et al., (1993) found U-Pb ages of 1712, 1754 and 1775 Ma for rocks within the

Mealy Mountains, but interpreted the data to represent the oldest section of Labradorian crust. This assumption was premature, and with further research, Philippe et al., (1993) may not have come to this conclusion. Wasteneys et al., (1997), discovered the presence of inherited 2.1 Ga zircons in an orthogneiss within the Pinware terrane which was suggestive of the existence of pre-Labradorian crust in the area. Both of these studies were early indicators of the existence of Pre-Labradorian crust within the eastern Grenville Province, but were overlooked due to misconceptions about the events that could have occurred prior to the Labradorian orogeny.

Dickin, (2000), used Nd-isotope data with U-Pb ages as a constraint to give a more accurate crustal formation age of the southern Labrador area, which led to the hypothesis that older Pre-Labradorian crust was indeed present in the eastern Grenville. His research contradicted Scharer's Nd analysis by pointing out a possible error in methodology. Scharer used mineral separates in his data for the Sm-Nd isochron, but because of the uncertainty of fractionation in rare earth elements during the melting phase, a coherent crustal formation isochron could not be resolved. Dickin then proposed an important terrane boundary between older crust that was derived from the Makkovikian orogeny (≈1.9 Ga), and the juvenile Labradorian crust (≈1.7 Ga) (Figure 1.9). This proposed boundary separated the Mealy Mountain terrane and the rest of the Grenville lithotectonic terranes to the north as Paleoproterozoic crust (termed Makkovikia), and the Pinware terrane as juvenile Proterozoic crust (Labradoria).

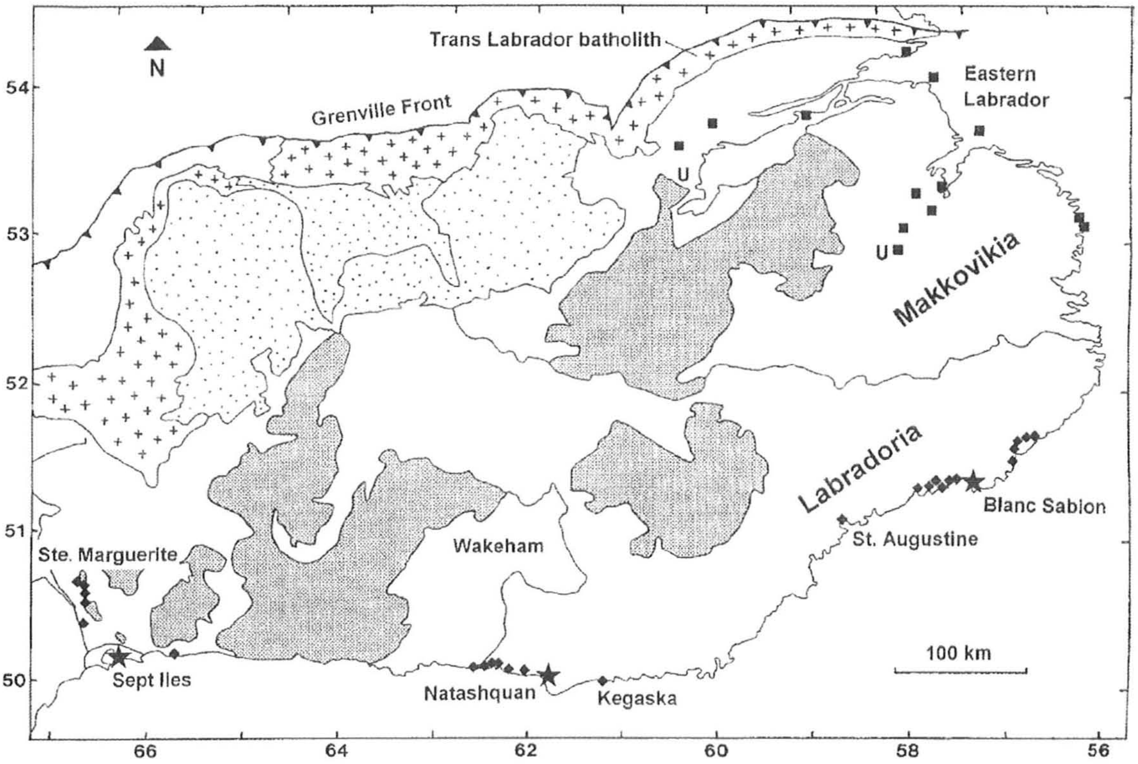

Figure 1.9 Crustal formation age map illustrating Dickin's proposed boundary between Makkovikia and Labradoria. The region with crosses represents the Trans Labrador Batholith; the light stipple, metasedimentary rocks, and the darkly shaded areas represent anorthositic rocks. (Dickin, 2000)

In the last decade, more recent evidence of the existence of older dates within the southeast Labrador region came from Krogh et al., (2002), and Gower et al., (2008). Krogh et al.,(2002), recorded an older U-Pb age for a location south of the Grenville front, dated at $1799\pm_{2}^{3}$ Ma, which had no evidence of Pb loss, indicative of the absence of subsequent metamorphism by later orogenies. This date confirmed the presence of older pre-Labradorian crust in a location south of the Makkovik Province. This was also corroborated by Gower et al., (2008) whose U-Pb study presented samples of Pre-Labradorian crust with an age range of 1800-1770 Ma within the Mealy Mountains terrane. The studies by Gower et al., (2008), and Krogh et al., (2002) combined with earlier U-Pb and Sm-Nd data indicates that although the presence of older dates within the eastern Grenville Province have now been established, the extent of Pre-Labradorian crust has not been determined for this region in southeast Labrador.

The Pinwarian Orogeny

The Pinwarian orogeny, which affected the Grenville Province in southeast Labrador, was first recognized as the "Pinwarian event" by Tucker and Gower in 1994. This widespread granitoid plutonism was dated by the U-Pb method which gave ages of 1490 ±5 Ma for a quartz monzonite and 1479 ± 2 Ma, and 1472 ± 3 Ma for two granitoids located in the Pinware terrane.

The Pinwarian event was officially upgraded to orogenic status by 1997, when Wasteneys et al., (1997) provided evidence of high grade metamorphism from a migmatitic quartz monzonite which gave an age of $1450\pm^{15}_{21}$ Ma. This was confirmed by Heaman et al., (2004), who stated that "significant deformation and amphibolite to granulite facies metamorphism were also involved", in the Pinwarian and that this was evidence to support the idea that the event should be considered an orogeny. The Pinwarian orogeny was seen to have affected much of the eastern Grenville Province, but especially within the southern region of the Pinware terrane. Although previous models suggest a continental margin arc tectonic setting, Heaman et al., (2004) claim that no juvenile Pinwarian crust has been detected within the eastern Grenville Province. Interestingly, Dickin, (2000) reported a significant crust forming event at 1.55 Ga, which he termed Quebecia, which is located to the west of the Pinware terrane.

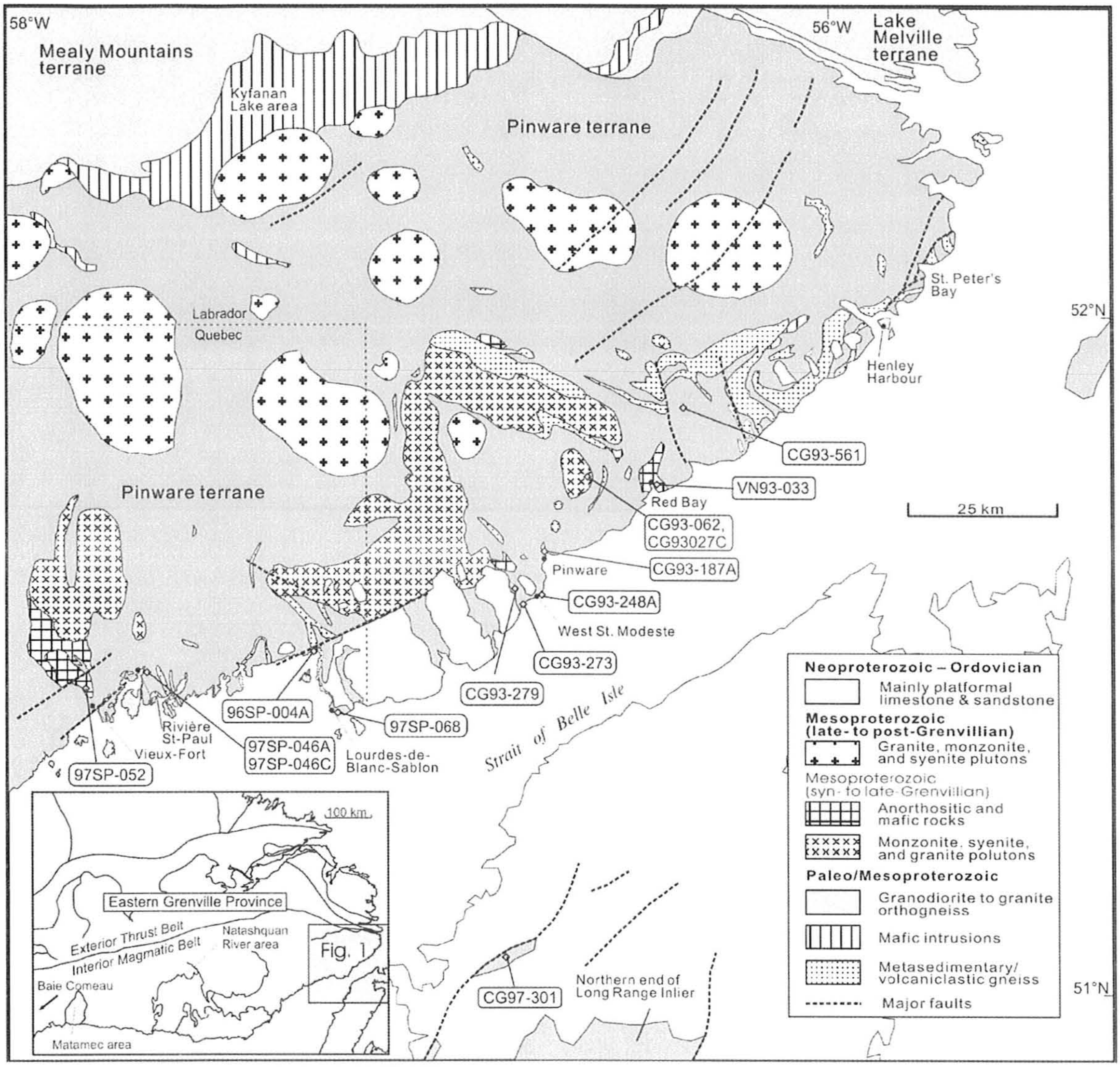

Figure 1.10 Location of samples taken by Heaman et al, within the Pinware terrane of southeastern Labrador. (Heaman et al., 2004)

With the intent to identify the extent of Pre-Labradorian, Labradorian and Pinwarian crust within the eastern Grenville Province, a large scale detailed U-Pb study was conducted by Gower et al., (2008), which proposed a newly defined Labradorian-Pinwarian crustal boundary. This study provided evidence for the extent of the effect of Pinwarian magmatism within the southeast Labrador region.

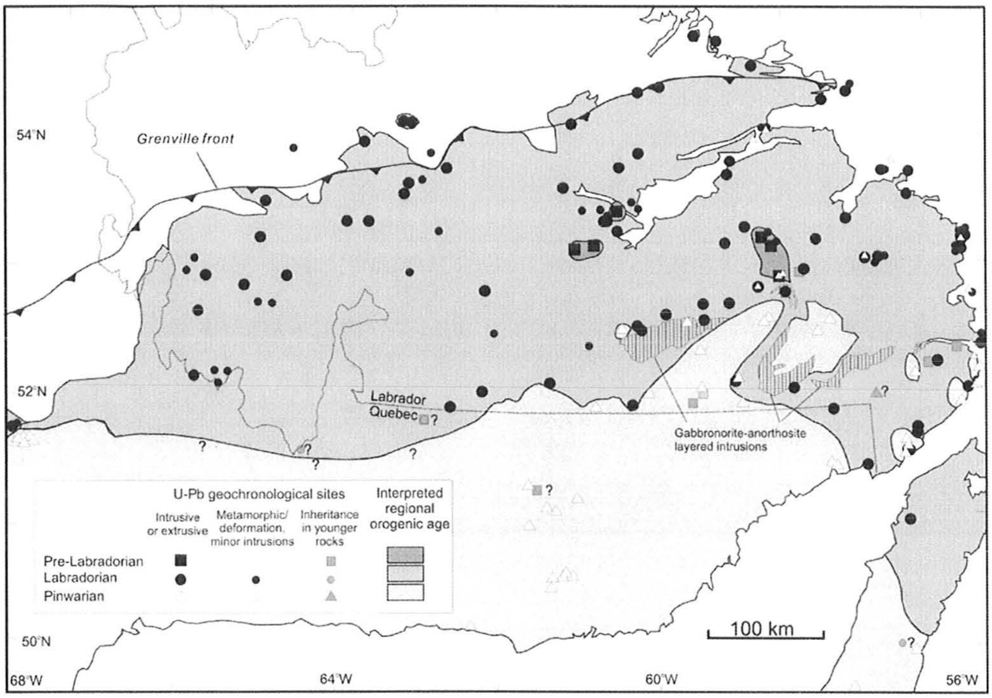

Figure 1.11 Illustration of the eastern Grenville Province defining the extent of Pinwarian orogenic magmatism. (Gower et al., 2008).

The Grenvillian Orogeny

The Grenville Province in southeast Labrador is defined by the effects of the Grenvillian orogeny that took place between 1085Ma and 985 Ma (Gower et al., 2008). Although the province consists of lithologic units that date from the Archean to the Late Mesoproterozoic, the structural configuration of the geological province that is recognized today resulted from a continental collision between the southeastern margin of Laurentia and the continent of Amazonia (Figure 1.12). Windley, (1986) used the Himalayas as a modern analogue for the Grenville orogeny comparing the continental collision of Laurentia and Amazonia with the continent of India colliding into the Asian plate. This early interpretation of the tectonic events that occurred during the Grenville orogeny sparked the interest of structural geologists who began to search for geological evidence which would provide a more comprehensive view of the tectonic processes that shaped the Grenville Province.

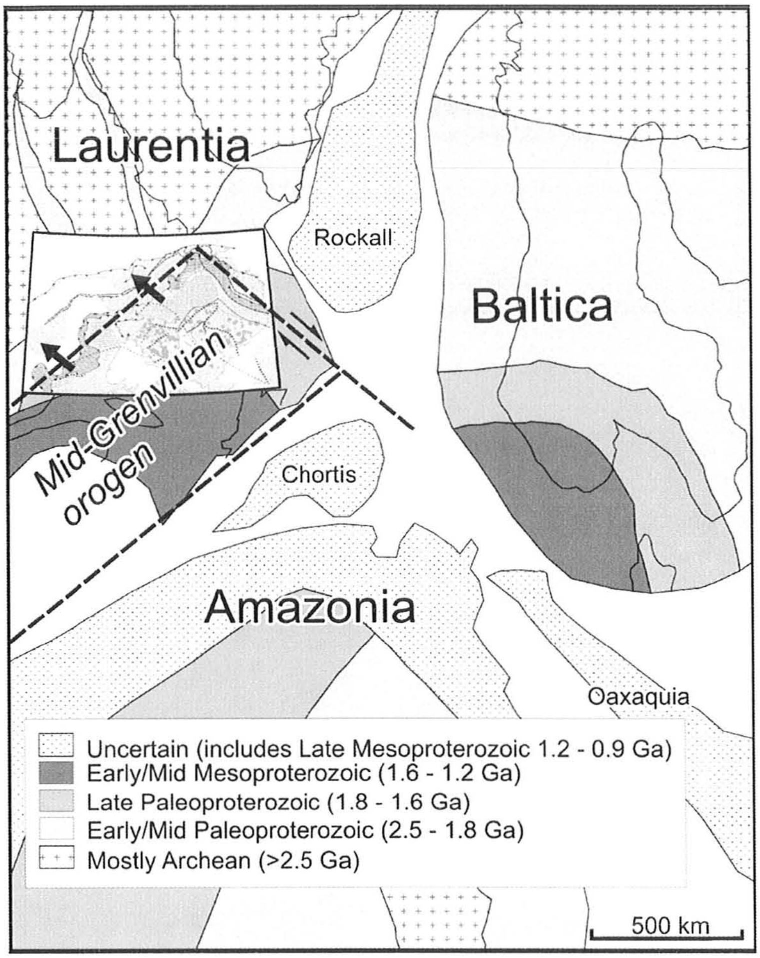

Figure 1.12 Reconstruction of the junction between the continents of southeastern Laurentia, Amazonia and Baltica. (Gower et al., 2008)

Gower (2005) reconstructed the geologic events of the Grenville orogeny by investigating the displacement of lithotectonic terranes in the southeast Labrador region through the evidence of kinematic structural data. His focus was on the area of the St. Lewis River Inlet, which is situated between three Grenville-age lithotectonic terranes: Lake Melville, Mealy Mountains and the Pinware Terrane (Figure.1.13) (Gower, 2005).

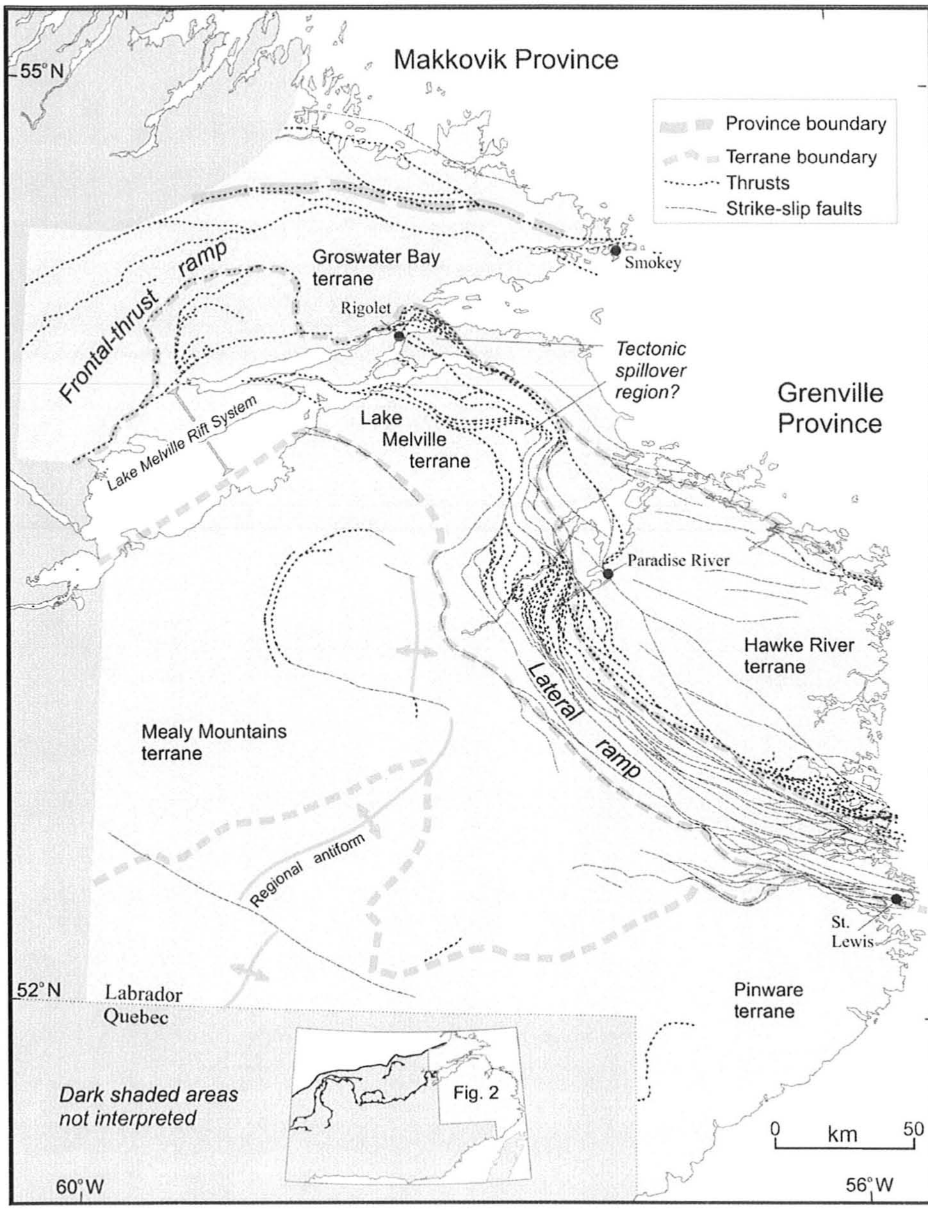

Figure 1.13 Major structural features within the eastern Grenville Province in southeast Labrador. (Gower et al., 2008)

The Lake Melville terrane north of the St. Lewis Inlet contains a highly sheared zone that Gower *et al.* (1987) termed the Gilbert River shear belt (subsequently named the Gilbert River belt by Hanmer and Scott (1990)). He reported "dextral transcurrent shear-sense" kinematic indicators in the Lake Melville terrane, relative to the Pinware terrane in the south. In addition, Gower mapped the boundary between the Pinware terrane and the

Mealy Mountains (southwest of the St. Lewis River Inlet) as a zone of thrusting (Gower, 2005). Here, he proposed that the Mealy Mountains terrane was thrust to the southeast over the Pinware terrane. However, there is also a thin sliver of the Mealy Mountains terrane that appears to extend eastwards from the thrust zone and run between the Pinware and the Lake Melville terranes. Hence, this sliver of the Mealy Mountains terrane has a similar sense of shearing to the Gilbert River shear belt. The strike-slip fault that trends down the St. Lewis River Inlet (the Long Harbour fault) actually runs between the Pinware and the Mealy Mountains terranes (Figure 1.14).

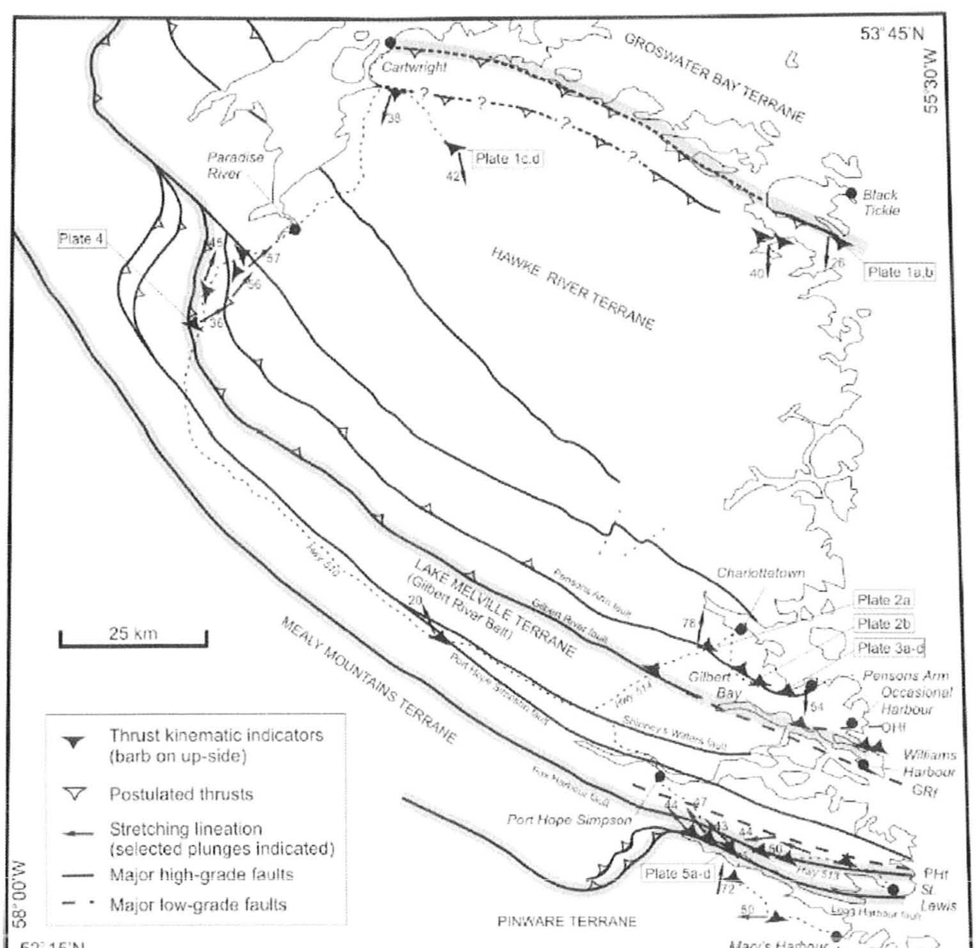

Figure 1.14 Locations of thrust-sense and oblique-slip shear indicators taken within the Gilbert River shear belt. (Gower, 2005)

This structural interpretation of the St. Lewis River Inlet provides evidence that major tectonic movements occurred on two separate boundaries. However, Gower (2008) has argued that these motions can be related, using an Indentor Model for the eastern Grenville province. In this model, the dextral motion of the Gilbert River Belt is attributed to lateral 'escape' of crustal units that were sandwiched between two converging continental masses. According to this model, the thrusts in the NW part of the study area represent crustal ramps which likewise provide an 'escape route' for the Mealy Mountains crustal block.

Gower et al., (2008), used this indentor tectonic model to reconstruct the geologic events that took place in the eastern Grenville Province during the Grenvillian orogeny. He used the Himalayan-Tibet tectonic system as a modern analogue for the Grenvillian orogeny with respect to the eastern Grenville Province. In contrast to Quebec and central Labrador where this resulted in frontal-thrust ramp tectonics, the region of eastern Labrador is shown to represent a "dextral strike-slip, lateral-ramp regime" which is translated as the indentor corner. Although there are similarities between the eastern Grenville Province and the Himalayas, the Himalayan-Tibet tectonic system is a result of India being subducted under the Asian plate, where as the crust of the eastern Grenville Province was thrust over the Laurentian continental plate. Using this analogy, if a cross section of the north to south section for the Grenville Province is compared with the reverse (south to north) section of the Himalayas, the tectonic elements are very similar (Figure 1.15).

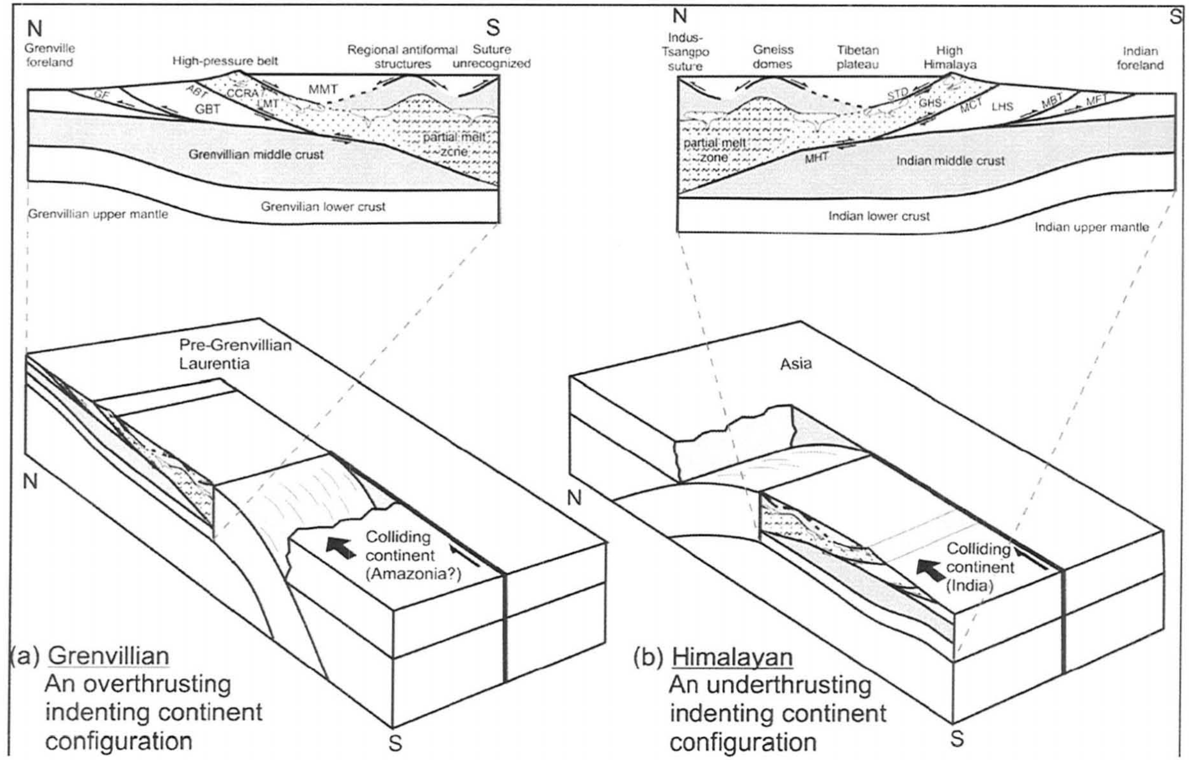

Figure 1.15 Block diagram illustrating subduction of the Indian plate versus the overthrusting of the indenting crust of the eastern Grenville Province. Abbreviations for Labrador portion; GF: Grenville Front; ABT : Allochthonous Boundary Thrust; CCRA : Cape Caribou River Allochthon; LMT : Lake Melville terrane; MMT : Mealy Mountains Terrane. Abbreviations for the Himalayas, GHS: Greater Himalayan sequence; LHS: Lesser Himalayan sequence; MBT: Main Boundary thrust; MCT: Main Central thrust; MFT: Main Frontal thrust; MHT: Main Himalayan thrust; STD: South Tibetan detachment system. (Gower et al., 2008)

Chapter 2: The Sm-Nd Dating Method

Introduction

The formation of continental crust requires melting of the mantle, thereby releasing lighter less dense material that will be unable to undergo subduction. This can occur in volcanic arcs, which are then subsequently accreted to existing cratons. Over time, as more arcs are accreted to the craton tectonically, the resulting continents are also subjected to collisions, which can also form new crust magmatically. The resulting magmatism and metamorphism of multiple accretions and orogenies that occurred during the history of the formation of the North American craton make it difficult to define the individual crust forming events.

To define the boundaries of each successive addition of new crust to the southeastern Labrador region, the crustal formation ages, or the time the crust was extracted from the mantle, must be established. The U-Pb method which is used for most geochronological studies, defines the crystallization age, but this may be much later than the original time of formation of the crust in any particular area. Since the Grenville Province in southeast Labrador has undergone many orogenies, the Sm-Nd method is an ideal choice to determine the crustal formation ages of individual crustal segments, because the Sm-Nd system is resistant to resetting during metamorphic episodes.

The Sm-Nd Dating Method

Samarium (Sm) is a rare earth element (REE) that has seven naturally occurring isotopes. The Samarium isotopes, ^{147}Sm, ^{148}Sm and ^{149}Sm are radiogenic, and decay into Neodymium (Nd). ^{147}Sm and ^{148}Sm decay to ^{144}Nd and ^{145}Nd respectively, but do not produce measurable variations in the daughter isotope abundances due to their extremely long half-lives of 1 x 10^{16} years (DePaolo, 1988). The samarium isotope ^{146} Sm has a relatively long half-life of 103 Myrs, but Sm/Nd fractionation does not occur within a few hundred million years of the nucleosynthesis of Sm. However, ^{147}Sm has a half-life of 106 Ga, and can produce measurable changes in the abundance of ^{143}Nd over millions of years (Dickin, 2005).

Neodymium (Nd) has three naturally occurring isotopes that are the products of radioactive decay of Samarium (Dickin, 1997). Of these three, ^{144}Nd decays to ^{140}Ce and has a half-life greater than 1 x 10^{14} years. This has resulted in a 1.5 x 10^{-4}% decrease in the abundance of ^{144}Nd throughout the history of the earth (Depaolo, 1988). Since ^{144}Nd has a relatively constant abundance, we can use this isotope to normalize the Sm-Nd decay system.

We can use the present day sample ratios of ^{143}Nd/^{144}Nd and ^{147}Sm/^{144}Nd and the initial isotopic ratio of ^{143}Nd/^{144}Nd to analyze the decay of ^{147}Sm to ^{143}Nd. The following equation describes this relationship:

$$^{143}\mathrm{Nd}/^{144}\mathrm{Nd} = {}^{143}\mathrm{Nd}_{I}/^{144}\mathrm{Nd}_{I} + {}^{147}\mathrm{Sm}/^{144}\mathrm{Nd}\ (e^{\lambda t} - 1)$$

where I is the initial abundance, λ is the decay constant, and t is the age of the system. This equation makes it possible to determine the age of crystallization.

This Sm-Nd method allows us to calculate isochron model ages that are similar to Uranium-Lead dating (Lugmair and Marti, 1978). Since the only significant fractionation that occurs to this system is during the extraction of the crust from the mantle, geologic processes such as erosion, metamorphism and sedimentation have a minimal effect on the isotopic ratios of Sm-Nd. This method is more complex than

Rubidium-Strontium and Uranium-Lead (U-Pb), but allows us to determine crustal ages in cases when metamorphism has obscured this data (Dickin, 1997).

The theory of Nd model ages is based on the assumption that Sm and Nd were formed when the primordial solar nebula was condensed and cooled (Dickin, 1997). Chondritic meteorites are believed to have been the result of this original nebular composition, and therefore also represent the initial composition of the earth. By using the isotopic ratios of chondritic meteorites, Depaolo and Wasserberg defined the Chondritic Uniform Reservoir (CHUR) model to define the initial ratios of continental rocks based on the evolution line of Nd (Figure 2.1). The evolution line of Nd for continental igneous rocks plotted against time reflects a trend that follows CHUR (DePaolo and Wasserburg, 1976a). With the measurement of Sm-Nd ratios we can calculate its age of formation, provided that a sufficient amount of Sm/Nd fractionation took place during crustal extraction of the mantle to yield a realistic divergence between crustal and mantle evolution lines.

In terrestrial rocks, DePaolo and Wasserberg also noted that the difference of the $^{143}Nd/^{144}Nd$ ratio from the CHUR evolution line were very insignificant in relation to the slope of the line. This is due to the fact that Sm and Nd are only two atomic numbers apart, and only undergo slight fractionation during the crystal-liquid process. This led DePaolo and Wasserberg to develop the Epsilon notation, which allowed the initial $^{143}Nd/^{144}Nd$ ratio to be recorded in parts per 10^4 deviations from the CHUR evolution line.

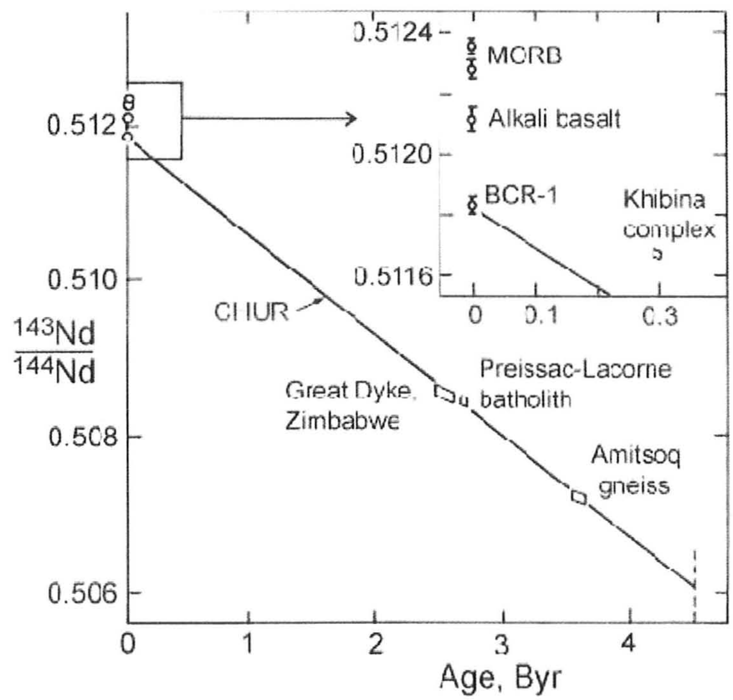

Figure 2.1 Diagram demonstrating the correlation between terrestrial igneous rocks and CHUR (Chondritic Uniform Reservoir evolution line) by plotting the $^{143}Nd/^{144}Nd$ ratio versus time. (DePaolo and Wasserburg, 1976a)

Younger rocks such as mid-ocean ridge basalts (MORB) did not evolve in correspondence with the CHUR model, leading to the development of the depleted mantle model (Figure 2.2). DePaolo (1981) proposed the Depleted Mantle (T_{DM}) model stating that Sm and Nd must fractionate during mantle melting from the crustal extraction process, therefore enriching the magma with Nd, and leaving the mantle source depleted in Nd. Consequently, subsequent extractions from the mantle would then have lower levels of Nd, explaining the depletion of Nd as these samples diverge away from the CHUR evolution line. The depleted mantle model is then used when Nd values occur above the CHUR line (Figure 2.3) for younger samples derived from crust that have been Nd depleted.

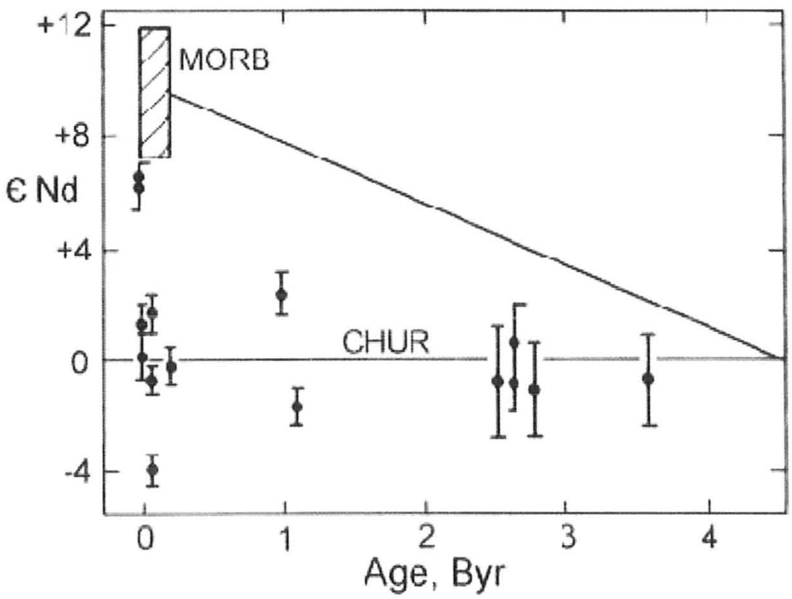

Figure 2.2 .Nd isotope evolution line plotted against time, displaying the deviation of younger samples such as MORB (Mid ocean ridge basalts) from the chondritic evolution line. (DePaolo and Wasserburg, 1976b)

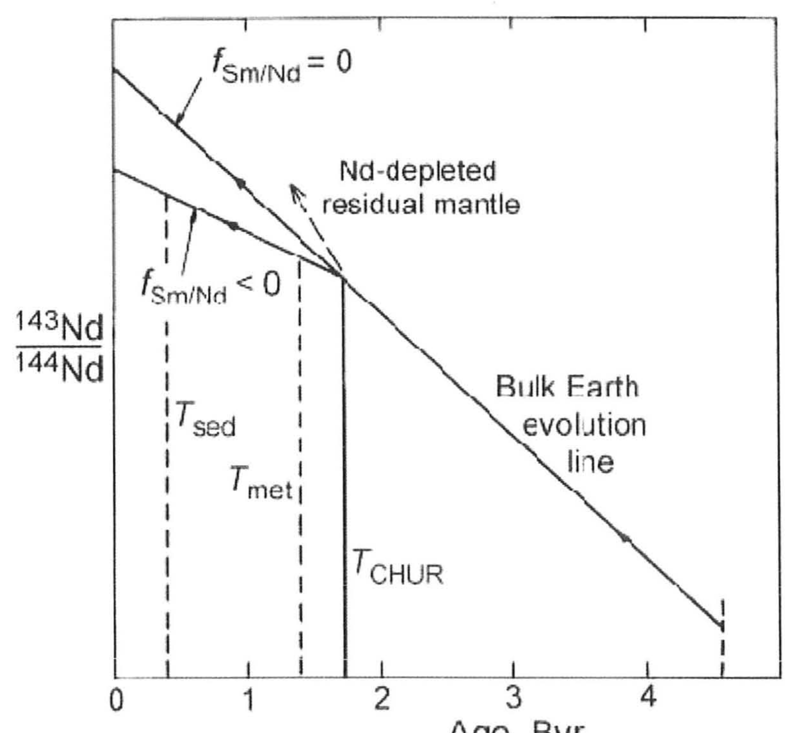

Figure 2.3 Nd isotope evolution diagram. Tsed and Tmet represent the ages of sedimentation and metamorphic events, while the dashed vector represents the development of a depleted mantle resulting from extraction of the crust. (McCullogh and Wasserburg, 1978)

To calculate depleted mantle model ages, the composition of the depleted reservoir is measured in relation to the CHUR at time T, and represented in the following equation:

$$\varepsilon \, Nd \, (T) = 0.25T^2 - 3T + 8.5$$

These depleted mantle model ages (T_{DM}) are used to yield accurate crustal formation ages. Once the crustal formation ages are determined, terranes and other important geological boundaries can be distinguished.

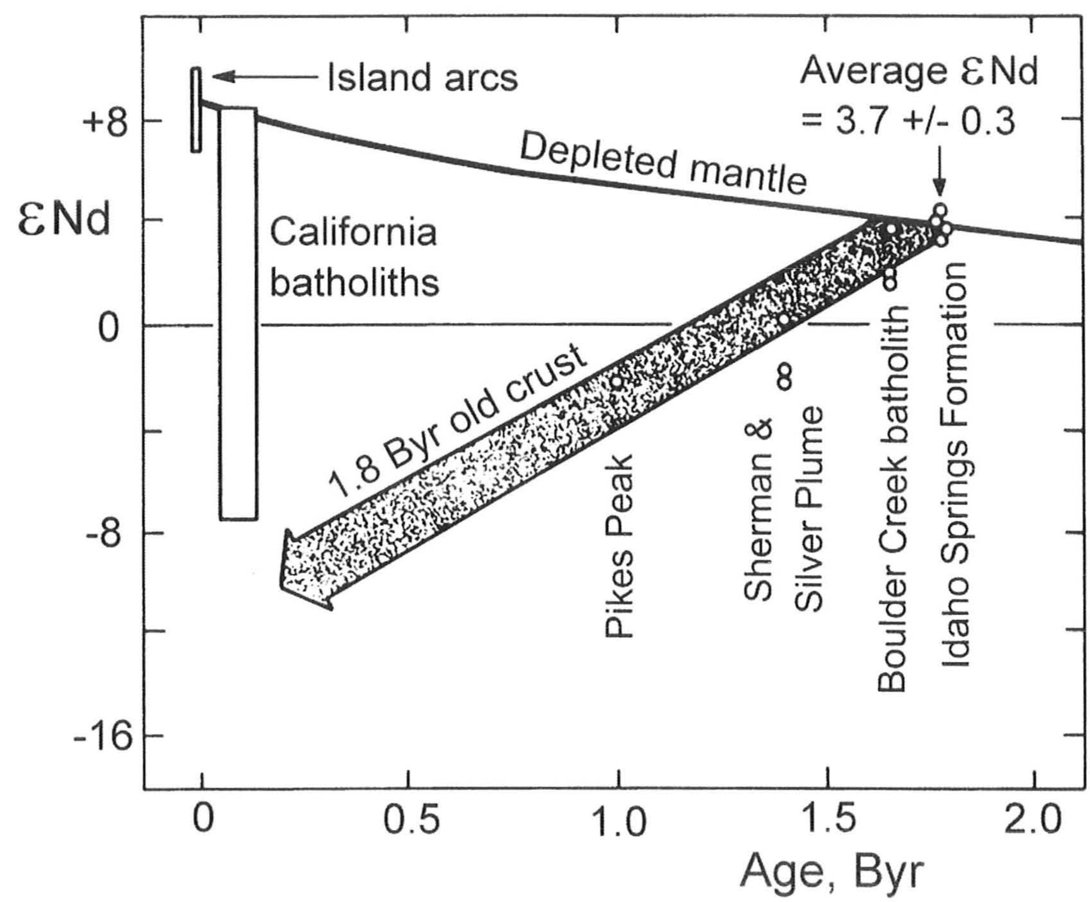

Figure 2.4 Diagram of ε versus time, illustrating data from Colorado in relation to a model depleted-mantle evolution curve. After DePaolo (1981)

A possible source of error in using model ages occurs when the results do not correlate with previously recorded igneous crystallization ages. This was seen in the study by Bennett and DePaolo (1985), where old model age dates were measured for younger known events. This can be explained by the concept of mixing, which occurs when younger mantle derived magmas are mixed with older larger amounts of re-melted Archean crust (Figure 2.5). Since the Nd model age method can be a powerful tool to see back through complex geological history, it should not be dismissed due to this possible source of error. The solution to this problem is to use other geochronological tools (such as U-Pb), to act as a constraint for the Nd data. This method will be applied to the southern Labrador region, as illustrated in the following chapters.

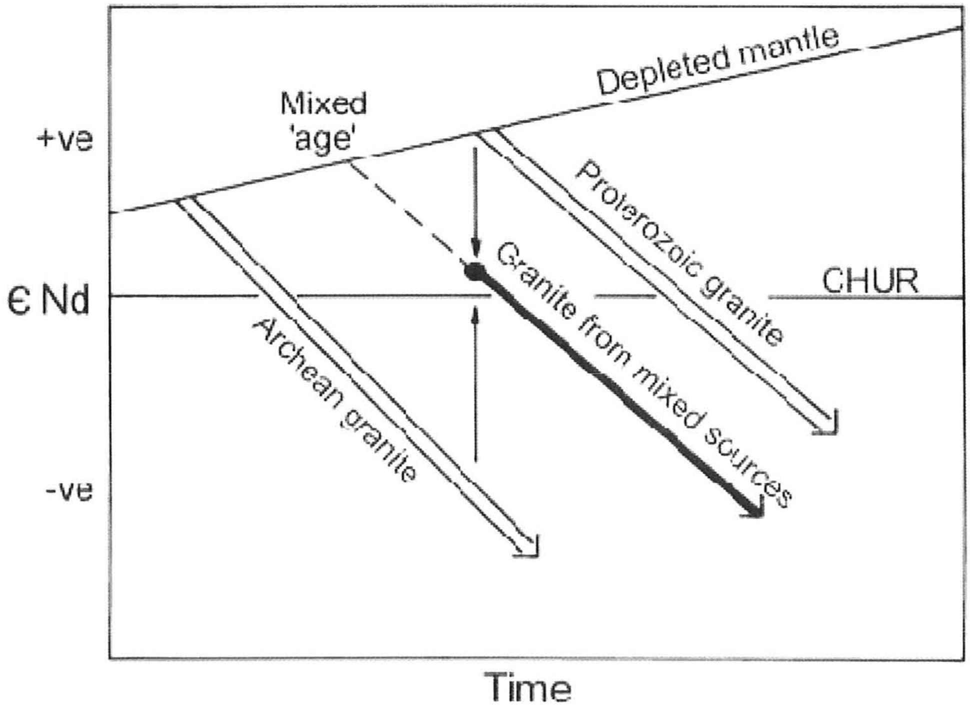

Figure 2.5 Image demonstrating the magma mixing as a possible method for creating mixed provenance ages that are not representative of a real geologic event. Modeled after Arndt and Goldstein (1987).

Chapter 3: Results

Sampling

Samples of high-grade orthogneisses were collected from the southeast Labrador region, between the cities of Cartwright and Red Bay (Route 510), and along the eastern part of the newly constructed highway between Route 510 and Happy Valley-Goose Bay. The transects covered four of the Grenvillian lithotectonic terranes: Hawke River, Lake Melville, Mealy Mountains, and the northern part of the Pinware (Figure 3.1).

An unpublished data set was also made available by C. Gower for comparison with my own samples. These samples come from a wide spread of localities all over eastern Labrador. In addition, Figure 3.1 shows localities of published data points.

Sampling was limited to granitoid orthogneisses, since it has been shown in previous studies that this type of protolith, normally formed in arc systems, provides Nd isotope signatures that are more reliable and consistent than other lithologies. Therefore, mafic gneisses, paragneisses, and anorthositic rocks were avoided when sampling to reduce the possibility of processing rocks that could have been formed by mixing with a younger mantle component, or have been derived from an unknown sedimentary source.

These samples were then transferred to McMaster University where approximately 1 kg of rock was crushed into a fine powder that is representative of the whole rock. The samples were then subjected to chemical dissolution and elemental extraction before being analyzed by Thermal Ionization Mass Spectrometry (TIMS). The details of this methodology are outlined in Appendix A.

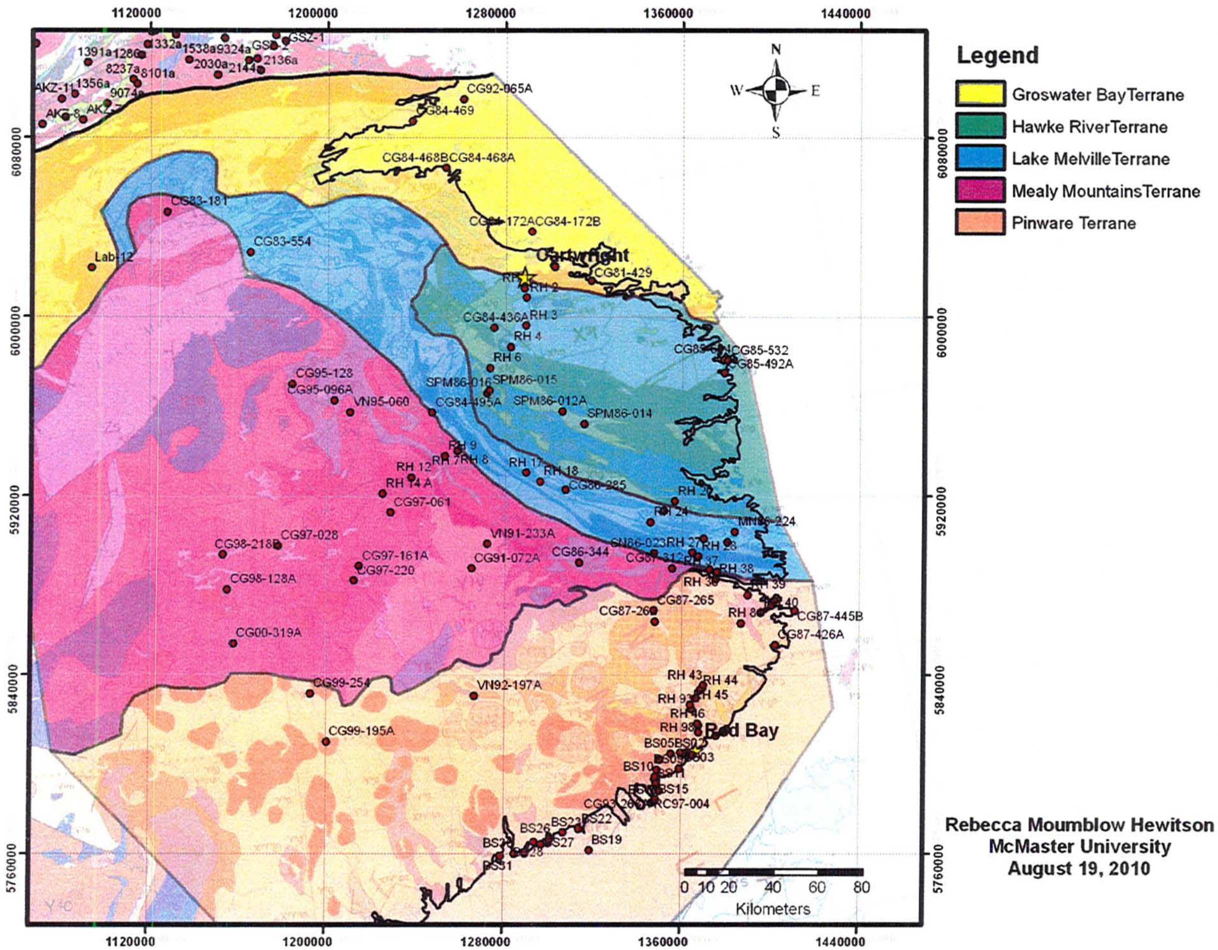

Figure 3.1 Sample locations for isotopic dating within the four lithotectonic terranes: Hawke River, Lake Melville, Mealy Mountains, and the Pinware. RH: Rebecca Hewitson samples. Source: Geological Survey of Canada map (Davidson, 1998)

Isotopic Analysis

New Nd isotope data are presented here in Table 3.1, and are listed according to lithotectonic terrane as discussed previously, with the additional division of the Pinware terrane into north and south parts, based on a proposed new boundary located immediately north east of Red Bay.

Age Frequency

Histograms of TDM model ages for southeast Labrador were plotted for the various lithotectonic terranes, arranged from north to south (Figure 3.2). The histograms were based on a bin size of 50 m.y., which provides optimal resolution of the data, bearing in mind the analytical error of ±20 m.y. for each model age. The new data complement published data (represented by darker shading) from Prevec et al., (1990), Scharer (1991) and Dickin (2000) by filling in major gaps in the previous data sets.

Dickin (2000) attributed the Pinware South terrane to the accretion of a ca 1750 Ma juvenile arc formed shortly before the Labradorian orogeny. In contrast, he proposed that the crust to the north was Pre-Labradorian. Therefore, it follows that any Nd model ages less than 1.74 Ga in the northern area probably represent a younger mantle derived component. These ages are not representative of the age of crustal formation of the terrane as a whole. Therefore ages less than 1.74 Ga will be removed from the main data set into a separate category characterized as "young mantle", and will not be included in calculated averages or regressions.

The strongest concentration of older T_{DM} ages in both the new data and the published data set comes from the Hawke River terrane which has a mean of 1.94 Ga, attributed to the presence of Pre-Labradorian crust. The new data for the Mealy Mountains terrane provides a mean age of 1.91 Ga, once the young mantle samples are removed. This old age is significant, considering that the only published Nd data from this terrane gave a younger model age. The Lake Melville terrane, which lies between the Hawke River and the Mealy Mountains terrane produced a slightly younger mean of 1.87 Ga. Since this terrane is sandwiched between two older age ranges, it is logical to suggest that the Lake Melville terrane lies within the same age range as its two neighbours, but has been subject to inadequate sampling. This conclusion is suggested by the small sample size, and a standard deviation of 0.10 which is higher than the other terranes.

Since the samples from the Hawke River and Mealy Mountains terranes show overlapping ranges of T_{DM} model ages this suggests they may be derived from one original crustal block. The Pinware North terrane has a mean of 1.83 Ga, suggesting a somewhat younger Pre-Labradorian crustal source than the more northerly terranes. However, it also differs from the Pinware South terrane which has consistently younger ages. After the removal of three samples attributed by Dickin (2000) to a post Labradorian mantle component, this yields an average model age of 1.77 Ga.

Table 3.1 Nd Isotope Analysis of southeast Labrador samples

Sample #	Easting	Northing	Nd (ppm)	Sm (ppm)	147Sm/144Nd	143Nd/144Nd	TDM age (Ma)
Hawke River Terrane							
RH 1	497367	5946177	29.0	5.12	0.1066	0.511677	1940
RH 2	497721	5941903	21.3	3.93	0.1117	0.511767	1905
RH 3c	495224	5929707	7.2	1.11	0.0938	0.511568	1875
RH 4a	486903	5921581	31.9	5.64	0.1070	0.511708	1905
RH 6	476200	5914021	47.9	10.04	0.1267	0.511968	1880
Lake Melville Terrane							
RH 17	484563	5865394	22.5	3.92	0.1055	0.511782	1770
RH 18	490277	5860481	78.0	13.98	0.1083	0.511758	1855
RH 19	494720	5856516	57.5	8.75	0.0920	0.511679	1710
RH 20	548043	5841835	44.9	6.75	0.0909	0.511604	1780
RH 22	542680	5838376	13.2	2.31	0.1057	0.511734	1850
RH 24a	535874	5834517	71.1	9.65	0.0821	0.511493	1790
RH 27b	552256	5818135	38.6	7.65	0.1199	0.511888	1875
RH 28	554680	5816050	133.0	25.02	0.1137	0.511838	1830
Mealy Mountains Terrane							
RH 7b	456286	5880166	39.7	7.37	0.1123	0.511753	1935
RH 8c	455758	5879978	47.9	9.26	0.1167	0.511860	1855
RH 9	450034	5878693	48.0	9.33	0.1174	0.511841	1900
RH 12	433759	5871849	36.0	7.27	0.1220	0.511936	1840
RH 13	430601	5870785	49.7	7.03	0.0855	0.511625	1685
RH 14A	419825	5866870	44.4	6.92	0.0941	0.511627	1800
RH 15	456183	5880232	77.7	15.34	0.1193	0.511913	1820
RH 30e	558609	5809378	21.9	4.47	0.1233	0.511842	2030
RH 35 A	561802	5807843	35.97	6.66	0.1120	0.511744	1945
RH 36d	561801	5807876	28.1	5.04	0.1085	0.511654	2010
RH 37b	561726	5807935	27.8	4.51	0.0980	0.511544	1975

Table 3.1 Cont'd

Sample #	Easting	Northing	Nd (ppm)	Sm (ppm)	147Sm/144Nd	143Nd/144Nd	TDM age (Ma)
Pinware North							
RH 31b	561649	5807059	38.6	6.69	0.1047	0.511718	1850
RH 32c	560713	5803486	96.8	17.13	0.1070	0.511865	1680
RH 33b	567479	5797301	80.2	12.69	0.0957	0.511758	1650
RH38c	560681	5804868	52.1	9.58	0.1111	0.511800	1845
RH 39a	573731	5795474	14.8	2.63	0.1074	0.511789	1795
RH 40c	577987	5786814	6.2	1.16	0.1126	0.511827	1830
RH 43	547764	5759233	40.5	7.51	0.1119	0.511777	1860
RH 44	545688	5757261	35.1	6.04	0.1041	0.511729	1825
RH 45	540546	5751528	37.2	6.58	0.1069	0.511724	1880
RH 46a	542414	5742768	30.2	5.79	0.1157	0.511843	1865
RH 80c	579360	5794660	53.6	10.11	0.1139	0.511861	1803
RH 84	568530	5783600	44.9	8.29	0.1117	0.511779	1890
RH 88b	547370	5758300	44.7	7.76	0.1048	0.511780	1765
RH 91c	543400	5754100	50.9	8.9	0.1056	0.511744	1830
RH 93	540720	5749700	43.9	6.9	0.0951	0.511623	1820
RH 96	542840	5741900	38.1	6.64	0.1052	0.511688	1900
RH 98c	542260	5738900	24.2	4.04	0.1010	0.511712	1800
RH 101e	554740	5738000	39.7	7.41	0.1127	0.511833	1825
RH 104c	549670	5736300	44.4	7.18	0.0977	0.511711	1750
RH 108	538050	5729500	43.2	7.93	0.1108	0.511802	1840
RH 110a	531210	5724500	45.1	8.52	0.1142	0.511845	1830
Pinware South							
RH 111	535800	5731100	46.8	7.92	0.1023	0.511755	1760
RH 112a	534450	5730900	38.1	6.84	0.1083	0.511814	1775
RH113a	532920	5731500	53.8	10.4	0.1168	0.511907	1784

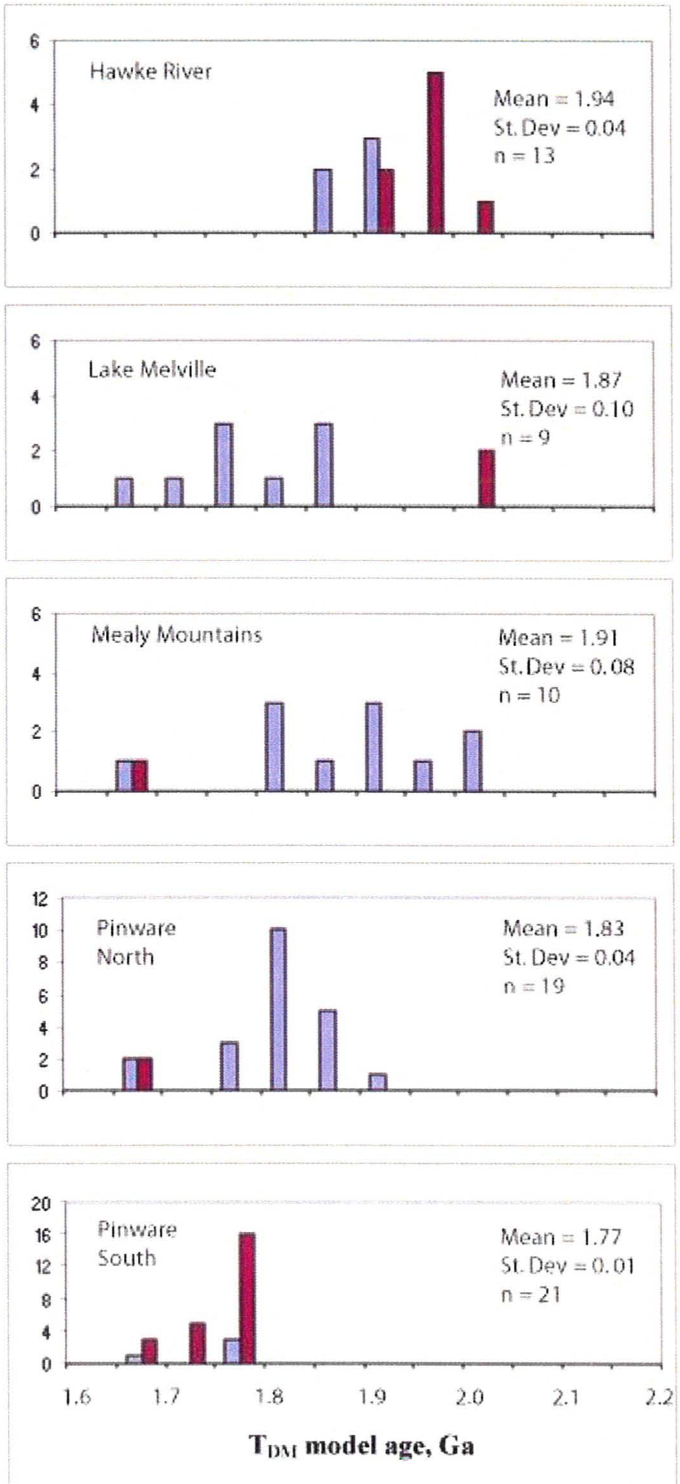

Figure 3.2 Histograms of TDM model ages for the different terranes of the SE Grenville Province. Dark red shading indicates published data by Scharer (1991), Prevec et al., (1990), and Dickin (2000)

Sm-Nd Isochron Diagram

Since the samples from the Hawke River, Lake Melville and Mealy Mountains terranes show overlapping ranges of T_{DM} model ages suggesting that they may be derived from a single crustal block, the samples were grouped into a category labelled Cartwright South. The samples were then compiled into three main groups: Pinware South, Pinware North, and Cartwright South.

All three groups of samples were then plotted on a Sm-Nd isochron diagram (Figure 3.3). As suggested from the histograms, three distinct arrays can be distinguished on the Sm-Nd isochron, but generate sub-parallel slopes. Samples from Pinware South are represented by triangles, and lie close to a 1.75 Ga reference line. Using the 1.75 Ga reference line as an indicator of the presence of juvenile Labradorian age crust, we can see that samples from both Pinware North (represented by blue diamonds) and Cartwright South (represented by solid and open squares) yield regression lines that are parallel to the 1.75 Ga reference line, but are displaced downwards. This implies derivation from older crustal sources composed of Pre-Labradorian crust, but the slope of the isochron arrays shows that these crustal blocks were intensely affected by Labradorian plutonism.

The category labelled Young Mantle with model ages below 1.75 Ga (solid and open circles) are clearly not representative of the Nd signatures of their respective crustal blocks, since these samples lie above the juvenile Labradorian array, even though they come from areas of Pre-Labradorian crust. These samples represent a much younger mantle component and are possibly related to Pinwarian plutonism.

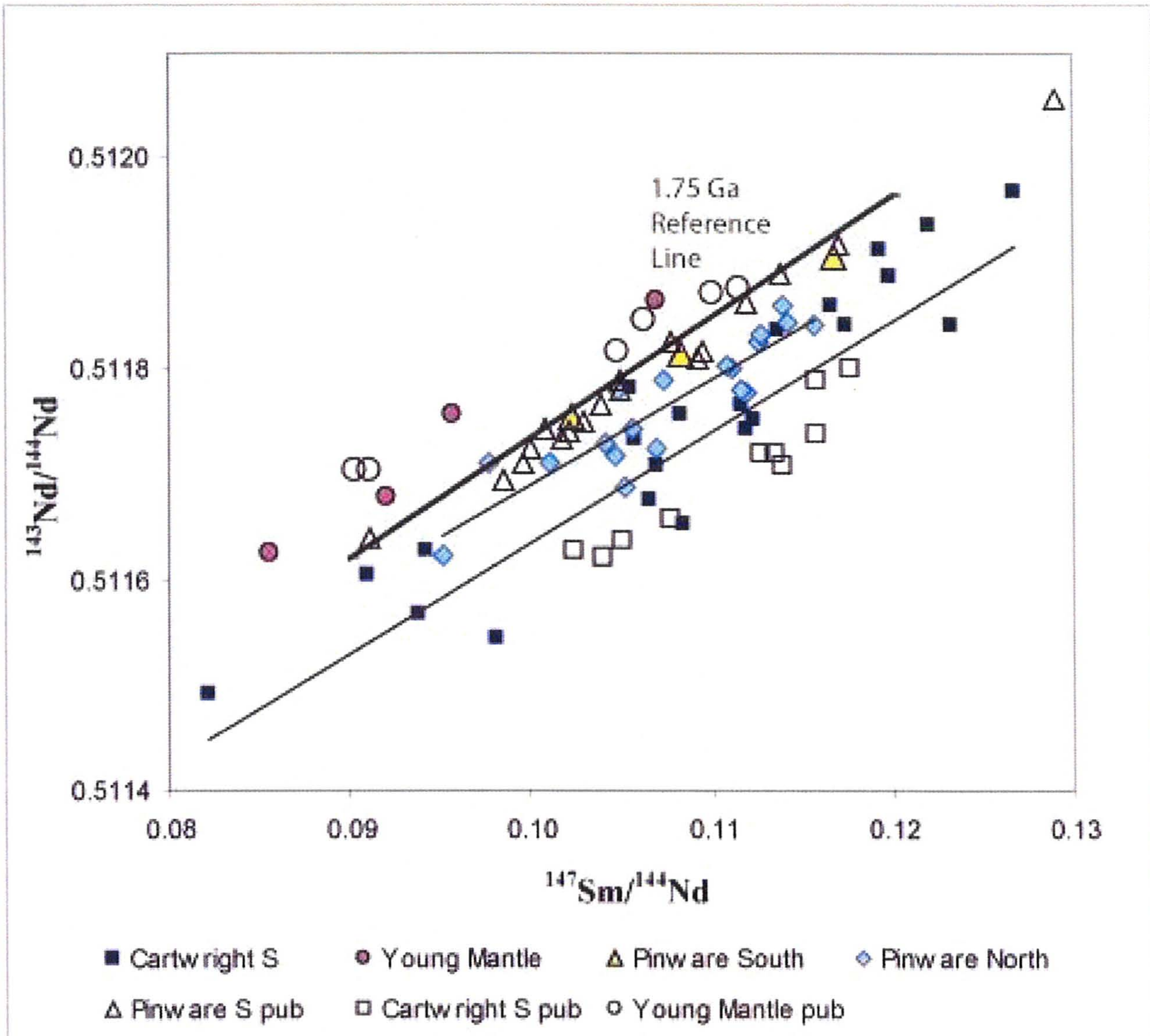

Figure 3.3 Sm-Nd Isochron diagram displaying trend lines for samples from Cartwright S, Pinware North, Pinware South and samples indicating a younger mantle source. New data is represented by solid symbols. Previously published data by Scharer (1991), Prevec et al., (1990), and Dickin (2000), is shown by open symbols.

Geographical Distribution of Age

The data were then displayed on a North-South plot to illustrate any possible trends with respect to geographical location (Figure 3.4). T_{DM} model ages (Ma) were plotted against UTM northing (m), and the northerly terranes were grouped together based on the histogram distributions. It should be borne in mind that terrane boundaries within the Hawke River, Lake Melville, and Mealy Mountains terranes are striking NW-SE. However, since it has shown on the histograms that these terranes have overlapping ranges in model age; this does not bias the data. Samples from the Pinware North terrane show minor overlap with the Pinware South terrane at Red Bay, but do not overlap with the northerly terranes at the Gilbert River (see Figure 3.1). Trend lines were calculated for each group, including published data excluding samples identified as containing a younger mantle component (circles in Figure 3.4). Samples from each of the three groupings show no internal trend with respect to geographical location, as indicated by the essentially horizontal trend lines. However, the diagram does display the distinct appearance of three discrete crustal blocks: Pinware South, Pinware North, and Cartwright South.

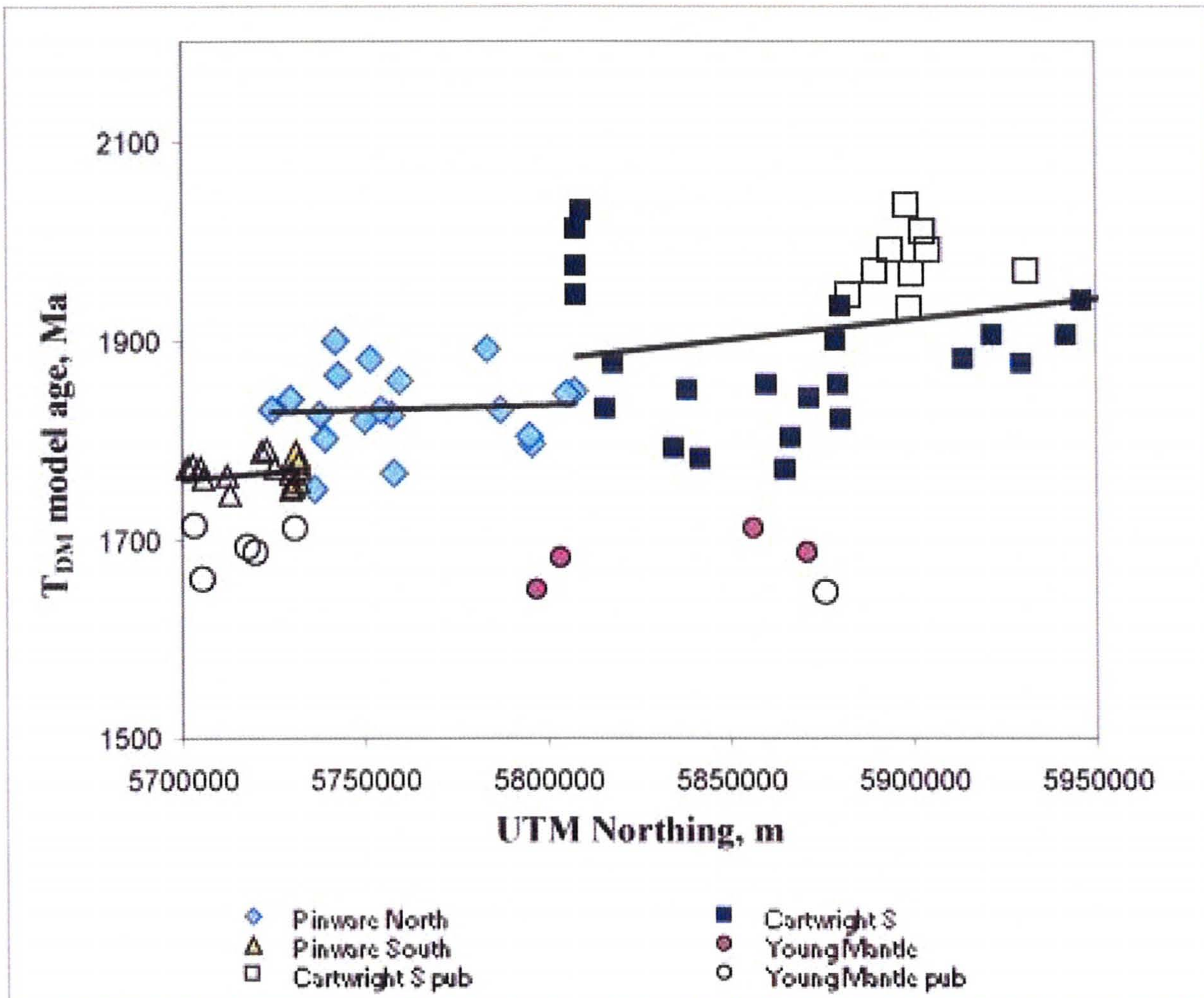

Figure 3.4 North-South plot for T_{DM} model ages displaying the trend for samples from Cartwright S, Pinware South, Pinware North, and samples indicating a younger mantle source. New data is indicated by solid symbols. Previously published data by Scharer (1991), Prevec et al., (1990), and Dickin (2000), are shown by open symbols.

Major Element Analysis

Major elemental analysis was performed on dated samples for the Pinware North and South terranes. These terranes were selected due to the lack of sampling done in previous studies from these areas. The geochemical analysis was performed by Activation Laboratories, and the results are listed in Appendix D. This data complements the previous geochemical data for the southeast Labrador region done by Scharer (1991), and Dickin (2000) and are plotted on a petrochemical grid based on Debon and LeFort's (1983) Streckeisen classification of granitoids (Figure 3.5).

The petrochemical grid is based on the variation of quartz and plagioclase compositions, and is modeled in figure 3.5 by:

$$\mathbf{Q = Si/3-(K+Na+2Ca/3) \qquad P = K-(Na+Ca)}$$

The model is classified into different lithologies to differentiate the composition of each individual sample. The grid is separated into 12 different granitoid fields: TN-tonalite, GD-granodiorite, MG-monzogranite, GR-granite, QD-quartz diorite, QMD-quartz monzodiorite, QMZ-quartz monzonite, QSY-quartz syenite, DI-diorite, MD-monzodiorite, MZ-monzonite, SY-syenite and FOID-feldspathoidal granitoids. The difference between the classifications is a direct reflection of the evolution of alkali content.

The data for Pinware South, Pinware North and the data from Scharer (1991), are scattered between most of the fields on the right hand side of the petrochemical grid. The lack of samples that fall in the diorite-tonalite fields supports the evidence of severe reworking during the Labradorian by an ensialic arc. This type of signature was argued by Martin and Dickin (2006) to be indicative of magmatism in thickened crust such as an ensialic arc, in contrast to the greater abundance of tonalities in juvenile accreted arcs.

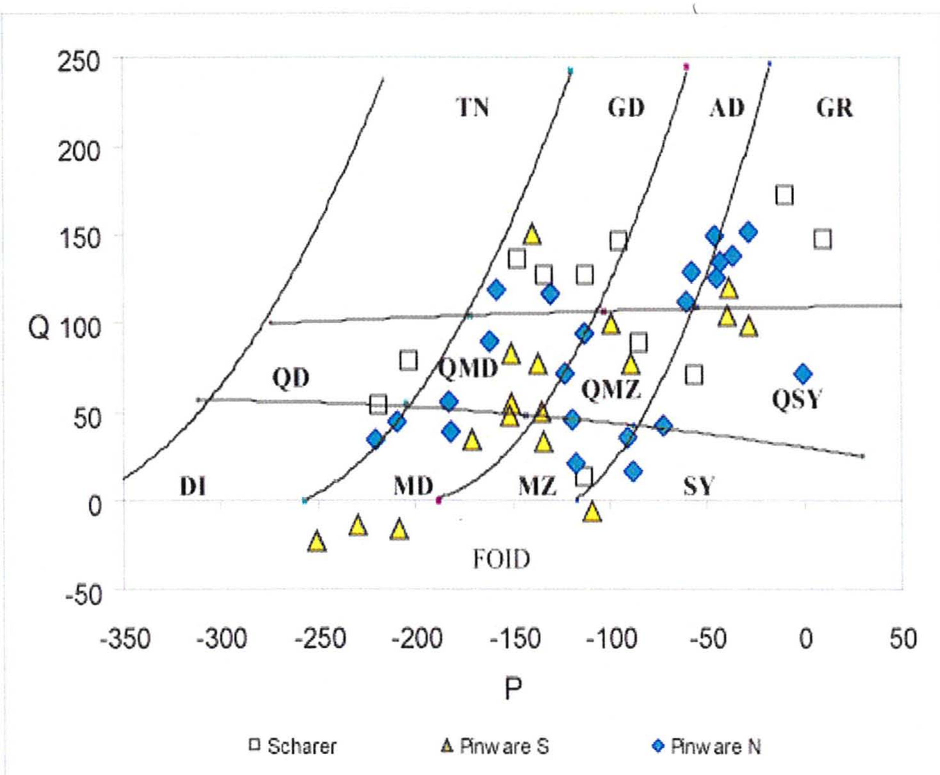

Figure 3.5 Petrogenic Quartz-Plagioclase grid. TN-tonalite, GD-granodiorite, MG-monzogranite, GR-granite, QD-quartz diorite, QMD-quartz monzodiorite, QMZ-quartz monzonite, QSY-quartz syenite, DI-diorite, MD-monzodiorite, MZ-monzonite, SY-syenite and FOID-feldspathoidal granitoids. (after Debon and LeFort, 1983)

Isotopic Analysis for data from Gower et al.

Unpublished Nd data from SE Labrador was made available by C. Gower for comparison with the new data collected for this thesis. The new Nd isotope data from samples collected by Gower et al. are presented here in Table 3.2, and are also divided into lithotectonic terranes as discussed previously, with the addition of data from the more northerly Groswater Bay terrane.

Table 3.2 Nd Isotope Analysis of Gower et al., southeast Labrador samples

Sample #	Easting	Northing	Emplace age	Sm (ppm)	Nd (ppm)	147Sm/ 144Nd	143Nd/ 144Nd	eNd	TDM age (Ma)
Groswater Bay Terrane									
CG81-429	527372	5944530	1645	16.44	148.7	0.0668	0.511272	**0.7**	**1.83**
VO81-540A	512370	5953219	1660	3.98	31.3	0.0783	0.511381	**0.7**	**1.87**
VO81-539C	512301	5953596	1660	2.86	24.3	0.0726	0.511323	**0.8**	**1.85**
VO81-539A	512301	5953596	1660	4.65	27.1	0.1058	0.511696	**1.0**	**1.90**
VO81-021A	512092	5954071	1660	1.72	10.1	0.1057	0.511674	**0.6**	**1.93**
VO81-021B	512092	5954071	1660	4.71	27.3	0.1067	0.511702	**0.9**	**1.90**
CG84-172A	504835	5970254	1654	6.78	28.9	0.1114	0.511683	**-0.6**	**2.02**
CG84-172B	504835	5970254	1658	3.94	28.8	0.0828	0.511425	**0.5**	**1.88**
CG84-468B	471486	6004486	1580	5.74	31.4	0.1102	0.511638	**-1.0**	**2.06**
AKZ-9	250495	6015923	1650	13.50	69.5	0.1150	0.511738	**-0.3**	**2.01**
AKZ-10	252079	6018987	1650	6.50	42.4	0.0940	0.511518	**-0.1**	**1.94**
CG84-469	460400	6027550	1649	11.40	32.7	0.1191	0.511837	**0.8**	**1.94**
CG84-468A	471486	6004486	1709	6.46	27.1	0.1393	0.512011	**0.3**	**2.11**
CG92-065A	484461	6033363	1800	3.65	26.0	0.0848	0.511353	**0.7**	**1.99**
Lake Melville Terrane									
CG86-746A	568254	5820114	1670	6.30	33.2	0.1147	0.511827	**1.7**	**1.86**
SN86-023	535405	5820793	1670	3.93	25.8	0.0920	0.511515	**0.5**	**1.91**
CG86-053B	558203	5823217	1670	5.79	35.9	0.0974	0.511666	**2.3**	**1.80**
MN86-224	572379	5824056	1670	7.59	41.1	0.1117	0.511750	**0.9**	**1.93**
CG86-285	500706	5854970	1670	5.74	28.6	0.1212	0.511854	**0.9**	**1.95**
Lab-13	275409	5972063	1677	2.55	14.1	0.1086	0.511598	**-1.4**	**2.09**
Lab-12	307977	5987460	1632	13.30	83.7	0.0955	0.511566	**0.2**	**1.90**
CG83-181	345362	6006382	1628	9.54	55.8	0.1034	0.511691	**1.0**	**1.86**

Table 3.2 Cont'd

Sample #	Easting	Northing	Emplace age	Sm (ppm)	Nd (ppm)	147Sm/ 144Nd	143Nd/ 144Nd	eNd	TDM age (Ma)
Mealy Mountains Terrane									
CG99-254	373843	5784611	1500	5.55	31.7	0.1058	0.511753	**0.2**	**1.82**
CG87-312	542156	5812851	1650	13.63	83.7	0.0985	0.511667	**-0.1**	**1.81**
CG97-161A	404410	5836945	1750	5.63	35.5	0.0960	0.511638	**-0.2**	**1.81**
VN91-233A	462216	5837217	1500	13.25	71.3	0.1123	0.511785	**-0.5**	**1.89**
CG97-220	400988	5830857	1650	8.14	41.2	0.1196	0.511863	**-0.3**	**1.91**
CG91-072A	453625	5827650	1500	10.56	62.8	0.1016	0.511643	**-1.1**	**1.90**
CG00-319A	343243	5812334	1640	10.37	52.9	0.1186	0.511847	**-0.4**	**1.91**
CG86-344	501582	5822227	1650	7.89	43.3	0.1101	0.511669	**-0.4**	**2.02**
CG98-128A	344444	5836488	1750	8.76	48.4	0.1096	0.511726	**0.4**	**1.92**
CG97-028	369905	5851921	1650	15.21	83.3	0.1104	0.511803	**1.8**	**1.82**
CG98-218B	344843	5852094	1650	2.23	10.5	0.1286	0.511974	**1.3**	**1.91**
CG97-061	422025	5858075	1750	5.59	30.3	0.1114	0.511757	**0.9**	**1.91**
CG95-128	388071	5921794	1646	9.38	47.2	0.1201	0.511813	**0.1**	**2.00**
VN95-060	411624	5904951	1786	6.17	34.8	0.1072	0.511669	**1.6**	**1.96**
Pinware North									
CG87-445B	593253	5785005	1640	6.77	41.6	0.0985	0.511710	**2.5**	**1.76**
CG87-265	531172	5795707	1450	8.03	45.3	0.1072	0.511808	**2.7**	**1.76**
CG87-426A	582445	5771571	1479	12.63	70.4	0.1084	0.511836	**1.1**	**1.74**
CG87-445A	593253	5785005	1490	9.13	42.2	0.1309	0.512029	**0.7**	**1.86**
CG87-461	583666	5789085	1590	6.29	32.5	0.1169	0.511781	**-1.4**	**1.98**
CG87-262	530631	5790718	1450	11.41	50.7	0.1360	0.512008	**-1.0**	**2.03**
CG87-469	585145	5791116	1472	13.86	85.5	0.0980	0.511674	**-0.2**	**1.80**
CG99-195A	377348	5762342	1513	6.24	27.9	0.1351	0.511956	**-1.4**	**2.11**
VN92-197A	445850	5771550	1649	6.32	38.1	0.1003	0.511659	**1.3**	**1.85**
Pinware South									
RC97-004	516400	5711680	1467	14.61	67.4	0.1312	0.512038	**0.6**	**1.85**
RC97-005	520526	5716234	1500	9.17	59.8	0.0926	0.511614	**0.0**	**1.79**
RC97-006	519941	5719704	1466	2.91	21.8	0.0805	0.511496	**-0.5**	**1.76**
RC97-007	519941	5719704	1466	7.11	43.5	0.0988	0.511706	**0.2**	**1.77**
RC97-001	482579	5705449	1632	6.81	40.7	0.1013	0.511746	**2.6**	**1.75**
CG93-268A	517524	5712120	1637	4.07	24.0	0.1026	0.511747	**2.4**	**1.77**
CG93-027A	528574	5731649	1650	7.59	44.4	0.1035	0.511731	**2.0**	**1.81**

Major Element Analysis

Major elemental analysis was also performed for Gower's samples. This data complements the previous geochemical data for the southeast Labrador region done by Scharer (1991), and Dickin (2000) and my data set, and are plotted on a petrochemical grid based on Debon and LeFort's (1983) Streckeisen classification of granitoids (Figure 3.6).

The data for Gower, my data from Pinware South, Pinware North and the data from Scharer (1991) and Dickin (2000), are scattered between most of the fields on the right hand side of the petrochemical grid. The lack of samples that fall in the diorite-tonalite fields also supports the evidence from the previous major trace element analysis which suggests that there was severe reworking during the Labradorian by an ensialic arc.

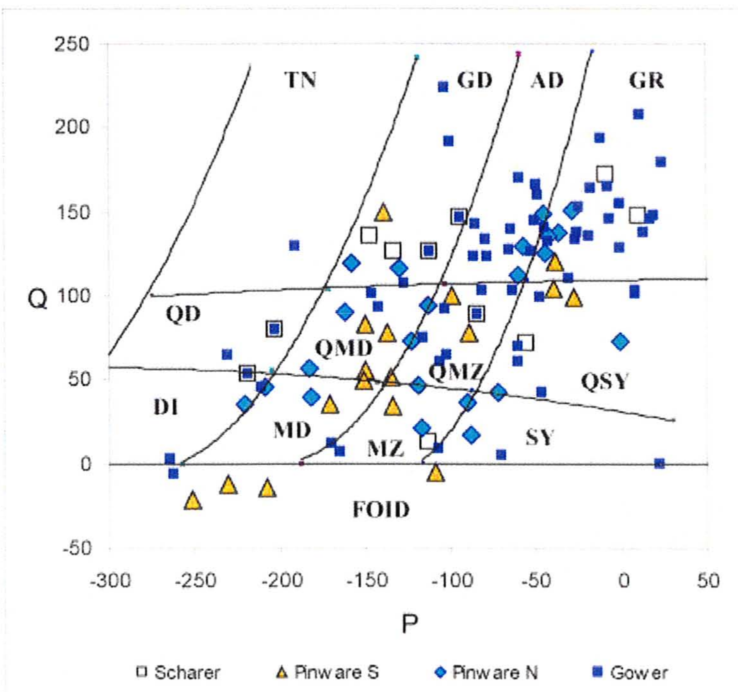

Figure 3.6 Petrogenic Quartz-Plagioclase grid. TN-tonalite, GD-granodiorite, MG-monzogranite, GR-granite, QD-quartz diorite, QMD-quartz monzodiorite, QMZ-quartz monzonite, QSY-quartz syenite, DI-diorite, MD-monzodiorite, MZ-monzonite, SY-syenite and FOID-feldspathoidal granitoids (after Debon and LeFort, 1983)

Age Frequency

Histograms of the T_{DM} model ages for southeast Labrador were calculated (Figure 3.7) for the various lithotectonic terranes, arranged from north to south. The data of Gower were treated in the same way as the data already discussed. The new data are again presented with published data from Prevec et al., (1990), Scharer (1991) and Dickin (2000).

The most significant concentration of older T_{DM} ages in Figure 3.7 is defined by the new data from the Groswater Bay terrane and published data from the Hawke River terrane. The ages for both these terranes can be attributed to the presence of Pre-Labradorian crust. The Lake Melville terrane, whose previously published data represented only older ages for this terrane, has a younger mean of 1.91 Ga, with a standard deviation of 0.09. This is also seen in the Mealy Mountains terrane which presents new data that are representative of a mean of 1.90 Ga, but with a smaller standard deviation of 0.07.

Similar to the previous dataset, the younger T_{DM} ages (<1.74 Ga) in both the new and published data sets are attributed to the addition of a young mantle component that is therefore not representative of the age of crustal formation of the terrane as a whole. Therefore ages less than 1.74 Ga were removed from the main data set into a separate category characterized as "young mantle".

The remaining samples in the Groswater Bay, Hawke River, Lake Melville and Mealy Mountains terranes also show overlapping ranges of T_{DM} model ages that suggest they may be derived from one original crustal block. In contrast, the data from Pinware North comes from a very limited sample set, and although it has a mean of 1.88 Ga, the large age range from 1.75 to 2.1 Ga, combined with the large standard deviation of 0.13, suggests that it is not derived from a single crustal source. The low frequency of ages is a result of the lack of sampling within this terrane, and does not accurately represent the terrane as a whole. Finally, the data from Pinware South is more tightly clustered with six samples yielding model ages between 1.75 and 1.81 Ga., representing juvenile Labradorian age crust. A single older model age (1.85 Ga) comes from a young Pinwarian granite with high Sm/Nd ratio, and the model age is therefore unreliable.

Although the histogram illustrates that the mean age for the Lake Melville and Mealy Mountains terranes is slightly younger than the Groswater Bay and Hawke River terranes, the overlapping age ranges suggest that they are representative of a distinct crustal body. The Pinware North terrane is not able to be defined in this dataset due to the lack of data available, but the Pinware South terrane is defined as a discrete crustal block with a mean age of 1.77 Ga.

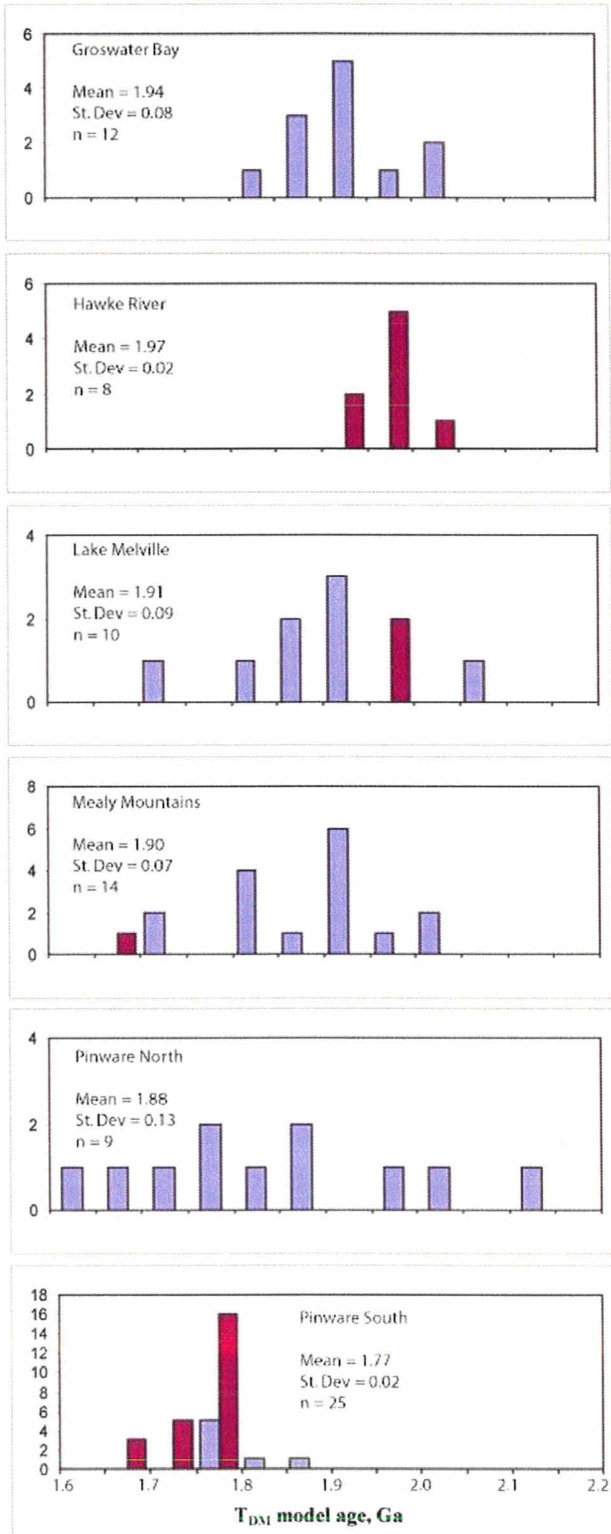

Figure 3.7 Histograms of T_{DM} model ages for the different terranes of the SE Grenville Province for data from Gower et al. Dark red shading indicates published data by Scharer (1991), Prevec et al., (1990), and Dickin (2000).

Sm-Nd Isochron Diagram

Since the samples from the Groswater Bay, Hawke River, Lake Melville and Mealy Mountains terranes show overlapping ranges of T_{DM} model ages indicating that they may be derived from a single crustal block, the samples were grouped into a category labelled Cartwright South. The samples were then compiled into three main groups: Pinware South, Pinware North, and Cartwright South.

The isotopic ratio of all three groups of samples was then plotted on a Sm-Nd isochron diagram (Figure 3.8). Once plotted, two distinct arrays can be distinguished on the Sm-Nd isochron, but with parallel slopes. Samples from Pinware South are represented by triangles, and lie close to a 1.75 Ga reference line. Pinware North does not fall on an isochron that is representative of a particular reference age. The lack of a trend in this terrane is a result of the small sample set. Using the 1.75 Ga reference line as an indicator of the presence of juvenile Labradorian age crust, we can see that samples from the Cartwright region (represented by squares) also fall on an isochron that is parallel to the 1.75 Ga reference line, but its lower position is representative of older crust. This indicates that the terrane is composed of Pre-Labradorian crust, but is obviously affected by Labradorian plutonism. Hence these data show a very similar result to my own data (Figure 3.3).

A category labelled Young Mantle was also created for this dataset for samples which were clearly not representative of the Nd signatures of their respective crustal blocks. These samples lie above the juvenile Labradorian array, even though they come from Pre-Labradorian crust, and represent a much younger mantle component.

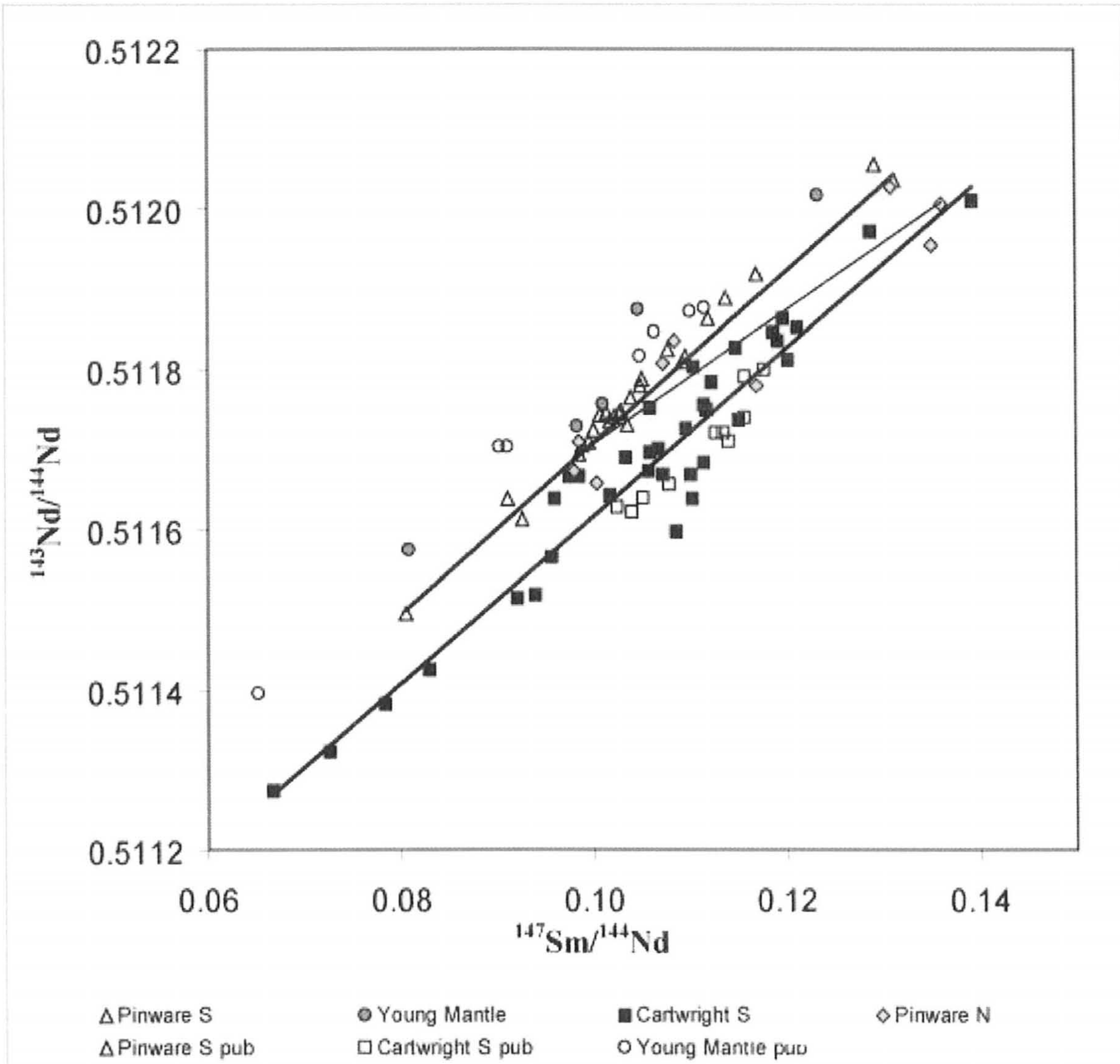

Figure 3.8 Sm-Nd Isochron diagram displaying trend lines for Gower et al., samples from Cartwright S, Pinware North, Pinware South and samples indicating a younger mantle source. New data is indicated by solid symbols. Previously published data by Scharer (1991), Prevec et al., (1990), and Dickin (2000), and is shown by open symbols.

Geographical Distribution of Age

The data for Gower et al. were then displayed on a North-South plot to illustrate any possible trends with respect to geographical location (Figure 3.9). T_{DM} model ages (Ma) were plotted against UTM northing (m), and groupings were made for the different terranes based on the histogram distributions, bearing in mind that the terrane boundaries with the Groswater Bay, Hawke River, Lake Melville, and Mealy Mountains terranes are NW-SE. Additionally, samples from north of the Grenville Province that represent ages with a juvenile Makkovik Nd isotope signature were displayed to compare geographically with the data from within the Grenville Province. These samples come from east of the 410000 grid line, where Archean influence on the Nd data is believed to be lacking.

Samples from the Pinware South show no obvious trend with respect to geographical location, as indicated by the nearly horizontal trend lines. However, the data from Cartwright South show a weak trend with respect to geographical location, shown by the slight positive slope. The trend lines for my own Cartwright South data set were also placed in the plot for comparison, and illustrate that the data from Gower et al., are consistent with the my own data, but that Pinware North differs due to the lack of sampling across the region geographically, which causes the appearance of an almost vertical trend line. In addition, the two samples with the oldest T_{DM} ages are relatively young (Pinwarian) granites with high Sm/Nd ratios which make these data unreliable. Although the Pinware North terrane is lacking the data to make any conclusions in this plot, the diagram does display the distinct appearance of discrete crustal blocks for Pinware South, and Cartwright South. The juvenile Makkovik data set indicate a general increase in TDM model ages as you transition from the southeast to the northwest, and also assist in providing evidence that the Cartwright South region has definitely been influenced by the Labradorian orogeny, with an increase in this influence as you move south.

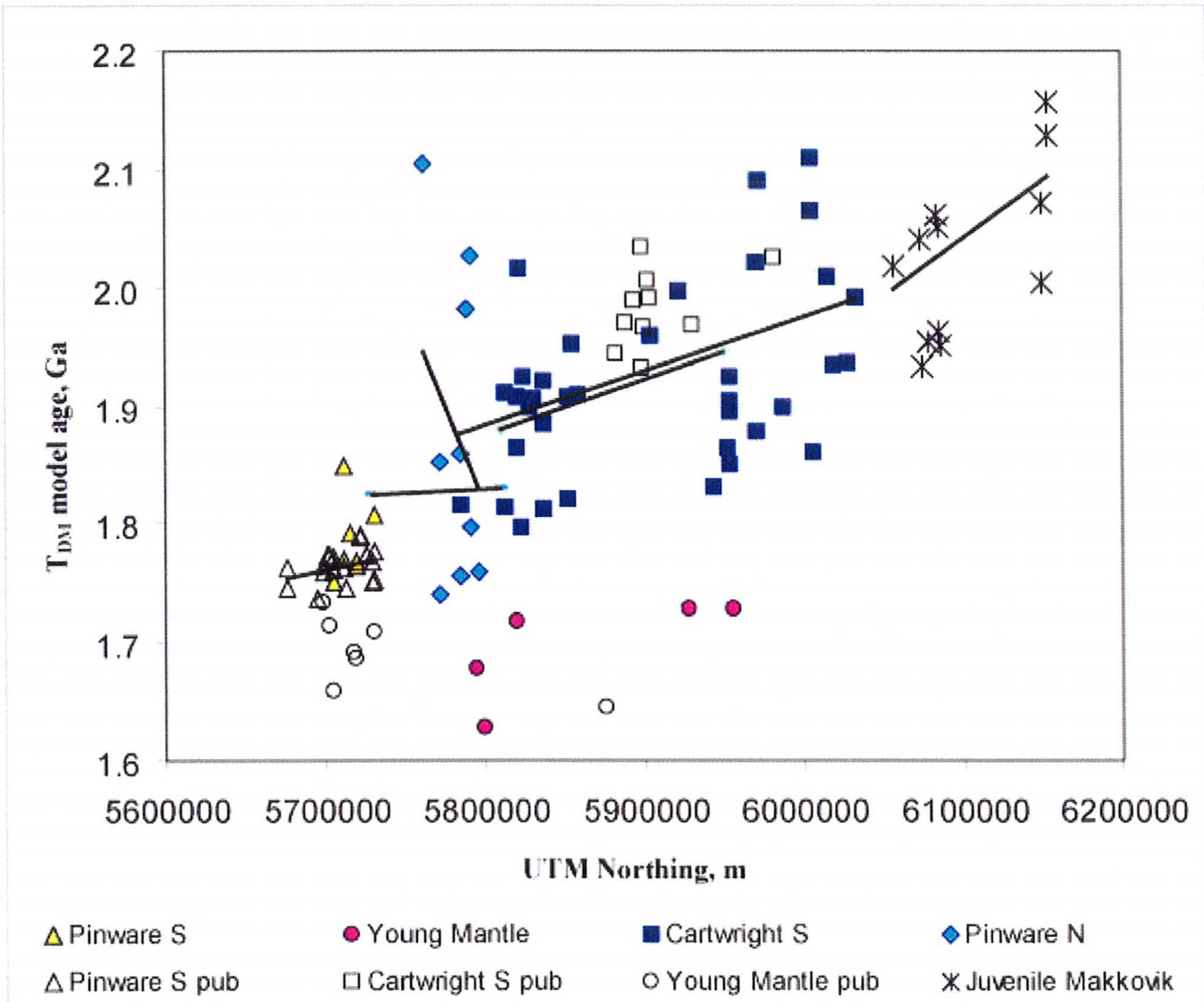

Figure 3.9 North-South plot for T_{DM} model ages displaying the trend for Gower et al., samples from Cartwright S, Pinware South, Pinware North, and samples indicating a younger mantle source. New data are represented by solid symbols. Previously published data by Scharer (1991), Prevec et al., (1990), and Dickin (2000), and is shown by open symbols.

Epsilon Vs U/Pb age

The dataset from Gower et al. and the previously published data from Scharer (1991) and Prevec et al., (1990) were then plotted on an epsilon versus U/Pb age diagram (Figure 3.10). The data were grouped in the same manner as the previous geographic distribution of age. A T_{DM} evolution line was plotted at the top of the diagram, and then average crustal evolution lines based on my own data for Pinware S, Pinware N, Cartwright S and the published juvenile Makkovik data were plotted to intersect with the T_{DM} line. When these average evolution lines are plotted, they intersect with the T_{DM} evolution line at 1.75, 1.85, 1.90, and 2.05 Ga respectively.

Above the 1.75 Ga evolution line for Pinware South, we see that samples with young mantle components are clearly not representative of the crustal formation of the crustal terranes into which they are emplaced. The data from Pinware South (triangles) fall on or below the evolution line, representing juvenile Labradorian crust. The Pinware North data are slightly scattered, suggesting that these are still largely sampling Labradorian crust. The larger data set for Cartwright South mostly falls below the 1.90 Ga evolution line for the terrane, with a few samples lying above representing the influence of the Labradorian orogeny. A few of the samples that lie below the Cartwright South evolution line are actually closer to the 2.0 Ga juvenile Makkovik evolution line. This suggests that these samples could be a direct melt of the juvenile Makkovik crust, and this overlap of data points from both Cartwright South and juvenile Makkovik could represent a mixing line between Pre-Labradorian and Labradorian crust.

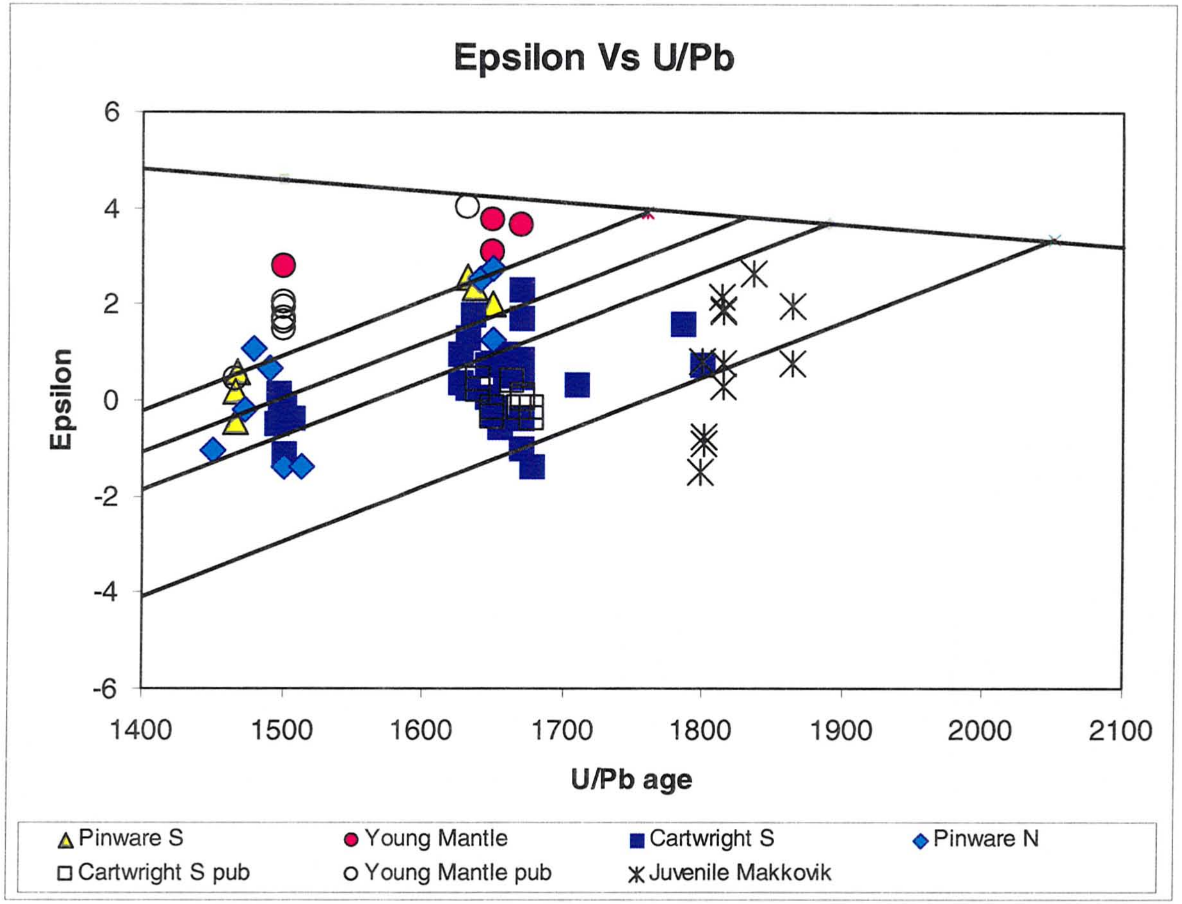

Figure 3.10 Epsilon versus U/Pb ages for data from Gower et al. indicated by solid symbols. Open symbols represent previously published data from Scharer (1991) and Prevec et al., (1990). The top line represents a T_{DM} evolution line, while the sloping lines shown (from left to right) represent average evolution lines for my own dataset from Pinware South, Pinware North, Cartwright South, and the published data from the juvenile Makkovik.

Inverse Distance Weighting

Lastly, all of the data sets were combined and plotted into the GIS program ArcMap 9.2 from ESRI, to create an interpolation map for the southeast Labrador region (Figure 3.11). An interpolation map can help to define the age boundaries between different crustal bodies. The interpolation creates an age contour map which digitally represents the spatial distribution of individual crustal formation ages. Contours were then separated into intervals of 100 Myr, starting at 1000 Ma, and ending at 3000 Ma.

The technique used in this study was the Inverse Distance Weighting (IDW) method, which uses the X and Y axes as the samples Northing and Easting coordinates, while the Z axis represents the T_{DM} model age of the sample. The IDW method is effective for this study because it interpolates the Z axis as a smooth contour.

The interpolation map created illustrates that the terrane of Pinware South is a discrete crustal body with an age range of 1700-1800 Ma, representative of a juvenile Labradorian arc. The boundary for this terrane is quite distinct in the southeast region. The middle terrane, Pinware North, falls in the contour interval of 1800-1900 Ma, but is not as distinct as the Pinware South terrane. It has clearly been affected by mixing between younger crust from the Pinware South terrane, as well as older crust from the Cartwright South terrane. The Cartwright South terrane is not clearly defined in terms of geographical extent, but is spread throughout the region and is represented by an age range of 2.0 to 2.3 Ga, indicative of a Pre-Labradorian crustal component. The demarcation of this unit could represent a new edge for the Makkovik crustal block.

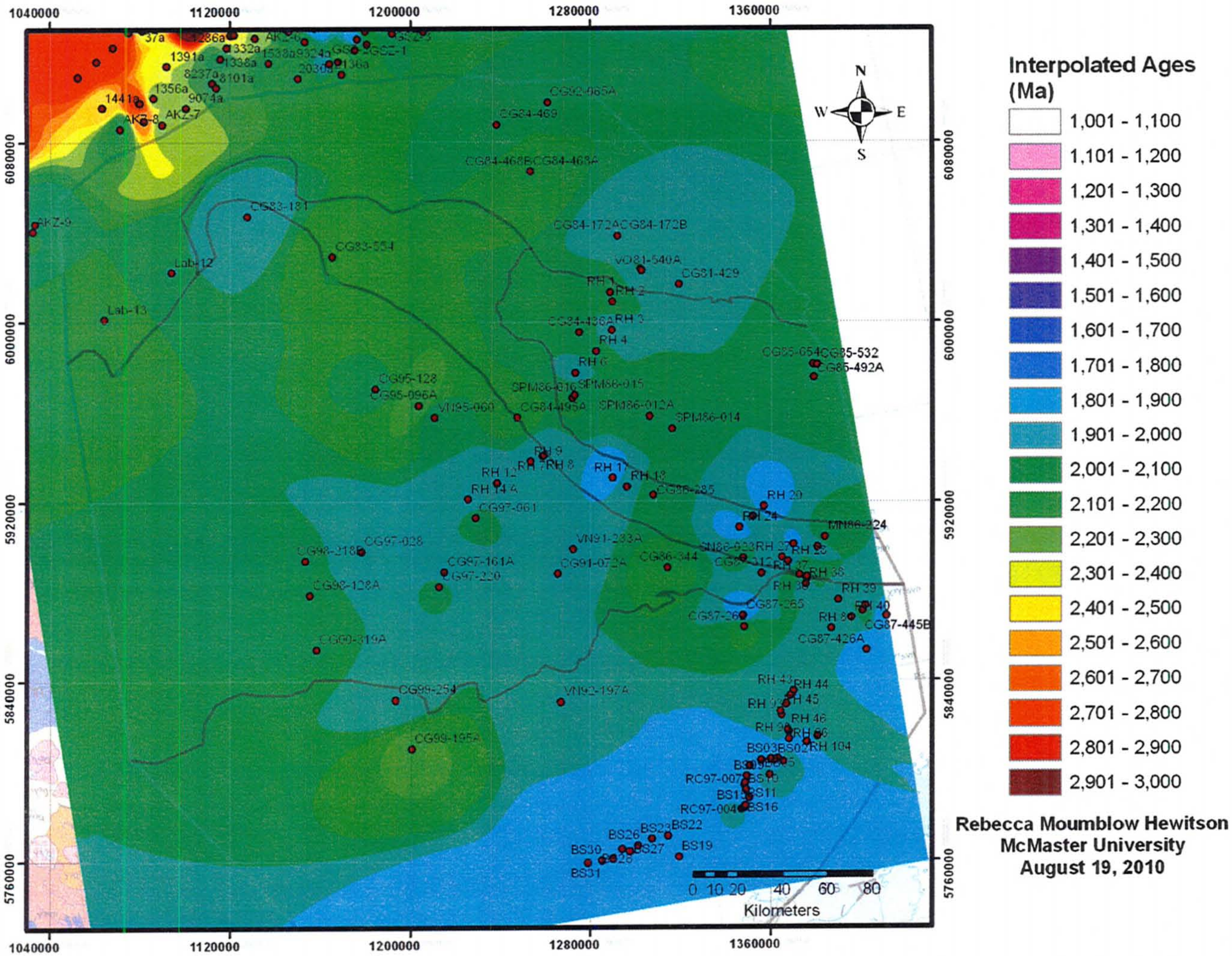

Figure 3.11 Inverse Distance Weighting interpolation contour age map for the area of southeast Labrador. Age intervals of 100 Myr were used to help indicate geological age boundaries. RH= Rebecca Hewitson samples.

Chapter 4: Discussion and Conclusions

The extent of Pre-Labradorian crust

The Grenville Province of southern Labrador has one of the most complex geological histories of any part of the Canadian Shield. As described in the introduction to this work, it records the effects of at least four major orogenic episodes, the Makkovik, Labradorian, Pinwarian and Grenville orogenies. Nd isotope work was performed in order to obtain a better understanding of the geological evolution of this segment of the shield, but the complexities of the geology may prevent decisive conclusions from being drawn.

One of the notable features of the Nd data presented in Chapter 3, including my own new data, the new data of Gower and the published data sets is the considerable isotopic heterogeneities seen within several of the terranes, whether represented as Nd model ages (Figures 3.2 to 3.8) or epsilon values (Figure 3.9). The only crustal block not to show this degree of heterogeneity was the juvenile Labradorian terrane referred to as Pinware South. Hence, it is possible that some of the scatter in the non-juvenile blocks may reflect mixing between Pre-Labradorian and Labradorian magmatism caused by the establishment of a continental margin arc in the region around 1.65 Ga. However, it can be seen in Figures 3.8 and 3.9 that the Makkovik crust to the north of the Grenville Province also shows considerable isotopic heterogeneity, even after the removal of any samples with evidence of Archean crustal influence. This raises the possibility that the isotopic heterogeneity seen in the Labradorian orogeny is partly a vestige of earlier heterogeneity inherited from the Makkovik crust-forming event.

To explore this model, my Nd data are combined with the published Makkovik and Labradorian data in an extended N—S transect in Figure 4.1.

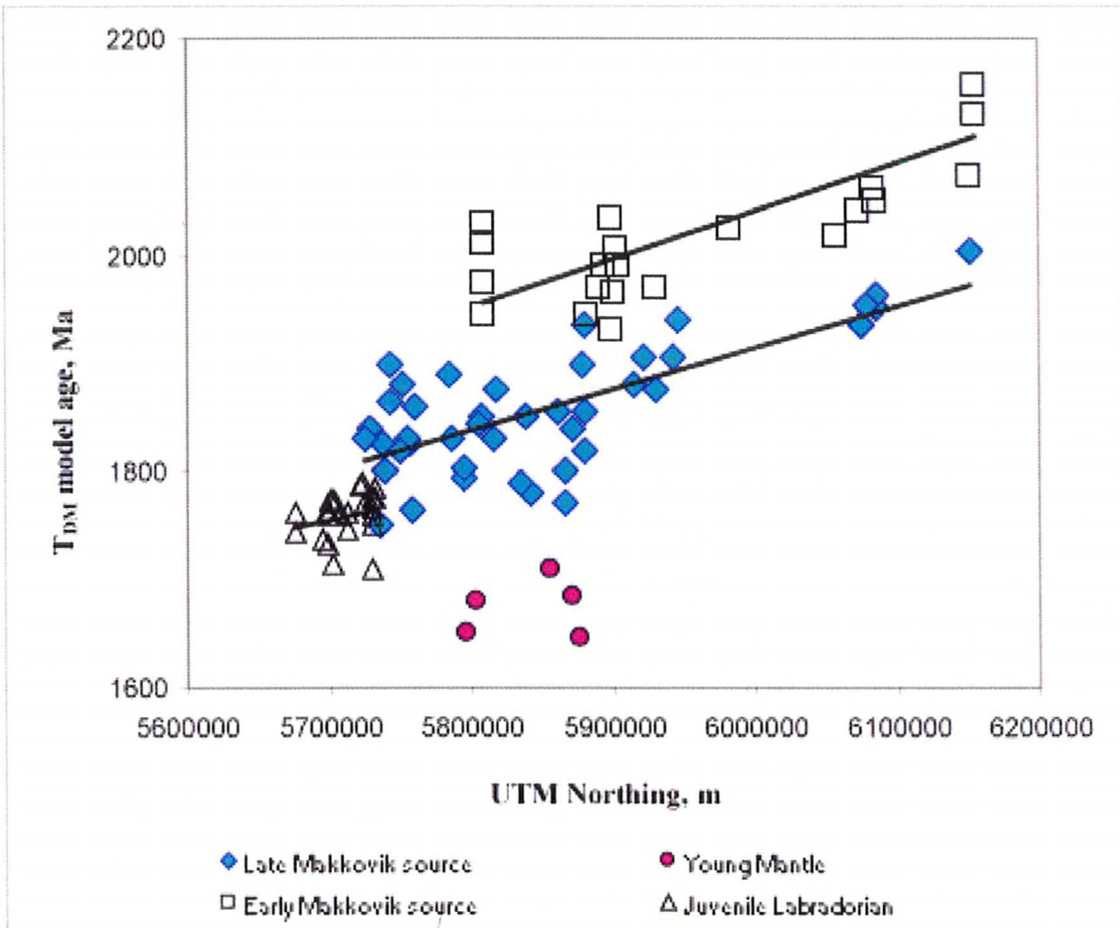

Figure 4.1 North-South plot for T_{DM} model ages displaying the trend for samples with an early and late Makkovikian source, juvenile Labradorian source and a younger mantle source. Additional Makkovik data from Kerr and Fryer (1994).

In this plot, the new and published data are combined and regrouped into four suites. Two of these consist of the Juvenile Labradorian and Young Mantle suites already discussed. However the other two suites were created by distinguishing areas of relatively older and younger pre-Labradorian crust, both north and south of the Grenville Front (which is around the 6000000 mark in Figure 3.8). The 'Older Makkovik' suite includes published data from the Hawke River terrane, along with a small patch of apparently old crust within the SE Mealy Mountains terrane (my data). In contrast the 'Younger Makkovik' suite includes all of my data from the Pinware North terrane, along with most of my Cartwright South suite.

The data distribution in Figure 4.1 still shows a slight younging of Nd model ages towards the south, consistent with an increase in reworking to the south caused by the Labradorian continental margin arc. However, it also explains the patchiness of the isotopic signatures from the pre-Labradorian crust. While not a final conclusion, it makes testable predictions. One of these predictions is that the original edge of the Makkovik continental margin passed just north of Red Bay and trends westwards into the interior (Figure 4.2). The second prediction follows from the first, in that relatively homogeneous Nd isotope signatures are expected to the south of this boundary, whereas heterogeneous signatures are expected to the north. The small data set of Gower from the Pinware North terrane lends some support to this model, since one old age has been discovered in the interior of SW Labrador (see contour map). This model can hopefully be tested in future work.

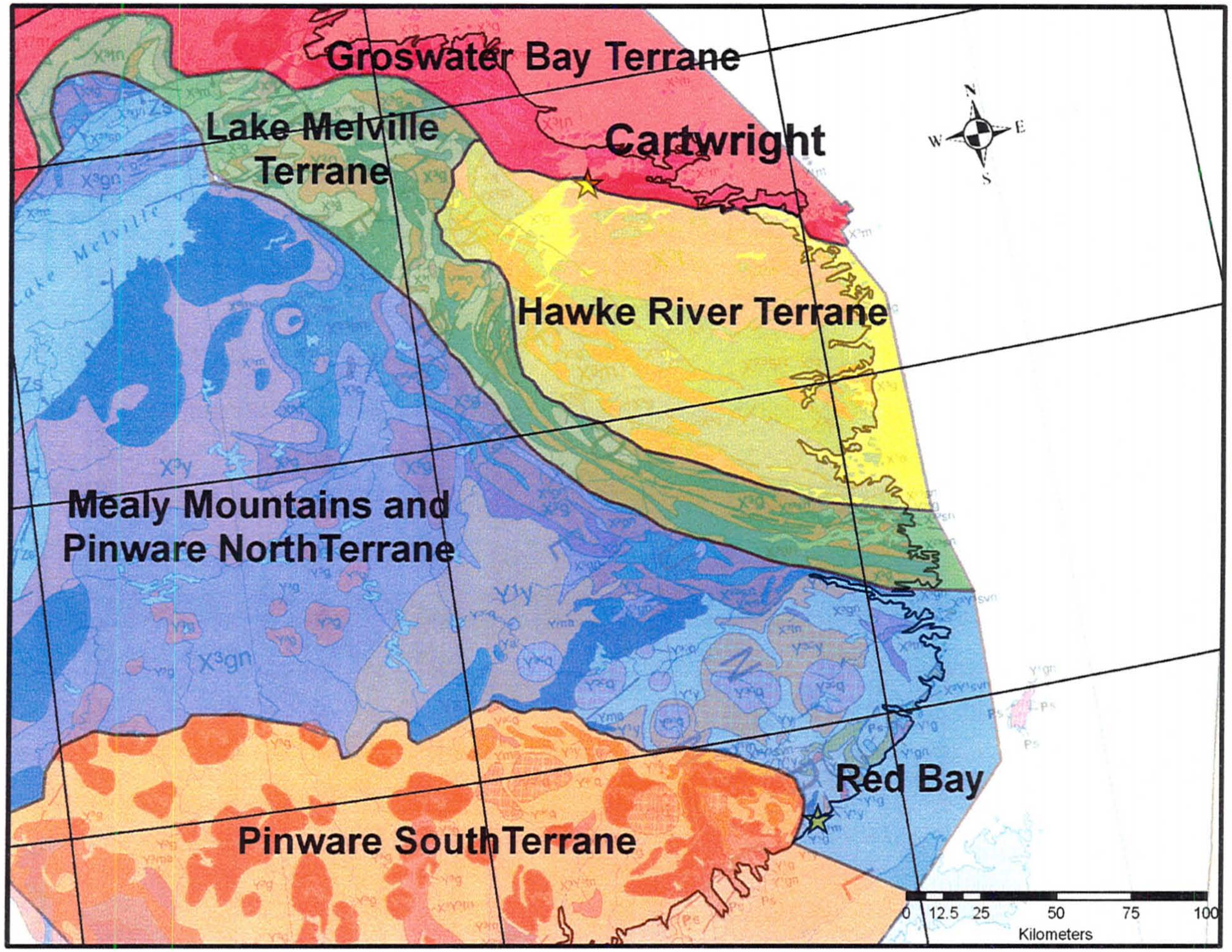

Figure 4.2 Image of southern Labrador. The boundary of the Pinware South terrane marks the newly proposed boundary between the original edge of the Makkovik continental margin which passes just north of Red Bay and trends westward towards the interior of the region.

Possible Analogue for the Labradorian orogeny

The Labradorian orogeny spans across both the earlier Pre-Labradorian continental margin, and a juvenile island arc. This interpretation leads me to propose an accretionary model for the Labradorian orogeny. The proposed model is based on the use of the Appalachian orogeny, (USGS, 2007), as a possible 'modern' analogue for the formation of the Grenville Province in southern Labrador (Figure 4.3).

The formation of the Appalachians began approximately 420 Ma in the late Silurian when the North American plate was being subducted towards the Avalonian island arc which had just formed off the coast within the western portion of the Iapetus Ocean. At this time, the Taconic terrane had already been accreted to the North American craton. By the late Devonian (370 Ma), the Acadian orogeny occurred, which accreted the Avalon terrane to the edge of the craton, and therefore closed the western Iapetus Ocean. The North American craton at this point was separated from the Proto-African plate (Gondwanaland) by the eastern Iapetus Ocean. At the beginning of the Alleghenian orogeny during the late Mississippian (320 Ma), the North American plate and the Proto-African plate collided, resulting in the formation of the supercontinent of Pangaea. This terminal orogeny reached its climax by the late Pennsylvanian (290 Ma), causing subsequent fold belt formation. Lastly, by the late Permian (250 Ma), Pangaea has been inactive, and erosion of the land surface has reduced the mountainous surface features.

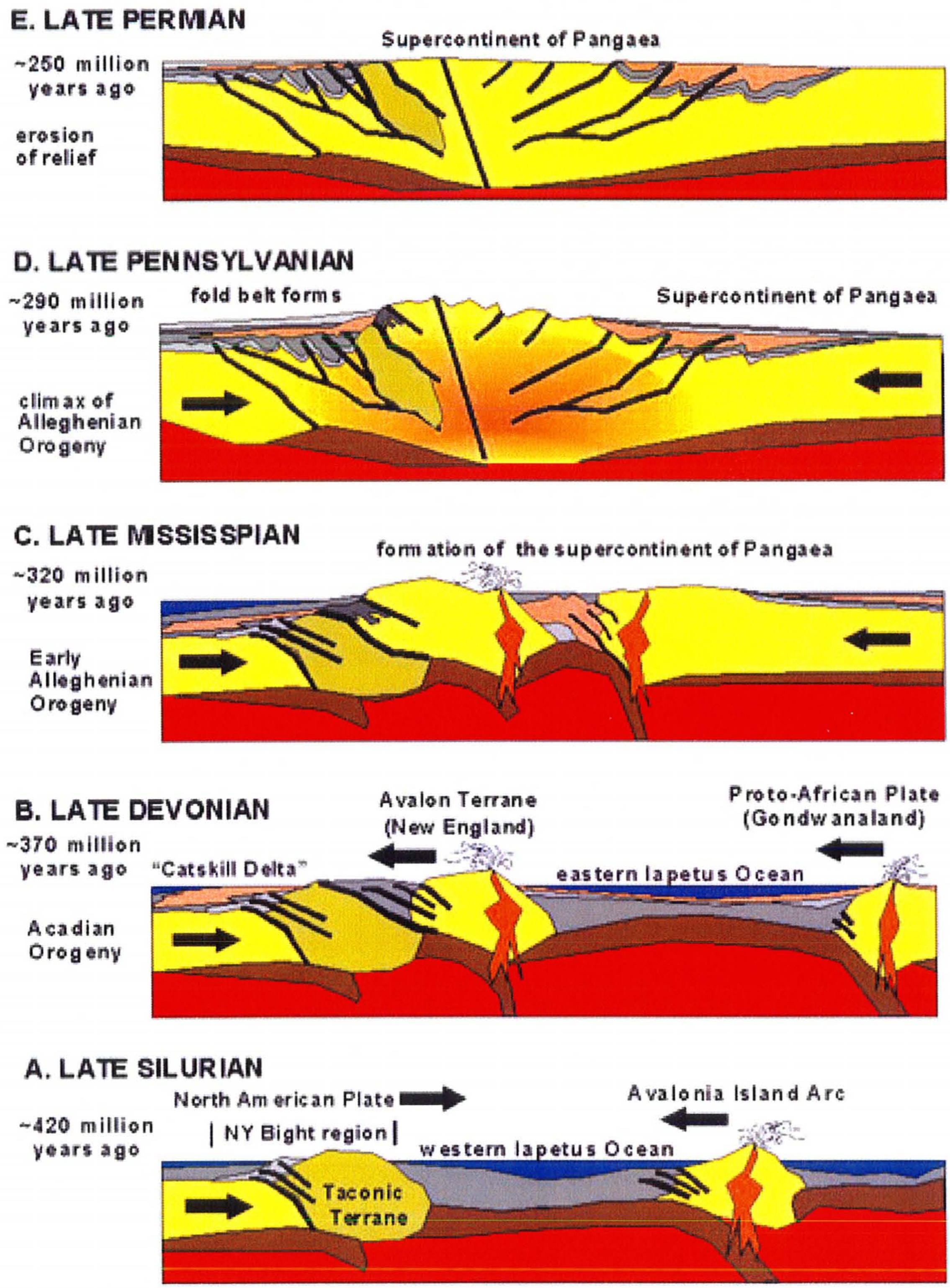

Figure 4.3 Model of the formation of the Appalachian Mountains (USGS, 2007)

Based on the evidence discussed above for a collisional suture north of Red Bay, I propose a similar model for the formation of the Grenville Province in southeast Labrador, with successive accretions to the North American continent, and a subsequent terminal orogeny (Figure 4.4). At approximately 1800 Ma, the Makkovik continental arc and the Cartwright island arc were formed. The Cartwright terrane (Makkovik juvenile arc) was accreted to the North American craton (Laurentia) by 1740 Ma, during the Makkovik orogeny. At this time, the Pinware South arc terrane was beginning to form. This period represents the late Silurian in the Appalachian model, with the Pinware South arc equivalent to the Avalonian arc. By 1650 Ma, the Labradorian orogeny occurred, accreting the Pinware South terrane (juvenile Labradorian arc) to the edge of the craton. This is comparable to the Acadian orogeny of the Appalachians, when the Avalon was accreted to the edge of the continent. The beginning of the terminal collision of the continent of Amazonia with Laurentia occurs by 1100 Ma, representing the Grenville orogeny. This orogeny concludes by 1050 Ma, producing the Grenville Mountain chain, which could be similar to the Appalachian Mountains, caused during the Alleghenian orogeny. Lastly, by 900 Ma, the supercontinent of Rhodinia had been formed, and the resultant post Grenville cooling allowed for erosion of the Grenville Mountain chain, producing the surface features of the Grenville Province seen today in southern Labrador.

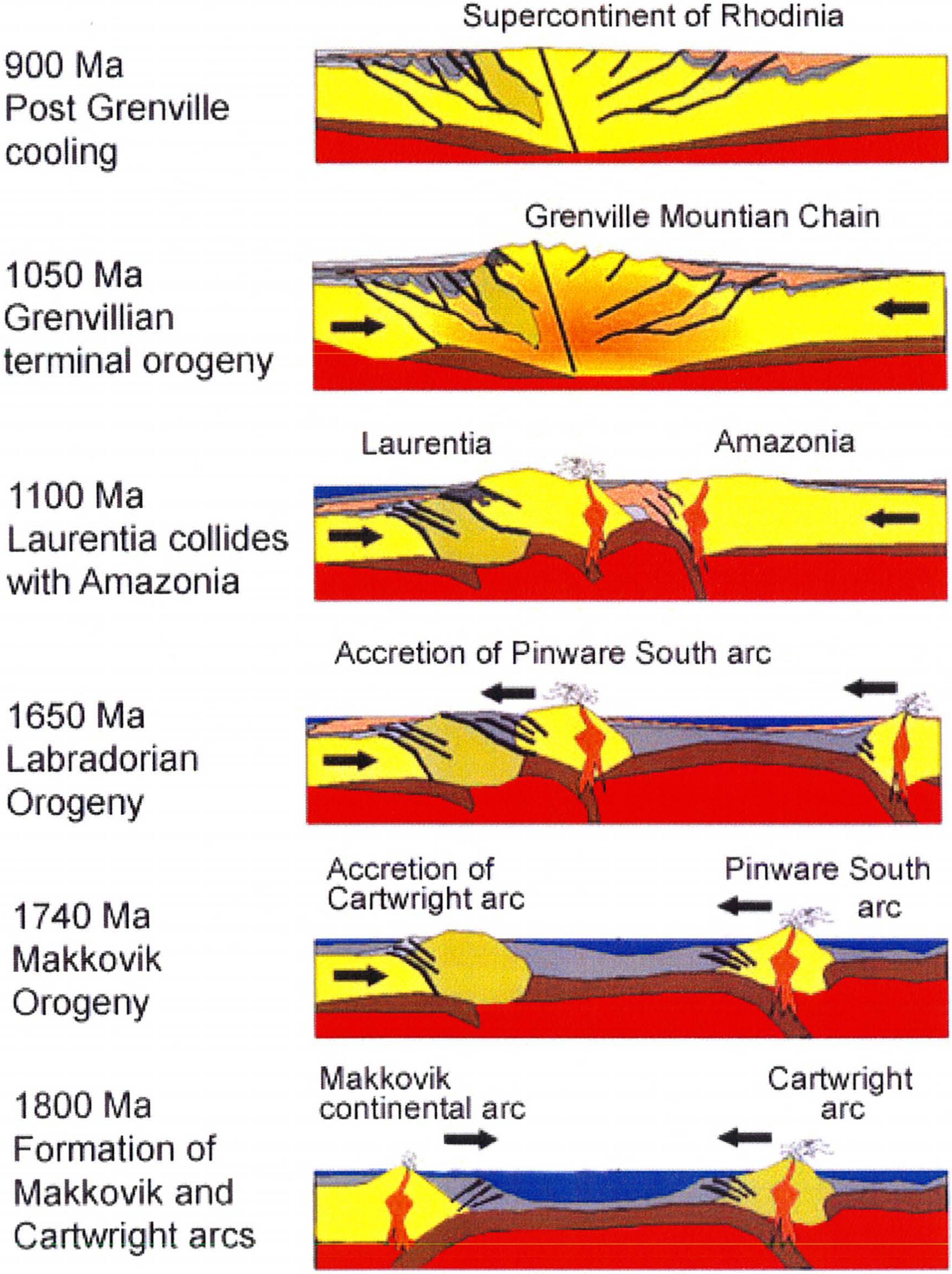

Figure 4.4 Proposed model for the formation of the Grenville Province in southeast Labrador

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Appendices

Appendix A: Methodology

Collection

Forty-eight samples of homogenous high-grade orthogneisses were taken along various exposed rock outcrops along Route 510, and along the highway currently being constructed between Route 510 and Happy Valley-Goose Bay. Since the samples were collected along newly constructed roads, they have very little weathering, but careful consideration was made to sample areas without veins. Careful monitoring of GPS points was taken at all sample locations. The samples were then transferred to McMaster University to be pulverized, chemically separated and then analyzed by mass spectrometry. Nd analysis will be performed by using the 143 Nd/144 Nd ratio to provide crustal formation ages of each sample.

Pulverization

After the samples were collected in the field and transported to McMaster University, they were analyzed and then the best samples were selected for processing. These samples were selected on the basis of homogeneity, and lack of weathering on the surface. Since these samples had come from a fairly pristine environment (had not weathered significantly), little effort was needed to prepare them for pulverization.

To prepare the samples for pulverization into powder, they were first cleaned with a wire brush to remove any debris or dirt, and then split into smaller pieces using a hydraulic jaw splitter. These smaller pieces would be more manageable for the jaw crusher. Two hand samples were also saved as mineral specimens, labelled and catalogued.

The jaw crusher produced gravel sized particles, which were easier to grind down into powder. A small amount of the sample was loaded into the jaw crusher prior to the addition of the remaining sample pieces in order to prevent any cross-contamination of samples. The gravel-sized particles were then transferred to a tabletop splitter, to randomly divide the sample into smaller fractions. The samples were split approximately four times, and then any unused gravel was collected and stored in a labelled clear plastic bag. The remaining gravel was loaded into a tungsten carbide disc mill, which pulverized the sample into sand-sized sediment. This procedure takes about four or five minutes. The sample was divided again (one half was discarded), and then was pulverized again to produce fine-grained sediment (another two to three minutes). The finished powder was placed in a clear-labelled jar, and was ready for chemical analysis.

It is important to note that during the pulverizing process, intensive cleaning procedures were in place to reduce the high volume of dust, and any possible cross contamination of samples. Each piece of equipment was vacuum cleaned, wire brushed, and wiped down with a paper towel. The tabletop splitter was also cleaned with a high-pressure air gun. Lastly, the tungsten carbide disc mill was meticulously brushed with a fine paintbrush, and all surfaces were again wiped clean with a paper towel.

Chemistry: Weighing and Dissolution

The chemical separation and dissolution of the sample took place in the clean lab. To separate the rare elements Neodymium and Samarium from the rest of the sample, the other silicate and carbonate components must be dissolved.

Approximately 100 to 150 mg of sample was weighed out and placed into a Teflon bomb. The weight of the sample, the empty bomb and lid, as well as the combined weight of the bomb, lid and sample were measured and recorded. Concentrated nitric acid (<1 mL) was then added to prevent any danger from the subsequent stage involving hydrofluoric acid (HF). Next, 10 mL of HF was dissolved in each bomb, and placed in a safety jacket. These safety jackets were placed in an oven for 3 days at 140° C. After dissolution, each sample was then dried down on a hot plate over night. The following day, the sample was re-dissolved in concentrated HNO_3 (5mL), and then allowed to evaporate on the hot plates. Once the sample had evaporated, it was dissolved in 6M hydrochloric acid (HCl), placed back in the safety jacket and heated overnight in the oven.

Chemistry: Splitting and Spiking

The following day, samples were diluted with 5mL of milli-Q water. They were shaken to mix the solution, and weighed out to record the mass (in the bomb and lid). One third of the solution was then poured into a 15mL Teflon beaker, and put aside for spiking. The remaining bombs were reweighed and recorded. The solution was then spiked with a small amount of rare earth element solution (containing Sm^{149}-Nd^{150}). The spike bottle was weighed and tarred between each addition to the sample, and recorded. Once the spike was applied to each sample, the samples were dried down on hot plates and dissolved in 2mL of 1M HCl. The samples were then placed in the centrifuge on 1000RPM for 10 minutes.

Cation Exchange Chromatography

To separate the rare earth elements from the sample, a series of elutions must be applied. This chromatography process uses columns containing approximately 14 cm of Dowex Bio-Rad AG 50W (200-400 mesh) resin. Using a pipette, a measured 1mL of the sample was put into the columns, and then eluted with 3M HNO_3 in various volumes. First there was a dose of 3mL, and then 53mL was added. These elutions remove any of the major elements such as Calcium (Ca), Sodium (Na) and Potassium (K). Once this was complete, another 12mL of 7.5M HNO_3 was added to the column to collect the remaining rare earth elements. At this point, the columns were cleaned, and the samples were placed under heat lamps to dry down. The samples were then re-dissolved in 0.3M HCl for the next step in chromatography.

REE Chromatography

1mL of the sample was then added to rare earth element columns, which contain a hexyl di-ethyl hydrogen phosphate resin that is coated in Teflon beads. Then a series of washes were added to isolate the Samarium and Neodymium from the sample. Two washes of 1mL 0.3M HCl were conducted followed by an elution of 25mL 0.3M HCl. The unspiked samples were then collected in 12mL of 0.3M HCl, and then the columns were cleaned. The spiked samples were also collected in 12mL of 0.3M HCl (for Nd), but were also then washed with 2.5mL of 1M HCl to collect Samarium in 12mL of 1M HCl. These samples were then finally dried down under heat lamps until the liquid was about the size of a small pinhead.

Thermal-Ionization Mass Spectrometry ("TIMS")

The processed samples were then transferred onto a glass bead containing a tantalum side filament and a rhemium center filament. The sample was loaded onto the tantalum filament using 0.7 μL of 0.3M H_3PO_4 using a small amount of current to dry them into place. The samples were then placed in the barrel of a VG isomass 354 thermal ionization solid source mass spectrometer. The spiked samples were then measured for whole rock content. A La Jolla Standard was run with every barrel to compare for precision. All spiked samples within run precision of >0.02% were rejected, and all unspiked samples within run precision of >0.01% were rejected. These errors can represent an overall Nd-model age error of 20Myr (Dickin and McNutt, 1989). Blank samples were also run with each sample set to measure the accuracy of the chemistry.

Appendix B:

Table B.1: La Jolla Standards

Date	$^{143}Nd/^{144}Nd$	Standard Error (‰)
10/15/2007	.511874	.012
10/22/2007	.511862	.012
11/05/2007	.511873	.012
11/12/2007	.511881	.011
11/19/2007	.511862	.013
11/26/2007	.511876	.010
12/10/2007	.511867	.014

Date	$^{143}Nd/^{144}Nd$	Standard Error (‰)
01/11/2008	.511833	.030
01/18/2008	.511877	.011
01/25/2008	.511839	.013
03/01/2008	.511864	.019
03/08/2008	.511859	.009
03/15/2008	.511849	.011
03/22/2008	.511846	.016
04/05/2008	.511841	.012
04/12/2008	.511856	.013
05/31/2008	.511870	.012
06/07/2008	.511852	.014
06/14/2008	.511862	.012
06/21/2008	.511861	.012
08/18/2008	.511879	.011
08/25/2008	.511852	.012
09/08/2008	.511890	.012
09/15/2008	.511879	.011
09/22/2008	.511874	.012
09/29/2008	.511880	.009
10/27/2008	.511879	.014
11/03/2008	.511845	.011
11/10/2008	.511846	.011
11/17/2008	.511859	.010
11/24/2008	.511866	.011
12/01/2008	.511860	.012
12/08/2008	.511862	.011
12/29/2008	.511845	.013

Date	$^{143}Nd/^{144}Nd$	Standard Error (‰)
01/05/2009	.511835	.010
01/19/2009	.511880	.010
01/26/2009	.511841	.010
02/16/2009	.511847	.010
02/23/2009	.511858	.011
03/16/2009	.511867	.012
03/23/2009	.511856	.013
04/04/2009	.511864	.013
04/20/2009	.511868	.013
04/27/2009	.511884	.012
05/11/2009	.511861	.012
05/25/2009	.511853	.015
06/22/2009	.511852	.011
06/29/2009	.511881	.012
07/06/2009	.511860	.011
07/13/2009	.511876	.014
08/03/2009	.511866	.014
09/14/2009	.511862	.009
09/21/2009	.511871	.009
10/12/2009	.511846	.010
10/26/2009	.511873	.010
11/02/2009	.511842	.010
11/16/2009	.511831	.011
11/23/2009	.511828	.010
11/30/2009	.511862	.011
12/07/2009	.511863	.013
12/14/2009	.511843	.011

Date	$^{143}Nd/^{144}Nd$	Standard Error (‰)
01/11/2010	.511833	.030
01/18/2010	.511877	.011
01/25/2010	.511839	.013
03/01/2010	.511864	.019
03/08/2010	.511859	.009
03/15/2010	.511849	.011
03/22/2010	.511846	.016
04/05/2010	.511841	.012
04/12/2010	.511856	.013
05/31/2010	.511870	.012
06/07/2010	.511852	.014
06/14/2010	.511862	.012
06/21/2010	.511861	.012

Appendix C: Original Dataset with Duplicate Nd Runs

Table C.1. Original Dataset

Date	Sample #	Nd (ppm)	Sm (ppm)	147Sm/144Nd	143Nd/144Nd	Error per mil	TDM age (Ma)
	Hawke River Terrane						
May-08	RH 1	29.0	5.12	0.1066	0.511677	0.015	1940
Jul-10	RH 1a	29.4	5.28	0.1085	0.511702	0.018	1940
Nov-07	RH 2	21.3	3.93	0.1117	0.511767	0.017	1905
Nov-07	RH 3a	8.9	1.21	0.0826	0.511348	0.016	1970
Jun-10	RH3b	6.1	0.89	0.0889	0.511613	0.041	1744
Jul-10	RH 3c	7.2	1.11	0.0938	0.511568	0.013	1875
Oct-08	RH 4a	31.9	5.64	0.1070	0.511708	0.012	1905
Nov-07	RH 6	47.9	10.04	0.1267	0.511968	0.016	1880
	Lake Melville Terrane						
Sep-07	RH 17	22.5	3.92	0.1055	0.511782	0.012	1770
May-10	17c	18.8	3.31	0.1065	0.511815	0.013	1740
Sep-07	RH 18	78.0	13.98	0.1083	0.511758	0.010	1855
Apr-08	RH 18a	117.8	21.08	0.1082	0.511747	0.013	1870
Feb-09	RH 19	57.5	8.75	0.0920	0.511679	0.011	1710
Apr-09	RH 19a	57.9	8.76	0.0915	0.511673	0.019	1710
Feb-09	RH 20	44.9	6.75	0.0909	0.511604	0.010	1780
Nov-07	RH 22	13.2	2.31	0.1057	0.511734	0.018	1850
Sep-07	RH 24	42.0	5.78	0.0831	0.511491	0.041	1810
Apr-09	RH 24a	71.1	9.65	0.0821	0.511493	0.021	1790
Feb-09	RH 27b	38.6	7.65	0.1199	0.511888	0.013	1875
May-10	RH 27 d				0.511894	0.014	
Sep-07	RH 28	133.0	25.02	0.1137	0.511838	0.010	1830
	Mealy Mountains						
Oct-08	RH 7b	39.7	7.37	0.1123	0.511753	0.011	1935
Apr-09	RH 8b				0.511853	0.013	
Apr-10	RH8c	47.9	9.26	0.1167	0.511860	0.015	1855
Sep-07	RH 9	48.0	9.33	0.1174	0.511841	0.010	1900
Sep-07	RH 12	36.0	7.27	0.1220	0.511936	0.010	1840
Oct-08	RH13	49.7	7.03	0.0855	0.511625	0.012	1685
Apr-10	RH13c	47.9	6.77	0.0790	0.511622	0.022	1690
Sep-07	RH 14A	44.4	6.92	0.0941	0.511627	0.016	1800
Sep-07	RH 15	77.7	15.34	0.1193	0.511913	0.010	1820
Apr-10	RH30d	21.5	4.37	0.1227	0.511825	0.015	2040
Jun-10	RH 30e	21.9	4.47	0.1233	0.511842	0.014	2030
Feb-09	RH 35 A	35.97	6.66	0.1120	0.511744	0.010	1945
Apr-09	RH 36b				0.511645	0.013	
Apr-10	RH36c	25.2	4.56	0.1094	0.511649	0.018	2040
Jun-10	RH36d	28.1	5.04	0.1085	0.511654	0.011	2010
09-Feb	RH 37b	27.8	4.51	0.0980	0.511544	0.010	1975

Date	Sample #	Nd (ppm)	Sm (ppm)	147Sm/144Nd	143Nd/144Nd	Error per mil	TDM age(Ma)
	Pinware North						
Apr-08	RH 31a	42.3	7.36	0.1050	0.511747	0.013	1815
Apr-09	RH 31b	38.6	6.69	0.1047	0.511718	0.011	1820
Feb-09	RH 32a	176.4	31.40	0.1076	0.511869	0.014	1685
Apr-10	RH32c	96.8	17.13	0.1070	0.511865	0.013	1680
Sep-07	RH 33	85.9	13.89	0.0977	0.511789	0.011	1730
Apr-10	RH33a	85.7	12.7	0.0895	0.511752	0.013	1580
Jul-10	RH 33b	80.2	12.69	0.0957	0.511758	0.013	1660
May-08	RH 38	56.3	10.43	0.1119	0.511740	0.012	1950
Oct-08	RH 38a	52.3	9.66	0.1115	0.511744	0.013	1935
Apr-09	RH 38b				0.511780	0.011	
May-10	RH38c	52.1	9.58	0.1111	0.511800	0.010	1845
May-08	RH 39a	14.8	2.63	0.1074	0.511789	0.018	1795
Feb-09	RH 40c	6.2	1.16	0.1126	0.511827	0.024	1830
Apr-09	RH 40d	7.1	1.29	0.1106	0.511820	0.041	1805
Apr-09	RH 43	40.5	7.51	0.1119	0.511777	0.011	1860
Apr-09	RH 44	35.1	6.04	0.1041	0.511729	0.011	1825
Apr-09	RH 45	37.2	6.58	0.1069	0.511724	0.015	1880
Mar-10	RH 46a	30.2	5.79	0.1157	0.511843	0.010	1865
Apr-10	RH46b	31.2	5.88	0.1139	0.511817	0.013	1870
Oct-09	RH 80	64.6	12.16	0.1138	0.511838	0.024	
Apr-10	RH 80c	53.6	10.11	0.1139	0.511861	0.011	1803
Oct-09	RH 84	44.9	8.29	0.1117	0.511779	0.021	1890
Mar-10	RH 88b	44.7	7.76	0.1048	0.511780	0.014	1765
Jun-10	RH 88d	41.7	7.24	0.1051	0.511778	0.015	1770
Oct-09	RH 91	44.3	7.63	0.1041	0.511722	0.016	1830
Jun-10	RH 91c	50.9	8.9	0.1056	0.511744	0.013	1830
Oct-09	RH 93	43.9	6.9	0.0951	0.511623	0.020	1820
Jan-10	RH 93 b	47.1	7.07	0.0906	0.511569	0.040	1825
Oct-09	RH 96	38.1	6.64	0.1052	0.511688	0.015	1900
Mar-10	RH 98c	24.2	4.04	0.1010	0.511712	0.011	1800
Mar-10	98cTTR	24.6	4.09	0.1004	0.511717	0.011	1780
Oct-09	RH 101	40.1	7.52	0.1131			
Jan-10	RH 101 b				0.511823	0.015	
Mar-10	RH 101e	39.7	7.41	0.1127	0.511833	0.011	1825
Oct-09	RH104a	40.8	6.75	0.0999	0.511742	0.016	1740
Mar-10	RH 104 c	44.4	7.19	0.0977	0.511717	0.012	1740
Mar-10	104cTTR	44.4	7.18	0.0977	0.511711	0.012	1750
Oct-09	RH 108	43.2	7.93	0.1108	0.511802	0.013	1840
Oct-09	RH 110	45.9	8.63	0.1136	0.511829	0.029	1850
Dec-09	RH 110 a	45.1	8.52	0.1142	0.511845	0.013	1830
	Pinware South						
Oct-09	RH 111	46.8	7.92	0.1023	0.511755	0.016	1760
Mar-10	RH 112a	38.2	6.82	0.1081	0.511828	0.015	1750
Jun-10	112aTTR			0.1083	0.511814	0.012	1775
Jan-10	RH113a	53.8	10.4	0.1168	0.511907	0.013	1784

Appendix D:

Table D.1 Major Element Analysis

Sample #	Q	P
RH31	149	-45
RH32	21	-117
RH33	138	-36
RH38	151	-28
RH39	116	-130
RH40	119	-158
RH43	129	-58
RH44	36	-220
RH45	112	-61
RH46	57	-183
RH80	43	-73
RH84	90	-161
RH88	47	-119
RH91	72	-1
RH93	126	-45
RH95	94	-113
RH96	135	-43
RH98	17	-88
RH101	36	-90
RH104	39	-182
RH108	73	-123
RH110	45	-209

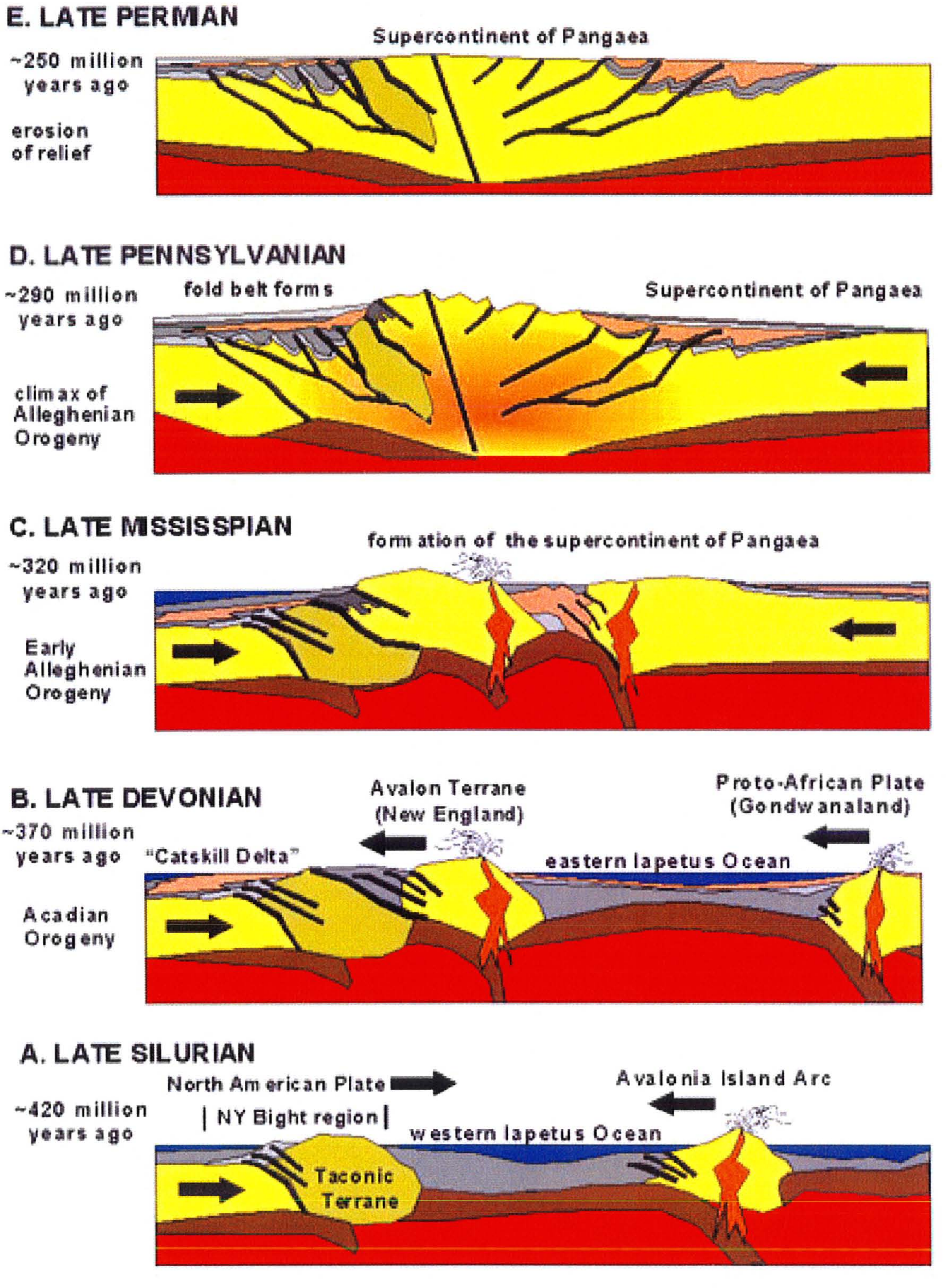

Figure 4.3 Model of the formation of the Appalachian Mountains (USGS, 2007)

Based on the evidence discussed above for a collisional suture north of Red Bay, I propose a similar model for the formation of the Grenville Province in southeast Labrador, with successive accretions to the North American continent, and a subsequent terminal orogeny (Figure 4.4). At approximately 1800 Ma, the Makkovik continental arc and the Cartwright island arc were formed. The Cartwright terrane (Makkovik juvenile arc) was accreted to the North American craton (Laurentia) by 1740 Ma, during the Makkovik orogeny. At this time, the Pinware South arc terrane was beginning to form. This period represents the late Silurian in the Appalachian model, with the Pinware South arc equivalent to the Avalonian arc. By 1650 Ma, the Labradorian orogeny occurred, accreting the Pinware South terrane (juvenile Labradorian arc) to the edge of the craton. This is comparable to the Acadian orogeny of the Appalachians, when the Avalon was accreted to the edge of the continent. The beginning of the terminal collision of the continent of Amazonia with Laurentia occurs by 1100 Ma, representing the Grenville orogeny. This orogeny concludes by 1050 Ma, producing the Grenville Mountain chain, which could be similar to the Appalachian Mountains, caused during the Alleghenian orogeny. Lastly, by 900 Ma, the supercontinent of Rhodinia had been formed, and the resultant post Grenville cooling allowed for erosion of the Grenville Mountain chain, producing the surface features of the Grenville Province seen today in southern Labrador.

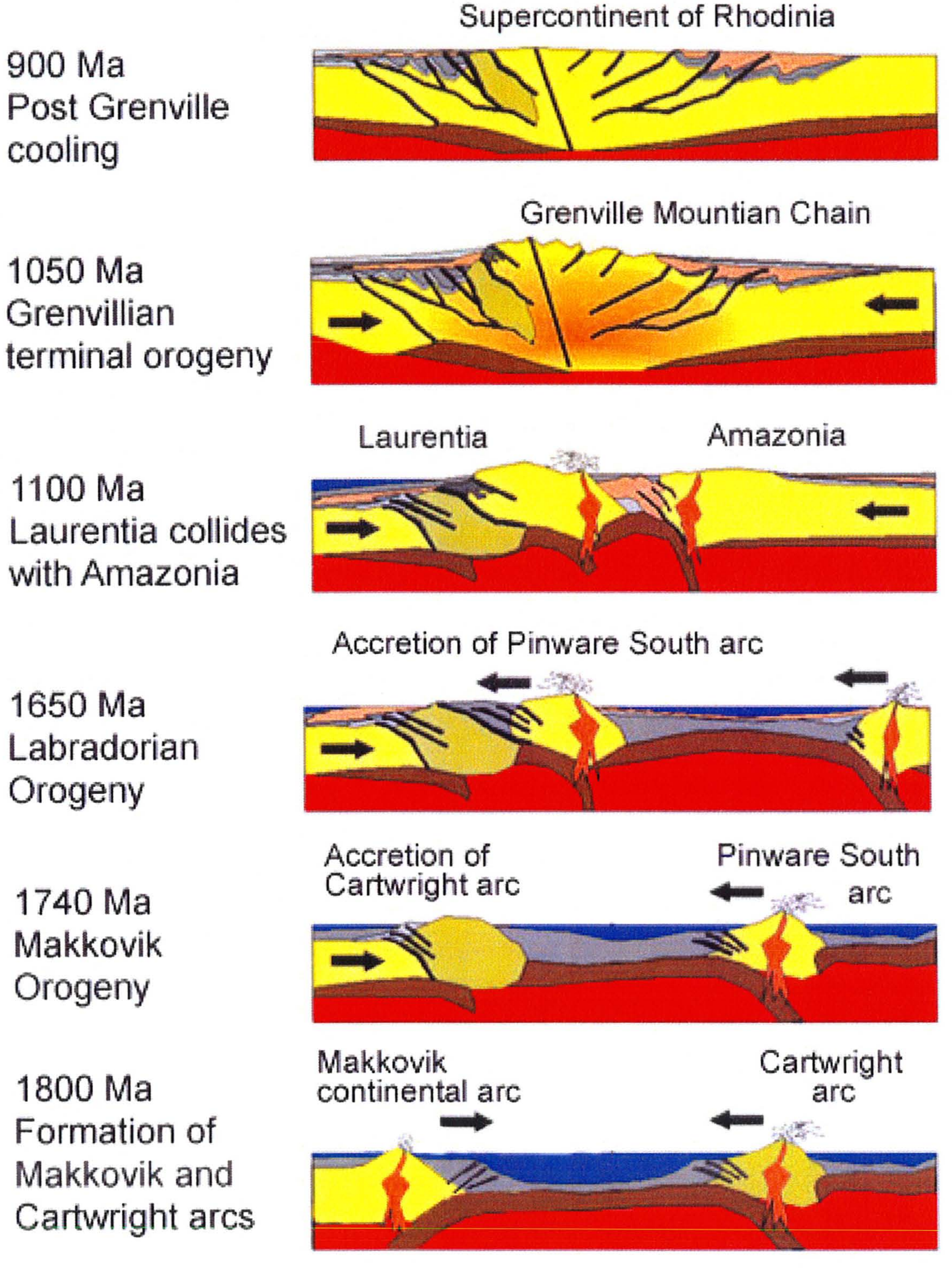

Figure 4.4 Proposed model for the formation of the Grenville Province in southeast Labrador

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Appendices

Appendix A: Methodology

Collection

Forty-eight samples of homogenous high-grade orthogneisses were taken along various exposed rock outcrops along Route 510, and along the highway currently being constructed between Route 510 and Happy Valley-Goose Bay. Since the samples were collected along newly constructed roads, they have very little weathering, but careful consideration was made to sample areas without veins. Careful monitoring of GPS points was taken at all sample locations. The samples were then transferred to McMaster University to be pulverized, chemically separated and then analyzed by mass spectrometry. Nd analysis will be performed by using the 143 Nd/144 Nd ratio to provide crustal formation ages of each sample.

Pulverization

After the samples were collected in the field and transported to McMaster University, they were analyzed and then the best samples were selected for processing. These samples were selected on the basis of homogeneity, and lack of weathering on the surface. Since these samples had come from a fairly pristine environment (had not weathered significantly), little effort was needed to prepare them for pulverization.

To prepare the samples for pulverization into powder, they were first cleaned with a wire brush to remove any debris or dirt, and then split into smaller pieces using a hydraulic jaw splitter. These smaller pieces would be more manageable for the jaw crusher. Two hand samples were also saved as mineral specimens, labelled and catalogued.

The jaw crusher produced gravel sized particles, which were easier to grind down into powder. A small amount of the sample was loaded into the jaw crusher prior to the addition of the remaining sample pieces in order to prevent any cross-contamination of samples. The gravel-sized particles were then transferred to a tabletop splitter, to randomly divide the sample into smaller fractions. The samples were split approximately four times, and then any unused gravel was collected and stored in a labelled clear plastic bag. The remaining gravel was loaded into a tungsten carbide disc mill, which pulverized the sample into sand-sized sediment. This procedure takes about four or five minutes. The sample was divided again (one half was discarded), and then was pulverized again to produce fine-grained sediment (another two to three minutes). The finished powder was placed in a clear-labelled jar, and was ready for chemical analysis.

It is important to note that during the pulverizing process, intensive cleaning procedures were in place to reduce the high volume of dust, and any possible cross contamination of samples. Each piece of equipment was vacuum cleaned, wire brushed, and wiped down with a paper towel. The tabletop splitter was also cleaned with a high-pressure air gun. Lastly, the tungsten carbide disc mill was meticulously brushed with a fine paintbrush, and all surfaces were again wiped clean with a paper towel.

Chemistry: Weighing and Dissolution

The chemical separation and dissolution of the sample took place in the clean lab. To separate the rare elements Neodymium and Samarium from the rest of the sample, the other silicate and carbonate components must be dissolved.

Approximately 100 to 150 mg of sample was weighed out and placed into a Teflon bomb. The weight of the sample, the empty bomb and lid, as well as the combined weight of the bomb, lid and sample were measured and recorded. Concentrated nitric acid (<1 mL) was then added to prevent any danger from the subsequent stage involving hydrofluoric acid (HF). Next, 10 mL of HF was dissolved in each bomb, and placed in a safety jacket. These safety jackets were placed in an oven for 3 days at 140° C. After dissolution, each sample was then dried down on a hot plate over night. The following day, the sample was re-dissolved in concentrated HNO_3 (5mL), and then allowed to evaporate on the hot plates. Once the sample had evaporated, it was dissolved in 6M hydrochloric acid (HCl), placed back in the safety jacket and heated overnight in the oven.

Chemistry: Splitting and Spiking

The following day, samples were diluted with 5mL of milli-Q water. They were shaken to mix the solution, and weighed out to record the mass (in the bomb and lid). One third of the solution was then poured into a 15mL Teflon beaker, and put aside for spiking. The remaining bombs were reweighed and recorded. The solution was then spiked with a small amount of rare earth element solution (containing Sm^{149}-Nd^{150}). The spike bottle was weighed and tarred between each addition to the sample, and recorded. Once the spike was applied to each sample, the samples were dried down on hot plates and dissolved in 2mL of 1M HCl. The samples were then placed in the centrifuge on 1000RPM for 10 minutes.

Cation Exchange Chromatography

To separate the rare earth elements from the sample, a series of elutions must be applied. This chromatography process uses columns containing approximately 14 cm of Dowex Bio-Rad AG 50W (200-400 mesh) resin. Using a pipette, a measured 1mL of the sample was put into the columns, and then eluted with 3M HNO_3 in various volumes. First there was a dose of 3mL, and then 53mL was added. These elutions remove any of the major elements such as Calcium (Ca), Sodium (Na) and Potassium (K). Once this was complete, another 12mL of 7.5M HNO_3 was added to the column to collect the remaining rare earth elements. At this point, the columns were cleaned, and the samples were placed under heat lamps to dry down. The samples were then re-dissolved in 0.3M HCl for the next step in chromatography.

REE Chromatography

1mL of the sample was then added to rare earth element columns, which contain a hexyl di-ethyl hydrogen phosphate resin that is coated in Teflon beads. Then a series of washes were added to isolate the Samarium and Neodymium from the sample. Two washes of 1mL 0.3M HCl were conducted followed by an elution of 25mL 0.3M HCl. The unspiked samples were then collected in 12mL of 0.3M HCl, and then the columns were cleaned. The spiked samples were also collected in 12mL of 0.3M HCl (for Nd), but were also then washed with 2.5mL of 1M HCl to collect Samarium in 12mL of 1M HCl. These samples were then finally dried down under heat lamps until the liquid was about the size of a small pinhead.

Thermal-Ionization Mass Spectrometry ("TIMS")

The processed samples were then transferred onto a glass bead containing a tantalum side filament and a rhemium center filament. The sample was loaded onto the tantalum filament using 0.7 μL of 0.3M H_3PO_4 using a small amount of current to dry them into place. The samples were then placed in the barrel of a VG isomass 354 thermal ionization solid source mass spectrometer. The spiked samples were then measured for whole rock content. A La Jolla Standard was run with every barrel to compare for precision. All spiked samples within run precision of >0.02% were rejected, and all unspiked samples within run precision of >0.01% were rejected. These errors can represent an overall Nd-model age error of 20Myr (Dickin and McNutt, 1989). Blank samples were also run with each sample set to measure the accuracy of the chemistry.

Appendix B:

Table B.1: La Jolla Standards

Date	$^{143}Nd/^{144}Nd$	Standard Error (‰)
10/15/2007	.511874	.012
10/22/2007	.511862	.012
11/05/2007	.511873	.012
11/12/2007	.511881	.011
11/19/2007	.511862	.013
11/26/2007	.511876	.010
12/10/2007	.511867	.014

Date	$^{143}Nd/^{144}Nd$	Standard Error (‰)
01/11/2008	.511833	.030
01/18/2008	.511877	.011
01/25/2008	.511839	.013
03/01/2008	.511864	.019
03/08/2008	.511859	.009
03/15/2008	.511849	.011
03/22/2008	.511846	.016
04/05/2008	.511841	.012
04/12/2008	.511856	.013
05/31/2008	.511870	.012
06/07/2008	.511852	.014
06/14/2008	.511862	.012
06/21/2008	.511861	.012
08/18/2008	.511879	.011
08/25/2008	.511852	.012
09/08/2008	.511890	.012
09/15/2008	.511879	.011
09/22/2008	.511874	.012
09/29/2008	.511880	.009
10/27/2008	.511879	.014
11/03/2008	.511845	.011
11/10/2008	.511846	.011
11/17/2008	.511859	.010
11/24/2008	.511866	.011
12/01/2008	.511860	.012
12/08/2008	.511862	.011
12/29/2008	.511845	.013

Date	$^{143}Nd/^{144}Nd$	Standard Error (‰)
01/05/2009	.511835	.010
01/19/2009	.511880	.010
01/26/2009	.511841	.010
02/16/2009	.511847	.010
02/23/2009	.511858	.011
03/16/2009	.511867	.012
03/23/2009	.511856	.013
04/04/2009	.511864	.013
04/20/2009	.511868	.013
04/27/2009	.511884	.012
05/11/2009	.511861	.012
05/25/2009	.511853	.015
06/22/2009	.511852	.011
06/29/2009	.511881	.012
07/06/2009	.511860	.011
07/13/2009	.511876	.014
08/03/2009	.511866	.014
09/14/2009	.511862	.009
09/21/2009	.511871	.009
10/12/2009	.511846	.010
10/26/2009	.511873	.010
11/02/2009	.511842	.010
11/16/2009	.511831	.011
11/23/2009	.511828	.010
11/30/2009	.511862	.011
12/07/2009	.511863	.013
12/14/2009	.511843	.011

Date	$^{143}Nd/^{144}Nd$	Standard Error (‰)
01/11/2010	.511833	.030
01/18/2010	.511877	.011
01/25/2010	.511839	.013
03/01/2010	.511864	.019
03/08/2010	.511859	.009
03/15/2010	.511849	.011
03/22/2010	.511846	.016
04/05/2010	.511841	.012
04/12/2010	.511856	.013
05/31/2010	.511870	.012
06/07/2010	.511852	.014
06/14/2010	.511862	.012
06/21/2010	.511861	.012

Appendix C: Original Dataset with Duplicate Nd Runs

Table C.1. Original Dataset

Date	Sample #	Nd (ppm)	Sm (ppm)	147Sm/144Nd	143Nd/144Nd	Error per mil	TDM age (Ma)
	Hawke River Terrane						
May-08	RH 1	29.0	5.12	0.1066	0.511677	0.015	1940
Jul-10	RH 1a	29.4	5.28	0.1085	0.511702	0.018	1940
Nov-07	RH 2	21.3	3.93	0.1117	0.511767	0.017	1905
Nov-07	RH 3a	8.9	1.21	0.0826	0.511348	0.016	1970
Jun-10	RH3b	6.1	0.89	0.0889	0.511613	0.041	1744
Jul-10	RH 3c	7.2	1.11	0.0938	0.511568	0.013	1875
Oct-08	RH 4a	31.9	5.64	0.1070	0.511708	0.012	1905
Nov-07	RH 6	47.9	10.04	0.1267	0.511968	0.016	1880
	Lake Melville Terrane						
Sep-07	RH 17	22.5	3.92	0.1055	0.511782	0.012	1770
May-10	17c	18.8	3.31	0.1065	0.511815	0.013	1740
Sep-07	RH 18	78.0	13.98	0.1083	0.511758	0.010	1855
Apr-08	RH 18a	117.8	21.08	0.1082	0.511747	0.013	1870
Feb-09	RH 19	57.5	8.75	0.0920	0.511679	0.011	1710
Apr-09	RH 19a	57.9	8.76	0.0915	0.511673	0.019	1710
Feb-09	RH 20	44.9	6.75	0.0909	0.511604	0.010	1780
Nov-07	RH 22	13.2	2.31	0.1057	0.511734	0.018	1850
Sep-07	RH 24	42.0	5.78	0.0831	0.511491	0.041	1810
Apr-09	RH 24a	71.1	9.65	0.0821	0.511493	0.021	1790
Feb-09	RH 27b	38.6	7.65	0.1199	0.511888	0.013	1875
May-10	RH 27 d				0.511894	0.014	
Sep-07	RH 28	133.0	25.02	0.1137	0.511838	0.010	1830
	Mealy Mountains						
Oct-08	RH 7b	39.7	7.37	0.1123	0.511753	0.011	1935
Apr-09	RH 8b				0.511853	0.013	
Apr-10	RH8c	47.9	9.26	0.1167	0.511860	0.015	1855
Sep-07	RH 9	48.0	9.33	0.1174	0.511841	0.010	1900
Sep-07	RH 12	36.0	7.27	0.1220	0.511936	0.010	1840
Oct-08	RH13	49.7	7.03	0.0855	0.511625	0.012	1685
Apr-10	RH13c	47.9	6.77	0.0790	0.511622	0.022	1690
Sep-07	RH 14A	44.4	6.92	0.0941	0.511627	0.016	1800
Sep-07	RH 15	77.7	15.34	0.1193	0.511913	0.010	1820
Apr-10	RH30d	21.5	4.37	0.1227	0.511825	0.015	2040
Jun-10	RH 30e	21.9	4.47	0.1233	0.511842	0.014	2030
Feb-09	RH 35 A	35.97	6.66	0.1120	0.511744	0.010	1945
Apr-09	RH 36b				0.511645	0.013	
Apr-10	RH36c	25.2	4.56	0.1094	0.511649	0.018	2040
Jun-10	RH36d	28.1	5.04	0.1085	0.511654	0.011	2010
09-Feb	RH 37b	27.8	4.51	0.0980	0.511544	0.010	1975

Date	Sample #	Nd (ppm)	Sm (ppm)	147Sm/144Nd	143Nd/144Nd	Error per mil	TDM age(Ma)
	Pinware North						
Apr-08	RH 31a	42.3	7.36	0.1050	0.511747	0.013	1815
Apr-09	RH 31b	38.6	6.69	0.1047	0.511718	0.011	1820
Feb-09	RH 32a	176.4	31.40	0.1076	0.511869	0.014	1685
Apr-10	RH32c	96.8	17.13	0.1070	0.511865	0.013	1680
Sep-07	RH 33	85.9	13.89	0.0977	0.511789	0.011	1730
Apr-10	RH33a	85.7	12.7	0.0895	0.511752	0.013	1580
Jul-10	RH 33b	80.2	12.69	0.0957	0.511758	0.013	1660
May-08	RH 38	56.3	10.43	0.1119	0.511740	0.012	1950
Oct-08	RH 38a	52.3	9.66	0.1115	0.511744	0.013	1935
Apr-09	RH 38b				0.511780	0.011	
May-10	RH38c	52.1	9.58	0.1111	0.511800	0.010	1845
May-08	RH 39a	14.8	2.63	0.1074	0.511789	0.018	1795
Feb-09	RH 40c	6.2	1.16	0.1126	0.511827	0.024	1830
Apr-09	RH 40d	7.1	1.29	0.1106	0.511820	0.041	1805
Apr-09	RH 43	40.5	7.51	0.1119	0.511777	0.011	1860
Apr-09	RH 44	35.1	6.04	0.1041	0.511729	0.011	1825
Apr-09	RH 45	37.2	6.58	0.1069	0.511724	0.015	1880
Mar-10	RH 46a	30.2	5.79	0.1157	0.511843	0.010	1865
Apr-10	RH46b	31.2	5.88	0.1139	0.511817	0.013	1870
Oct-09	RH 80	64.6	12.16	0.1138	0.511838	0.024	
Apr-10	RH 80c	53.6	10.11	0.1139	0.511861	0.011	1803
Oct-09	RH 84	44.9	8.29	0.1117	0.511779	0.021	1890
Mar-10	RH 88b	44.7	7.76	0.1048	0.511780	0.014	1765
Jun-10	RH 88d	41.7	7.24	0.1051	0.511778	0.015	1770
Oct-09	RH 91	44.3	7.63	0.1041	0.511722	0.016	1830
Jun-10	RH 91c	50.9	8.9	0.1056	0.511744	0.013	1830
Oct-09	RH 93	43.9	6.9	0.0951	0.511623	0.020	1820
Jan-10	RH 93 b	47.1	7.07	0.0906	0.511569	0.040	1825
Oct-09	RH 96	38.1	6.64	0.1052	0.511688	0.015	1900
Mar-10	RH 98c	24.2	4.04	0.1010	0.511712	0.011	1800
Mar-10	98cTTR	24.6	4.09	0.1004	0.511717	0.011	1780
Oct-09	RH 101	40.1	7.52	0.1131			
Jan-10	RH 101 b				0.511823	0.015	
Mar-10	RH 101e	39.7	7.41	0.1127	0.511833	0.011	1825
Oct-09	RH104a	40.8	6.75	0.0999	0.511742	0.016	1740
Mar-10	RH 104 c	44.4	7.19	0.0977	0.511717	0.012	1740
Mar-10	104cTTR	44.4	7.18	0.0977	0.511711	0.012	1750
Oct-09	RH 108	43.2	7.93	0.1108	0.511802	0.013	1840
Oct-09	RH 110	45.9	8.63	0.1136	0.511829	0.029	1850
Dec-09	RH 110 a	45.1	8.52	0.1142	0.511845	0.013	1830
	Pinware South						
Oct-09	RH 111	46.8	7.92	0.1023	0.511755	0.016	1760
Mar-10	RH 112a	38.2	6.82	0.1081	0.511828	0.015	1750
Jun-10	112aTTR			0.1083	0.511814	0.012	1775
Jan-10	RH113a	53.8	10.4	0.1168	0.511907	0.013	1784

Appendix D:

Table D.1 Major Element Analysis

Sample #	Q	P
RH31	149	-45
RH32	21	-117
RH33	138	-36
RH38	151	-28
RH39	116	-130
RH40	119	-158
RH43	129	-58
RH44	36	-220
RH45	112	-61
RH46	57	-183
RH80	43	-73
RH84	90	-161
RH88	47	-119
RH91	72	-1
RH93	126	-45
RH95	94	-113
RH96	135	-43
RH98	17	-88
RH101	36	-90
RH104	39	-182
RH108	73	-123
RH110	45	-209