ND ISOTOPE MAPPING OF CRUSTAL BOUNDARIES WITHIN THE EASTERN GRENVILLE AND MAKKOVIK PROVINCES, SOUTHERN LABRADOR

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ABSTRACT

The geological history of southeast Labrador has been resolved into four major orogenic events based on U-Pb dating: the Makkovik orogeny (1880-1790 Ma), the Labradorian orogeny (1710-1600 Ma), the Pinwarian (1520-1460 Ma) and the Grenville orogeny (1085-985 Ma). Although U-Pb ages represent the time of igneous and metamorphic events, they do not necessarily reflect the time of extraction of crustal material from the mantle. Nd isotopic data provide a tool for doing this, hence permitting regions having differing (and perhaps older) crustal formation ages to be recognized, even if this is not apparent in U-Pb geochronological data.

In this study, suites of Depleted Mantle model (T_{DM}) ages were determined for three large regions of southern Labrador. These comprise an east-west suite across the eastern Makkovik Province (Cape Harrison domain); a north-south suite along the Labrador coast of the Grenville Province (Groswater Bay, Hawke River, Lake Melville, Mealy Mountains and the Pinware terranes); and a reconnaissance suite from the Grenville Province in the interior of southern Labrador (Mealy Mountains, Pinware and Wilson Lake terranes, as well as the Trans Labrador Batholith).

New Nd isotope data for the eastern Makkovik Province suggest that accreted juvenile Makkovik crust was generated in the Cape Harrison domain during a single crust-forming event around 2.0 Ga. Based on these data, a tectonic model is proposed for the Paleoproterozoic Makkovikian orogeny that is similar to the Ketilidian orogeny.

In the eastern Grenville Province, Nd data indicate a southern extension of juvenile Makkovik crust, but with strong Labradorian reworking. A WNW-ESE boundary is proposed between Makkovik crust and juvenile Labradorian crust within the northern

part of the Pinware terrane near Red Bay. This boundary separates the Pinware terrane into a Pinware North block (T_{DM} ages often above 1.85 Ga), consisting of reworked Makkovik crust, and a Pinware South block (T_{DM} ages below 1.85 Ga), representing juvenile Labradorian arc crust. A new tectonic model is then proposed for the accretion of this juvenile terrane during the Labradorian orogeny.

Finally, Nd isotope data were determined in the interior of southern Labrador in order to trace the crustal boundary seen at the coast westwards. To the north of the Labrador-Quebec border, reworked Makkovik crust (TDM ages > 1.85 Ga) is present within a large regional fold in the north-western Pinware terrane, indicating that Makkovik basement does continue westwards in the northern part of this terrane.

The new Nd data indicate that juvenile Makkovik arc crust, of the type seen north of the Grenville Province, extends southwards across much of the Grenville Province of southern Labrador, but with increasing degrees of Labradorian reworking southwards. It is believed that the original edge of the Makkovik continental margin was located just north of Red Bay, with an approximately WNW-ESE trajectory. This crustal boundary is believed to continue westwards approximately along the provincial boundary, reflecting the presence of Makkovik basement in the northern Pinware terrane.

ACKNOWLEDGEMENTS

My passion for learning, and my inability to quit has kept me motivated over the last four years. However, there are many people who have been instrumental in the completion of this dissertation. I would like to take this opportunity to thank those who made this possible.

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I would also like to thank my supervisory committee members, Dr. Charles Gower and Dr. Robert McNutt. I am particularly indebted to Charlie who graciously offered to supervise me in the field in his home territory of southern Labrador, and most importantly for the wealth of data and knowledge he has cumulated over his career at the Geologic Survey of Newfoundland and Labrador. I am also grateful for Bob McNutt, who has been an immense source of support since the completion of my undergraduate degree, my masters, and now throughout my PhD. His input and advice have provided clarity to my project, and his counsel during committee meetings has provided the focus needed for the successful completion of my thesis.

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It is always nice to have friends who share a common purpose; and our shared love of the Grenville Province, has made my journey much more pleasurable.

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I would also like to thank my extended family, Scott, Tom and Jackie, for their continued support during my pursuit of education. I would not have been able to accomplish anything without the time you have given me, by looking after Evan and Emma while I was away at school. I am extremely lucky that you are in my life.

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I am very fortunate to have a partner, and friend, who has been an amazing source of support over the past four years. Joe, you have been there for me when I needed your advice and counsel, but most of all, you were there when I just needed someone to calm me down, and tell me I could do it. I realize that being the partner of someone who goes through this process, is not really a good time. So, I'm thankful for your patience and kindness when I needed it most.

Finally, I want to thank my beautiful children, Emma and Evan. It is a challenge to attempt a PhD, but it is an even harder challenge to do it while raising kids. I know that it wasn’t always fun when Mommy was busy doing schoolwork, but I hope that someday you will understand my passion for learning and that in turn, you will find your passion. It is for you that I dedicate this dissertation.

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PREFACE

This dissertation contains three results chapters, which represent manuscripts for peer- reviewed publication. The papers represent the results of research carried out by the author under the supervision of Dr. Alan P. Dickin in partial fulfillment of a Ph. D. degree. The first author on these research papers (dissertation author) carried out literature reviews, laboratory analyses, data interpretation, writing and revisions of these papers. Dr. Alan P. Dickin was closely involved with this dissertation by providing guidance and direction on the research objectives, discussion of the results and detailed editorial comments during preparation of manuscripts. Dr. Charles F. Gower co-supervised this dissertation by providing significant input and direction in the field, as well as editorial comments of manuscripts. In addition, Dr. Gower provided samples, major and trace element analysis from the Geologic Survey of Newfoundland and Labrador.

Collaboration with Dr. J. Stephen Daly and Dr. Robert A. Creaser consisted of Nd Isotope analyses for Chapters 3 and 4. Dr. Daly performed analyses at the University College in Dublin, and Dr. Creaser, at the University of Alberta.

Chapter 1: Introduction

1.1 Introduction

The eastern Grenville Province comprises approximately 300,000 km^2 of the Canadian Shield (Figure 1.1). Its geological makeup is the product of Makkovikian (1880-1790 Ma), Labradorian (1710-1600 Ma), Pinwarian (1520-1460 Ma) and Grenvillian (1085-985 Ma) orogenesis (Gower et al., (2008a), plus intervening events not obviously related to orogenic activity. The present structural configuration was largely achieved by major translational movement of crustal terranes during Grenville orogenesis.

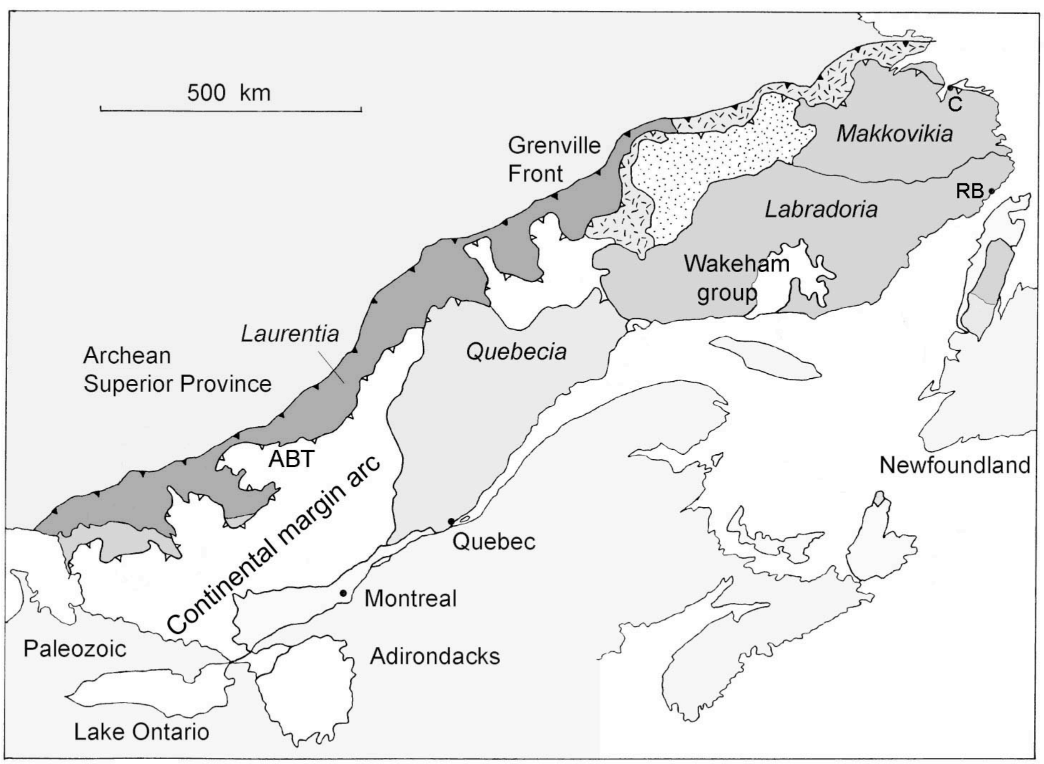

Figure 1.1. Current configuration of the Grenville Province, with major crustal terranes labeled (after Dickin, 2000 and Thomson et al., 2011). Coarse stipple = Trans Labrador Batholith. Fine stipple = Paleoproterozoic metasedimentary terranes. C = Cartwright; RB = Red Bay. ABT = Allochthon Boundary Thrust.

Most of the Eastern Grenville Province has been mapped at 1:100,000 scale by the Geological Survey of Newfoundland and Labrador, and by the Ministère de l'Énergie et des Ressources du Québec (MERQ). In addition, many U-Pb ages have been obtained, as summarized by Gower and Krogh (2002) and Gower et al. (2008a). This work has allowed the timing of major orogenic events in the area to be defined. However the times of original separation of crustal material from the mantle (crustal formation ages) have yet to be established in various parts of the region.

Formation-age mapping of the earth's crust can be achieved by Nd isotopic analysis of representative samples collected over a large geographical area. Schärer (1991) was the first to report Nd results from the eastern Grenville Province for regionally collected samples, but the first study specifically aimed at mapping crustal-formation ages was that of Dickin (2000).

Dickin (2000) proposed a terrane boundary between pre-Labradorian crust of the Makkovikian orogeny (≈1.9 Ga), and juvenile Labradorian crust (≈1.7 Ga), as shown in Figure 1.1. Dickin (2000) attempted to define the spatial extent of pre-Labradorian crust within the eastern Grenville Province, but the result was speculative, because of the dearth of samples available within remote areas of the region. Additional Nd isotopic information was subsequently acquired in specific areas (Gower, 2010), but has not been formally published, beyond reporting the results on geological maps. Hence the extent of pre-Labradorian crust within the Grenville Province remains unclear.

Another problem for understanding the history of pre-Labradorian crust in the Grenville Province is the limited amount of data for juvenile Makkovik crust to the north, which is necessary to provide a 'baseline' for evaluation of data from southern Labrador.

Previous Nd isotope work in the Makkovik Province was done by Kerr and Fryer (1993, 1994), which focused on mapping the extent of Archean crust within the Makkovik Province, and assessing the significance of post-orogenic crustal growth. Therefore, to properly understand crustal formation in the eastern Grenville Province, it was first necessary to conduct additional work on the Cape Harrison domain of the Makkovik Province, believed to consist largely of juvenile Makkovik crust (Fig. 1.2)

1.2. Study Area

The eastern Grenville Province has been divided into various lithotectonic terranes based on the present Grenvillian structures, whereas the Makkovik Province has also been divided into structural/tectonic domains (Figure 1.2).

The present configuration of these domains and terranes reflect the most recent orogenic events along the continental margin. Therefore, analysis of the Paleoproterozoic crustal evolution of southern Labrador must be made within the context of these lithotectonic units. However, Nd isotope analysis is ideally suited to seeing back through more recent tectono-metamorphic events to reconstruct the original crustal accretion history of the continents. When combined with U-Pb ages, which date the subsequent geological evolution of the crust, particularly its crystallization and subsequent metamorphism, a more comprehensive analysis of the geological history of southern Labrador can be achieved.

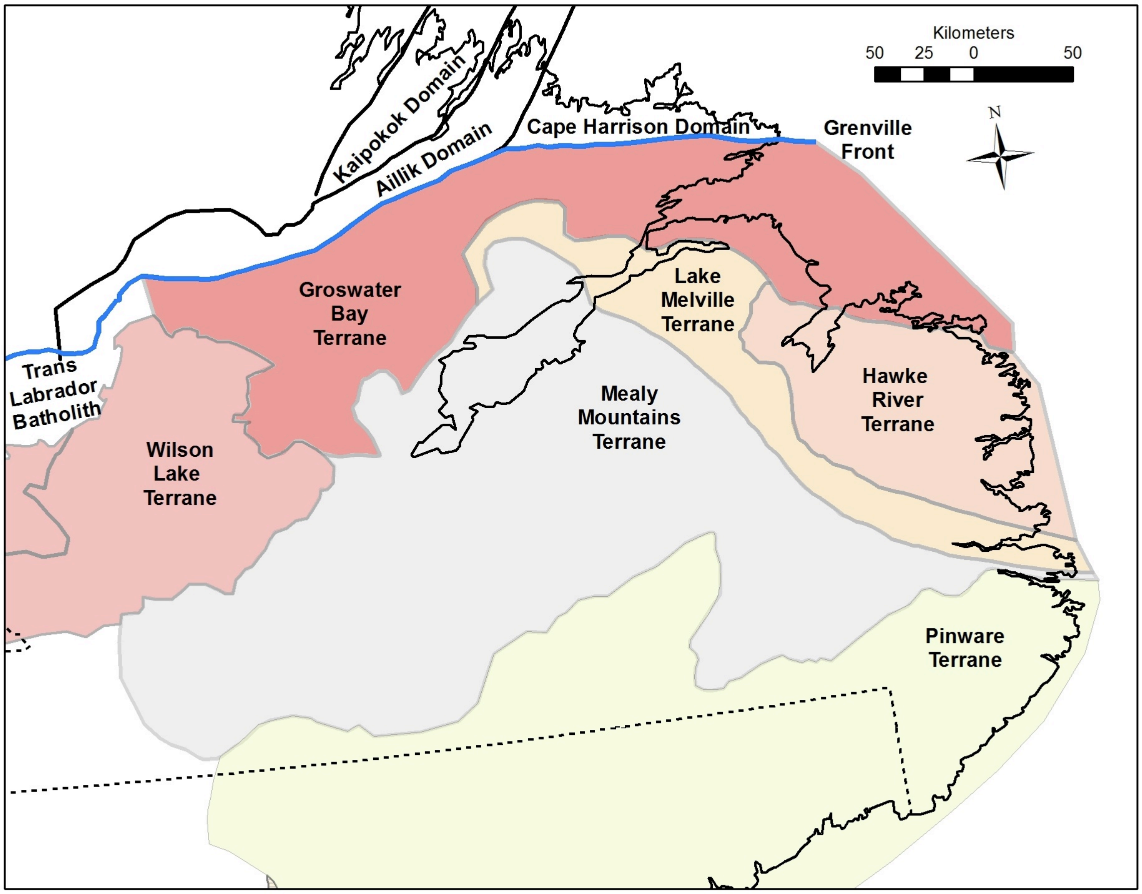

Figure 1.2. Location of the study area within southern Labrador. The Makkovik Province (in white) is divided into structural/tectonic domains, while the Grenville Province (coloured) is divided into lithotectonic terranes.

1.3. Research Objectives

The focus of the current study is to improve understanding of crustal development in the eastern Grenville and Makkovik Provinces by integrating results of previous studies with those of a new suite of samples across as much of the region as could be sampled. In this way, an improved crustal-formation age map of southern Labrador can be constructed, leading to an improved understanding of its geological evolution. Within this thesis, the research objectives are divided into three main chapters, which will address the following questions and areas of concern.

Chapter 2:

a) Refine the known extent of juvenile Makkovik crust, and determine the timing of crust-forming events during the Makkovik orogeny.

b) Test the current tectonic model for the Makkovik orogeny in order to determine how many arc accretion events were involved.

Chapter 3:

a) Determine the distinction between juvenile Labradorian crust and Labradorian crust that was emplaced within juvenile Makkovikian crust

b) Define the position of the boundary between juvenile Labradorian and pre-Labradorian crust, and propose a tectonic model for the Labradorian orogeny.

Chapter 4:

a) Determine if the trajectory of the proposed boundary between juvenile Labradorian and pre-Labradorian crust extends westward within the Grenville Province.
b) Provide a modern analogue for the collisional process involved during the Labradorian orogeny, and present evidence for the origin of metasedimentary rocks located within the southwestern portion of southern Labrador.

In the conclusions section, I will integrate all of the Nd data acquired to construct a tectonic model, which can be used to explain some of the evolution of the Laurentian craton during the Paleoproterozoic. In this model, I will attempt to highlight the main processes responsible for crustal growth, based on both the Nd and U-Pb data. The results from this thesis can form the foundation for future more detailed work.

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Chapter 2: The Makkovik Province

2.1. Introduction

The Makkovik Province contains remnants of a Paleoproterozoic accretionary orogen, exposed in eastern Labrador, that is correlated with the Ketilidian Mobile Belt in southern Greenland (Fig. 2.1, Kerr et al., 1997). The Makkovikian orogeny represents a significant period of crustal growth along the southern margin of the Laurentian craton from 2.0-1.7 Ga (Kerr and Fryer, 1994). The tectonic setting of the region during this period has been interpreted as an active continental margin that first underwent juvenile arc accretion and then continental margin arc plutonism (Kerr et al., 1992; Ketchum et al., 1997, 2002; Culshaw et al., 2000a).

U-Pb dating studies of the Makkovik Province (Kerr et al., 1992, Ketchum et al., 1997, Ketchum et al., 2001a,b, Ketchum et al., 2002, Schärer et al., 1988) demonstrate the presence of Archean crust of the Nain Province in the northwest and Paleoproterozoic crust in the southeast (Fig. 2.1). The younger crust has been conceptually subdivided into two separately-accreted arcs by Ketchum et al. (2002). However, original arc boundaries are obscured by extensive post-accretionary reworking of the composite margin by subsequent ensialic arc plutonism.

Nd isotopic results, used in conjunction with U-Pb dates, can assist in mapping the extent of crustal terranes and boundaries between them, thus augmenting understanding of the tectonic framework of an orogen. Nd isotope data provide information regarding the timing of magma extraction from the mantle, whereas U-Pb ages provide igneous crystallization ages. The combination of the two data types provides upper and lower constraints for the age of the crust. Through previous Nd isotope work in the Makkovik

Province, Kerr and Fryer (1993, 94) mapped both the edge of the Archean craton and assessed the significance of post-orogenic crustal growth. Newly acquired Nd isotopic data extend this mapping to the eastern Makkovik Province and adjacent Grenville Province, thus allowing tectonic evolution of the orogeny to be further addressed.

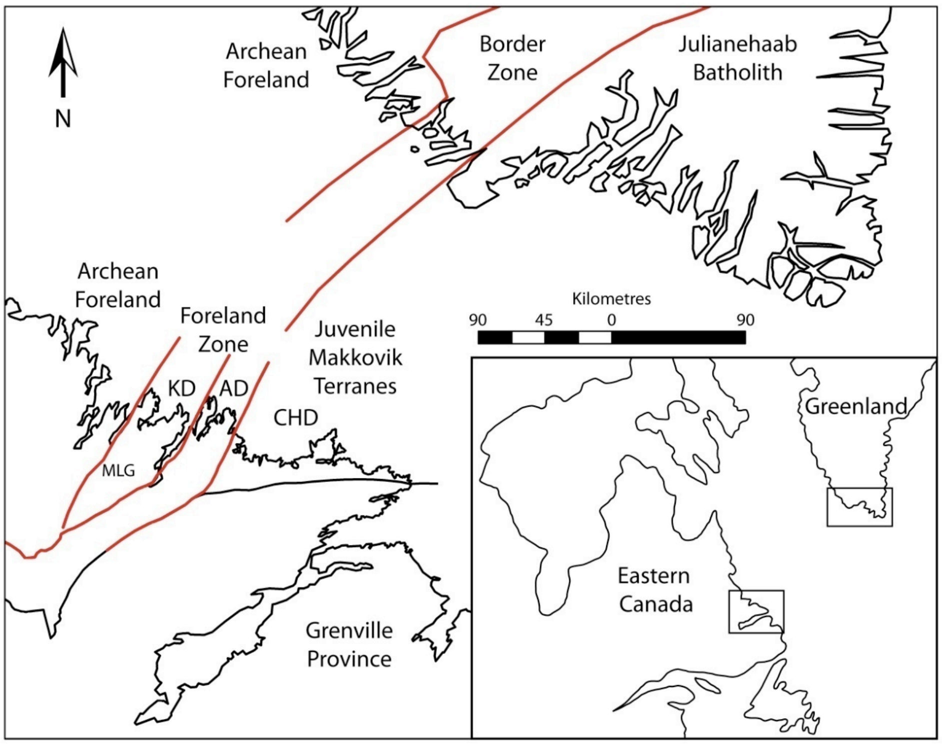


Figure 2.1. Map of the Makkovik Province of eastern Canada with Greenland restored to its pre-rifting location, showing the reworked edge of the Archean craton. Solid red lines separate the Archean foreland and the Foreland zones from the Paleoproterozoic crust. Inset shows current location of the Makkovik Province and Greenland. KD = Kaipokok Domain; AD = Aillik Domain; CHD = Cape Harrison Domain; MLG = Moran Lake Group.

2.2. Geologic Context

The Makkovik Province has been divided into three structural/tectonic entities (Fig. 2.1), comprising (from the northwest to the southeast) the Kaipokok, Aillik, and Cape Harrison domains (Kerr et al., 1996). The Kaipokok Domain has been interpreted to be the foreland of the orogen. It contains Archean crust upon which Paleoproterozoic metavolcanic and metasedimentary units (Figs. 2.1 and 2.2) of the Moran Lake Group and the Post Hill Group (the latter formerly termed the Lower Aillik group) were deposited. Both basement and cover were tectonized during Makkovikian orogenesis, which imparted increasing deformational and metamorphic effects progressing southeast. This domain has been correlated with the Border zone in Greenland. The Aillik domain represents a transitional zone, but, given that it locally contains intact remnants of Archean crust, and regionally, that Nd isotope data imply a cryptic Archean basement, it would appear to be physically linked to the Border Zone in Greenland. The Cape Harrison domain is correlated with the Julianehaab Batholith in Greenland (Gower and Ryan, 1986; Kerr and Wardle, 1996; Ketchum et al., 2002).

The boundary between the Kaipokok Domain and the Archean foreland is termed the Kanairiktok Bay shear zone (KNSZ, Fig. 2.2). However, this boundary is a deformational front rather than a suture (Kerr et al., 1997). Archean basement is continuous from the Nain Province to the northwest into the Kaipokok Domain, but with evidence of Makkovik deformation and metamorphism at the amphibolite facies grade (Culshaw et al., 2000).

Ketchum et al. (2001) presented U-Pb data for several units from the Post Hill Group. Zircons from a mafic metavolcanic rock, interpreted as a volcanic tuff, yielded a precise age of 2178 ± 4 Ma, attributed to rift-related magmatism on a passive margin. The metavolcanic rocks are underlain by quartzite having solely Archean provenance, but are overlain by psammite/semipelitic rocks containing both Archean and Paleoproterozoic zircons. The upper units contain several moderately discordant zircon grains with $^{207}Pb/^{208}Pb$ ages between 2160 and 2470 Ma, probably due to Pb loss from Archean zircons. In addition, a slightly discordant zircon gave a $Pb^{207}Pb^{206}$ age of 2035 Ma, and one concordant zircon gave an age of 2013 +/- 3 Ma. Ketchum et al. (2001) argued that this grain provides a maximum age for the deposition of the upper part of the Post Hill Group, possibly during the early stages of the Makkovik arc-accretion event. Hence, the Post Hill Group represents a time span of more than 165 million years, from rifting to accretion.

The Kaipokok domain records several episodes of Makkovikian and post-Makkovikian plutonism. The Island Harbour Bay Plutonic Suite provides evidence of early Makkovikian (1895-1870 Ma) calc-alkaline plutonism. Three episodes of granitoid plutonism followed, namely (i) ca. 1800 Ma (late Makkovikian - unfoliated), (ii) ca. 1720 Ma (post Makkovikian), and (iii) ca. 1650 Ma (Labradorian) (Barr et al., 2001, LaFlamme, 2012).

The Kaipokok domain is separated from the Aillik domain to the southeast by the Kaipokok Bay Shear Zone (KBSZ, Fig. 2.2) (Kerr et al., 1997, Ketchum et al., 2002). It was suggested that this deformation zone represents the surface expression of an east-dipping suture between the Archean and Paleoproterozoic crust (Kerr et al., 1997). However, it was later established that the Aillik domain contains a large block of Archean basement (Ketchum et al., 2002), making it less likely that the KBSZ follows the actual collisional suture.

The oldest supracrustal units of the Aillik Domain comprise Paleoproterozoic metavolcanic and metasedimentary rocks (termed the Aillik Group), which are in thrust contact with Archean basement. Some Aillik Group metavolcanic rocks from the easterly part of the domain have Archean Hf isotope signatures (LaFlamme et al., 2013), suggesting that Archean crust is extensive in the subsurface of the Aillik Domain well beyond its surficial exposure. Similar to the Kaipokok domain, the Aillik domain also includes both early and late Makkovikian intrusive suites, as well as the Labradorian intrusive suite (Barr et al., 2001, LaFlamme, 2012).

The Cape Harrison domain contains no recognized Archean crust, but includes foliated gneisses of the Cape Harrison Metamorphic Suite (CHMS) which were interpreted as possible remnants of Paleoproterozoic arc basement (Kerr et al., 1996). However, the oldest dated rocks, comprised of foliated Makkovikian plutons, yield 1815 Ma U-Pb ages which are interpreted as dating igneous crystallization (Ketchum et al., 2002). Any deformation associated with the CHMS must therefore have occurred at 1815 Ma or after. Subsequent stages of Late Makkovikian - Labradorian plutonism are also recognized (1800, 1720 and 1640-1650 Ma).

Rocks of the southern Makkovik Province were also affected by Labradorian and Grenvillian orogenesis. The northern border of the Labradorian orogen is usually considered to be defined by the Trans-Labrador Batholith, a 600-km-long granitoid belt coincident with the southern edge of the Grenville Front (Kerr and Krogh, 1990). However, Kerr (1989) argued that the location of the Trans-Labrador batholith in eastern Labrador is more like a series of scattered plutons rather than a single batholith. The geochemical data for the Trans-Labrador Batholith of eastern Labrador support this argument by showing that the plutonic rocks of the suite are not closely related magmatically. Pre-Labradorian U-Pb ages have since been obtained much farther south of the Grenville front in eastern Labrador (Krogh et al., 2002, Gower et al., 2008), showing that these plutons were emplaced far from the continental edge.

The Grenville Front marks the northward extent of Grenvillian deformation and metamorphism. The region immediately south of this boundary displays very little evidence of Grenvillian plutonism, however (Gower et al., 2008). Therefore it is not anticipated that the Nd signatures from the analyzed rocks of this study will be distorted by Grenvillian orogenesis (excluding the uncertain implications of potentially major displacements of crustal segments due to Grenvillian thrusting).

2.3. Tectonic History

Previous studies of the Makkovik Province have delivered both structural, seismic and geochronological evidence regarding the accretionary history of the Makkovik Province. Ketchum et al. (2002) provided a summary of previous studies and developed a tectonic model to explain the possible development of the Aillik and Cape Harrison domains during accretion to the Archean foreland zone (Figure 2.3).

A maximum age for the earlier stages of accretionary orogenesis is provided by detrital zircons. Based on the psammitic/semipelitic rock types of the upper Post Hill Group (Metasedimentary Formation), Ketchum et al. (2001) interpreted their formation as foredeep sediments having a maximum age of 2013 Ma, shed off an approaching arc and deposited on the Laurentian margin. Transport of sediment across the intervening subduction zone implies that the arc was already adjacent to the Archean margin at this time. Ketchum et al. (2002) tentatively dated the Makkovik arc to 2.0-2.15 Ga based on the detrital zircons analysed by Ketchum et al. (2001).

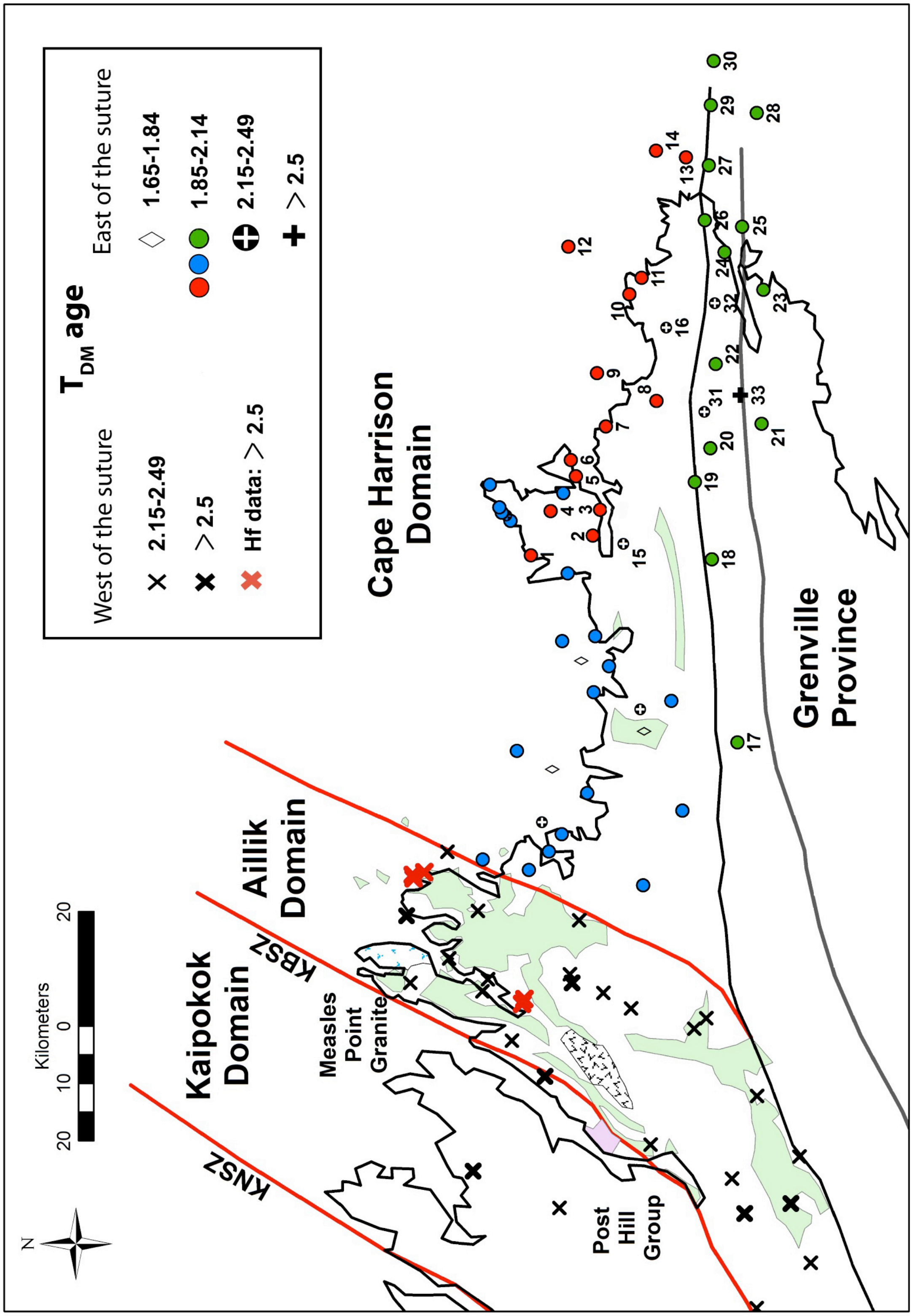

T_DM age
West of the suture
2.15-2.49
> 2.5
Hf data: > 2.5
East of the suture
1.65-1.84
1.85-2.14
2.15-2.49
> 2.5
Kilometers
20 10 0 20
N
Kaipokok Domain
Aillik Domain
Cape Harrison Domain
Grenville Province
KNSZ
KBSZ
Measles Point Granite
Post Hill Group

Figure 2.2 Map of the study area within the Makkovik and Grenville Provinces, illustrating the sample locations for published (un-numbered samples), and new Nd data (numbered samples). Published Nd data from Kerr and Fryer, (1994) and Ketchum et al. (2002). Published Hf data locations from LaFlamme et al. (2013). Purple shading = Post Hill Group; Green shading = Aillik Group. Blue circles = previously published data, red circles = current study, and green circles = samples within the Grenville Province.

Building on a study by Kerr et al. (1996), Ketchum et al. (2002) propose that the island arc was then accreted to the craton at the earliest by 1.89-1.88 Ga, which resulted in a switch to cratonward subduction, and initiated continental arc plutonism. The earliest concrete evidence for a Makkovikian accretionary event is provided by 1895 Ma early Makkovikian plutonic rocks that cut an older foliation in the Post Hill Group. Note that a U-Pb zircon age of 1929 ± $^{10}/_{9}$ Ma (Sinclair et al., 2002), for the Measles Point Granite (Figure 2.2), has since been rejected by Hinchey and Davis (2013), who presented a date of 1873 ± 10 Ma, for the same unit.

Ketchum et al. (2002) proposed that at 1.86-1.85 Ga, the Aillik Group (metasediments and metavolcanics) was deposited in a rifted arc or back-arc basin. According to their model, this was followed by tectonic inversion of the Aillik Group, which may have been precipitated by a second arc-accretionary event at 1.815 Ga, evidence of which is manifest by the Cape Harrison Metamorphic Suite, given its arc-like character. Subsequently, syn- to post-collisional granitoid plutonism occurred at 1.80 Ga and 1.74-1.70 Ga. Evidence for post-1.74 Ga tectonic reactivation is expressed through greenschist-facies metamorphism and A-type plutonism.

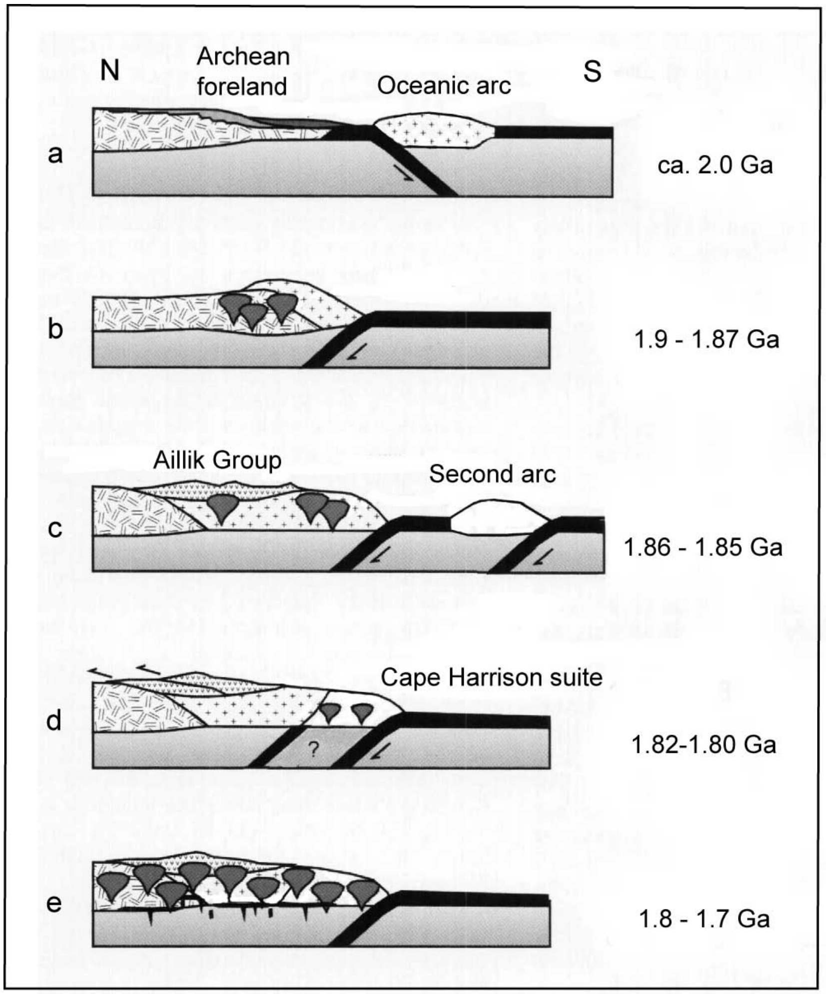


Figure 2.3. Tectonic model for the accretion of two juvenile Makkovik arcs to the Laurentian margin in Labrador. Modified from Ketchum et al. (2002).

2.4. Sampling and Analytical Methods

Thirty-three igneous whole rock powders were provided by the Geological Survey of Newfoundland and Labrador (collected by C.F. Gower). Sampling locations are indicated in Figure 2.2, and are located in both Makkovik and northernmost Grenville provinces. Sm-Nd analysis followed the procedure of Dickin and McNutt (1989) (Table A.1, Appendix A,). After dissolution using HF and HNO3, samples were split and one aliquot spiked with a mixed ^{150}Nd-^{149}Sm spike. Analysis by this technique yielded Sm/Nd

= 0.2280 ± 0.0002 for BCR-1, in agreement with Thirlwall (1982). Standard cation and reversed-phase column separation methods were used. Nd isotope analyses were performed on a VG isomass 354 mass spectrometer at McMaster University using double filaments and a four-collector, peak-switching algorithm, and were normalized to a $^{146}Nd/^{144}Nd$ ratio of 0.7219. Average within-run precision on the samples was ± 0.000014 (2 sigma), and an average value of 0.511856 ± 0.000020 (2 sigma population) was determined for the La Jolla standard during this work, in agreement with Thirlwall (1991). The reproducibility of $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ is estimated at 0.1% and 0.002% (1 sigma), respectively, leading to an average uncertainty on each model age of 20 million years (2 sigma), based on empirical experience over several years of analyzing duplicate dissolutions. Major- and trace- elemental analysis was carried out by the Geological Survey of Newfoundland and Labrador (Table A.2, Appendix A).

2.5. Nd Isotope Results

New Nd isotope data from the current study are used to calculate depleted mantle model ages (T_{DM}) using the model of DePaolo (1981). Sample localities are represented in Fig.2.2 by numbered points, along with locations for published data (not numbered).

Symbols plotted in Figure 2.2 are subdivided by tectonic domain and T_{DM} model age. Samples from the Foreland zone (Kaipokok and Aillik domains) are subdivided into two groups: **X** = Archean model ages (>2.49 Ga) attributed to remelting of Archean crust, and x = Paleoproterozoic model ages (< 2.49 Ga) attributed to Makkovik plutons with a variable Archean Nd component.

Samples from the Cape Harrison domain are subdivided into four groups: + = Archean model ages; open symbols = (2.15-2.49 Ga); solid circles = Makkovikian (1.85-

2.14 Ga) model ages (red = Cape Harrison East, blue = Cape Harrison West, green = Cape Harrison South); and open diamonds = Labradorian model ages (1.65-1.84). Based on these age categories, it can be seen that samples in the Cape Harrison domain within the Makkovik Province mainly present a range of T_{DM} model ages between 1.85-2.14 Ga (coloured circles). This implies that the majority of the crust in the Cape Harrison domain formed just prior to the Makkovikian orogeny. Samples to the south of this region, within the Grenville Province also follow this trend. Exceptions within this area include one sample that has an Archean provenance (+), and four samples with early Proterozoic TDM ages that may contain an Archean crustal component (black circles with a white cross).

2.6. Interpolation Contour Map

The T_{DM} data are displayed on an interpolation map in Figure 2.4. The technique used in this study is the Inverse Distance Weighting (IDW) method, with a grid cell of 4 km. The interpolation creates an age contour map from individual crustal-formation age results. The contours are colour shaded, and are draped over a satellite image of the Makkovik Province. Light-blue colours are interpreted as juvenile Makkovik arc crust (1.95-2.1 Ga), whereas green to yellow represent Archean crust heavily reworked by Makkovik plutonism, and orange, red and lilac represents less reworked Archean crust.

The interpolation map shows that the Cape Harrison domain is within 1.95- 2.1 Ga (blue and green). In contrast, previously published Nd isotopic data from the Aillik domain display older T_{DM} ages than those in the Cape Harrison domain. The model age data for the Aillik domain is within the same range as the Kaipokok domain, which is underlain by Archean crust and intruded by Makkovikian plutons having a significant Archean Nd component. This suggests that the Aillik – Cape Harrison domain boundary may represent the collisional suture between reworked Archean and juvenile Makkovik crust. This is further east than proposed by Kerr and Fryer (1993, 1994), who interpreted that the Archean crust was present at depth beneath the Aillik domain as an east-thinning wedge, and that the Cape Harrison domain- Aillik domain boundary was it's limit.

2.7. Nd Isotope Profile

T_{DM} model ages are plotted against the distance from the Aillik - Cape Harrison domain boundary in Fig. 2.5. A linear regression for the Cape Harrison East, West and South samples shows that they represent a single episode of crustal formation across the whole juvenile Makkovik Province. At the newly proposed suture location (zero on the x-axis), a definite change in T_{DM} age is evident. However, there is no observable trend of model age against distance across the Aillik Domain. This suggests that the Aillik domain once consisted dominantly of Archean crust that has been reworked with more-or-less equal intensity across its width by Makkovikian magmatism.

Nd data are shown on a Sm-Nd isochron diagram (Fig.2.6) using the same symbols. Three separate arrays are recognizable in the data, and fall along T_{DM} model age reference lines of 2.75, 1.95 and 1.75 Ga respectively. Samples from the Foreland zone with Archean model ages plot along a 2.75 Ga reference line, as do samples from the Superior Province (horizontal dashes). These were minimally affected by Makkovikian orogenesis. Data that fall between the 1.95 Ga and 2.75 Ga reference lines are mainly

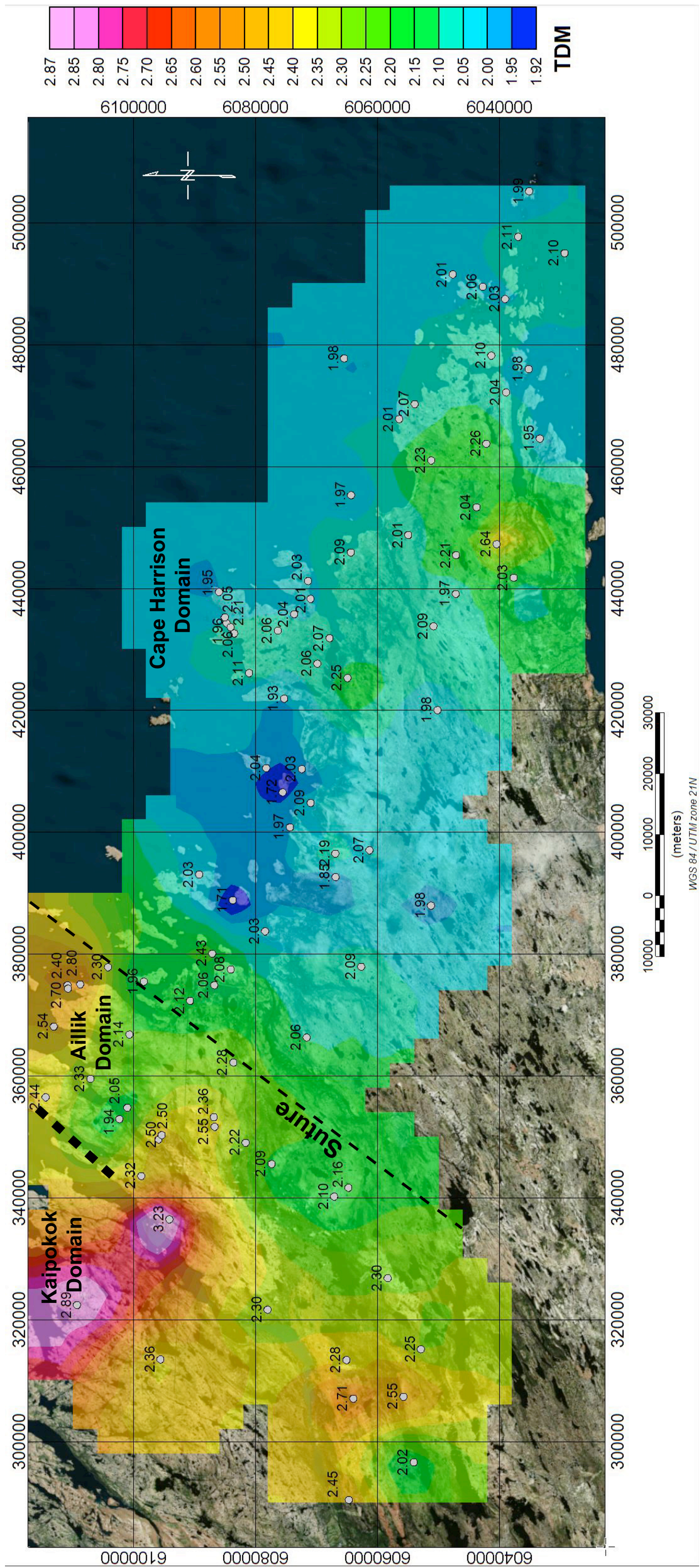

TDM
Cape Harrison Domain
Aillik Domain
Kaipokok Domain
Suture
(meters)
WGS 84 / UTM zone 21N

Figure 2.4. An interpolation contour map for the Makkovik Province using T_{DM} model ages. Contour intervals are displayed at 50 m.y.

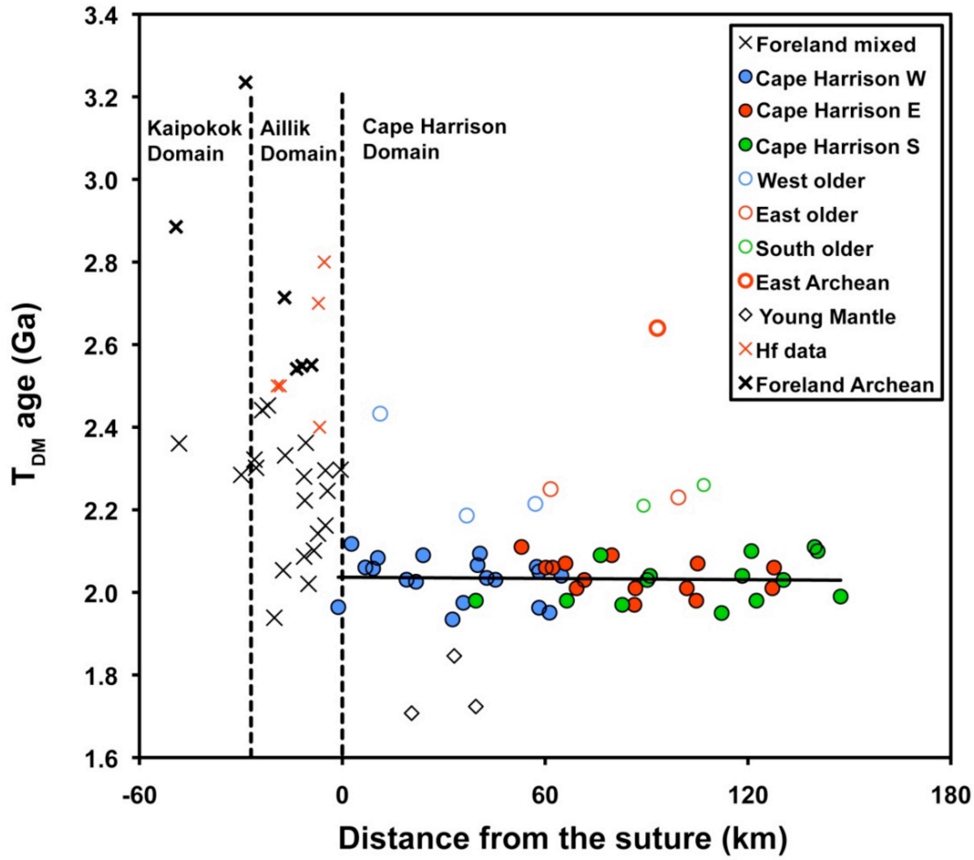


Figure 2.5. Plot of T_{DM} model age *versus* distance in km from the Aillik - Cape Harrison Domain boundary, interpreted as a collisional suture. Dashed lines represent the boundaries between domains. Colours are used to be consistent with later plots.

samples from the Foreland Zone with mixed Nd signatures, and represent variable contributions from Archean crust to juvenile Makkovikian plutonism. A few Cape Harrison East and South older samples (sample #'s 15,16,31,32) also fall between the two reference lines. These are interpreted as small pockets of pre-Makkovikian crust (at least one with Archean provenance; sample # 33) entrapped in the juvenile Makkovikian arc.

The majority of the newly obtained Nd analyses (# 1-14 and 17-30- Cape

Harrison East, and Cape Harrison South) fall along the reference line of 1.95 Ga, consistent with previously published samples from Cape Harrison West. This isochron age therefore strongly supports the average 2.0 Ga TDM model age of these samples, suggesting their derivation as juvenile crust immediately before Makkovikian orogenesis. Therefore, the data from both Figures 2.5 and 2.6 suggest that the Cape Harrison domain represents the juvenile component of the Makkovik orogen, which was generated during a single crust-forming event.

Open-diamond samples plot on the same 1.75 Ga line as 'Labradoria' samples from southernmost Labrador and adjacent eastern Quebec (Dickin, 2000). These samples are interpreted as representing a much younger mantle component, possibly related to Labradorian plutonism.

2.8. Petrochemical Data

Major- and trace element whole-rock analyses for the Cape Harrison East and South samples were obtained by the Geological Survey of Newfoundland and Labrador, and are presented in Table A.2, Appendix A. SiO_2 versus various elements are plotted in Figure 2.7, along with Cape Harrison West samples, that correspond to the plutons analyzed by Kerr and Fryer (1994). In addition, granitoid rocks from the Island Harbour Bay plutonic suite of the Aillik Domain (Barr et al., 2001), and samples from the Kohistan arc of the Himalayas (Jagoutz et al., 2009) are plotted for comparison. The Kohistan arc is used as a representative of a mature oceanic arc, therefore modeling the expected original composition of accreted juvenile Makkovikian arc crust.

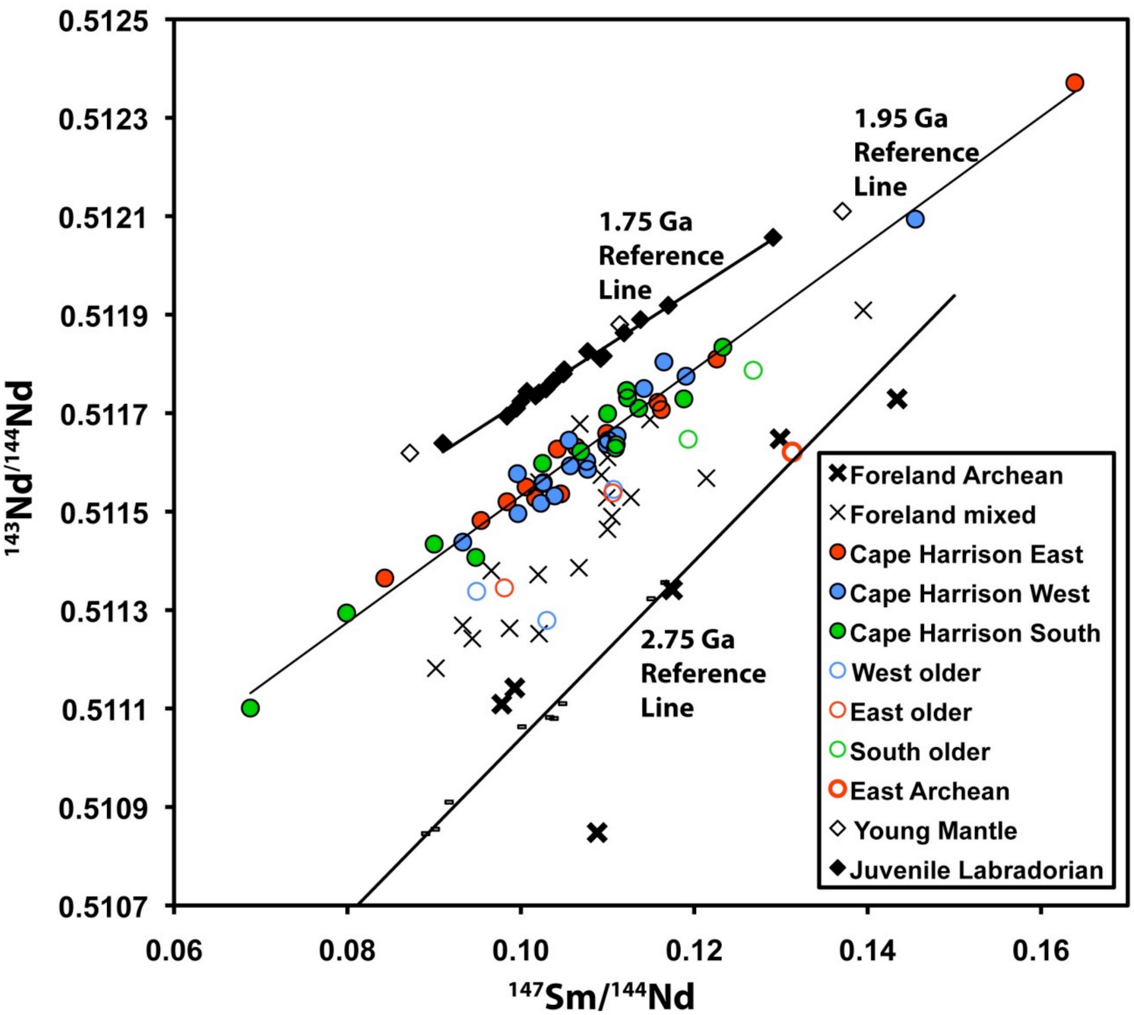


Figure 2.6. An Sm–Nd isochron diagram is presented for the Makkovik province. Reference lines of 1.75 Ga (Labradoria), 1.95 Ga (Makkovik), and 2.75 Ga (Archean) are shown for comparison. Data sets from Dickin (2000) for Labradoria (1.75 Ga) and Holmden and Dickin (1995) for the Superior province (2.75 Ga) are also plotted to demonstrate the trends seen in the data for the current study.

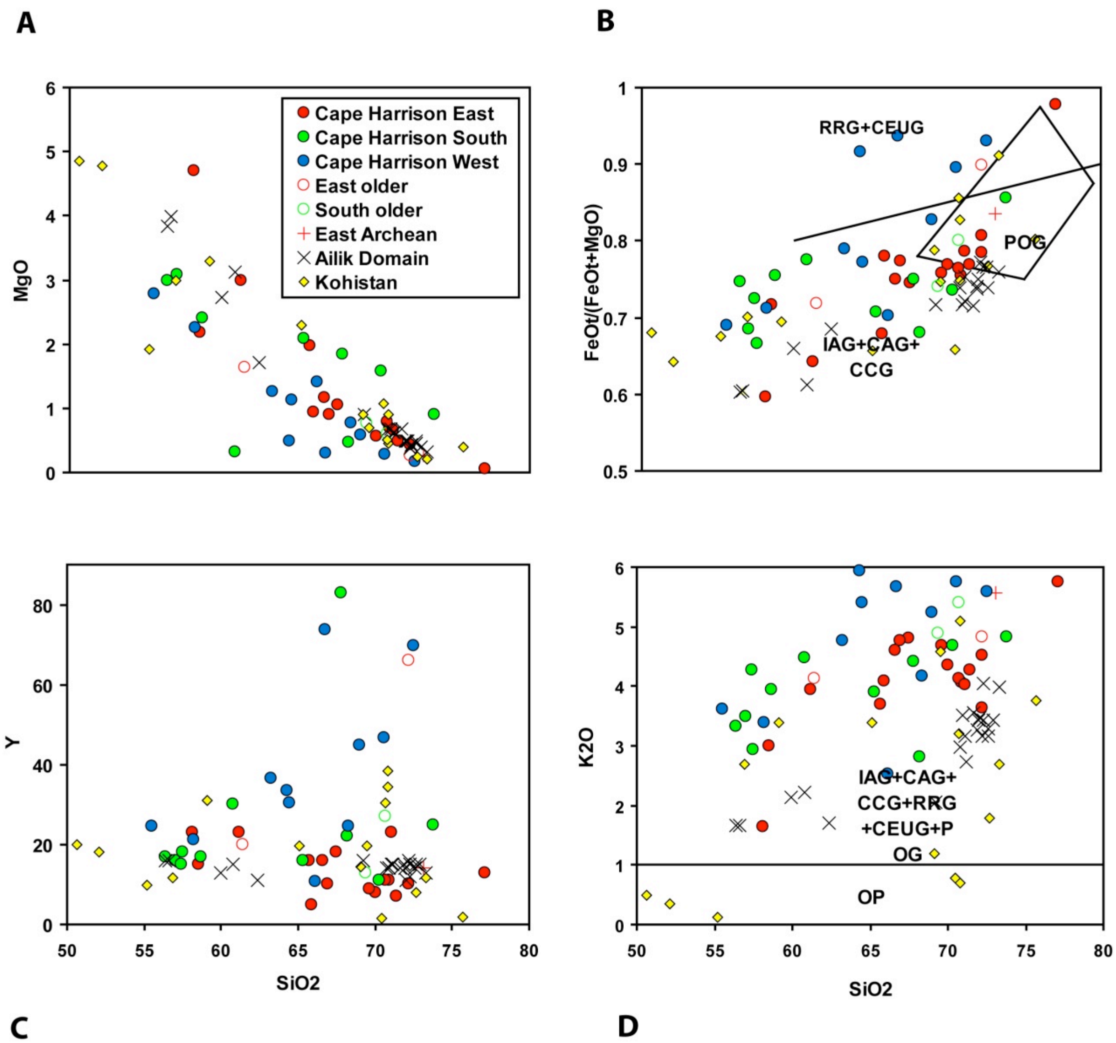


Figure 2.7. Plots of SiO_2 vs MgO, Y, FeOt/(FeOt+MgO) and K_2O are presented for rocks of the study area (Cape Harrison West, East and South). These are compared with previously published data for the Aillik domain (Barr et al., 2001) and the Kohistan arc (Jagoutz et al., 2009). Data are expressed in weight percent. IAG= Island arc granite, CAG=continental arc granitoids, CCG= continental collision granitoids, RRG= rift-related granitoids, CEUG= continental epeirogenic uplift granitoids, POG= postorogenic granitoids.

The scatter of data for both Cape Harrison and Kohistan show that these suites do not represent single fractionation trends but suites of partially related magmas, each intruded into a similar tectonic environment. From these diagrams, one is not able to identify the tectonic environment of the Cape Harrison and the Kohistan suites, although it is notable that the Cape Harrison suite defines the upper limit of the silica-potassium distribution, implying magmatic differentiation at deeper levels in the crust.

An alternative approach to defining the petrological character of the samples uses the Q (Quartz)–P (Plagioclase) diagram of Debon and LeFort (1983), which aims to classify granitoid rocks using their whole-rock chemical compositions (Figure 2.8).

Samples from the Kohistan arc, interpreted as a mature oceanic arc (Jagoutz et al., 2009) trend along the left side of the diagram. Next to these, Early Makkovik plutons from the Aillik domain (Island Harbour Bay Plutonic Suite, Barr et al., 2001) trend from the quartz diorite to granodiorite field, consistent with their emplacement at an early (possibly syn-collisional) stage in the Makkovik orogeny. In contrast, samples from Cape Harrison East and Cape Harrison South trend across the middle of the diagram from monzodiorite to monzogranite, indicative of a continental margin arc setting. Finally, plutons from the Cape Harrison domain West trend to the right side of the figure, indicative of a more alkaline suite, typical of ensialic arcs developed on thickened crustal sections.

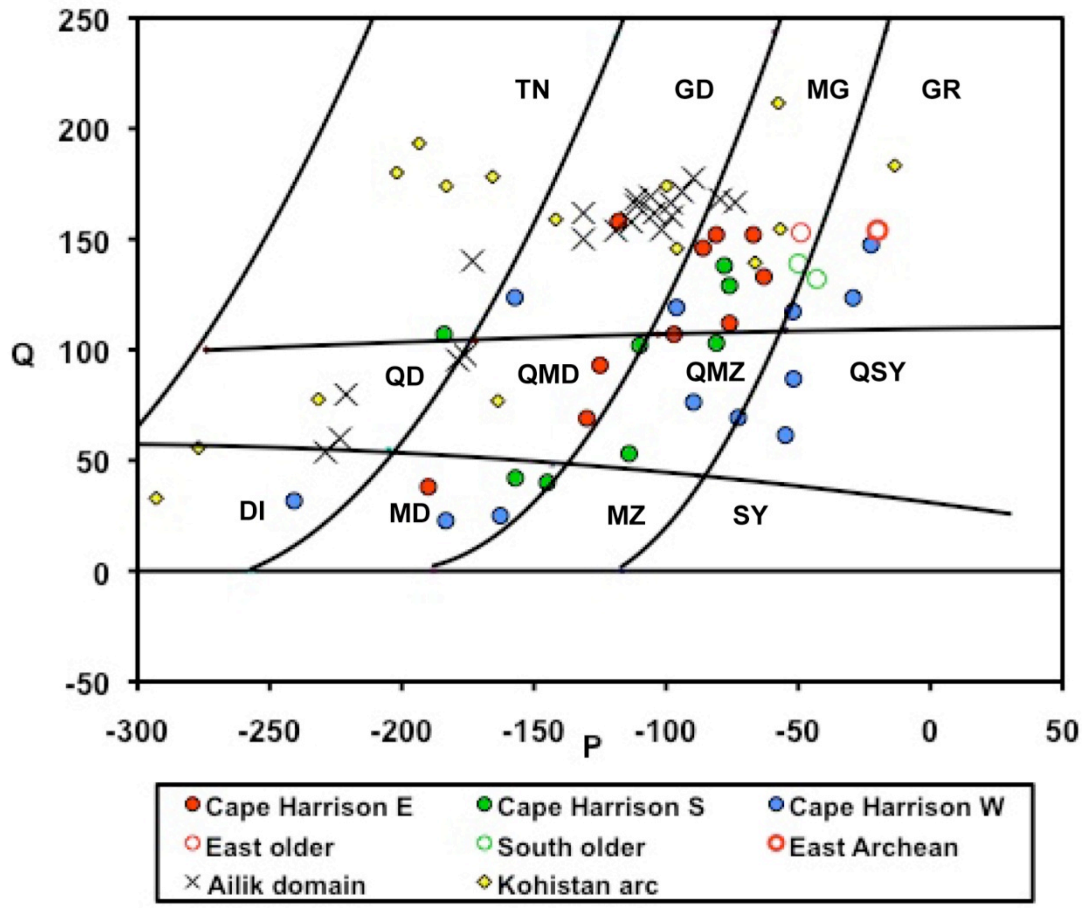


Figure 2.8. Samples from this study, along with previously published samples from the Cape Harrison West (Kerr et al., 1994), the Aillik domain (Barr et al., 2001) and the Kohistan arc (Jagoutz et al., 2009), are plotted on the petrochemical grid of Debon and Le Fort (1983), a chemical Streckeisen classification of granitoids. Q is an index of quartz content, and P is an index of plagioclase vs. K-feldspar content. 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. See text for discussion.

The geochemical data are also plotted using the de la Roche R1-R2 multi-cationic diagram (Batchelor and Bowden, 1985) in an attempt to further differentiate tectono-magmatic environments. R1- R2 represents limits that are calculated from chemical analyses or modal data (de la Roche et al., 1980). This model uses vectors to reflect the differences in magma composition during fractional crystallization and equilibrium to interpret the tectonic environment. The R1-R2 diagram (Fig. 2.9) yields a more distinct separation of the Makkovik data and the Kohistan arc. The samples from the Kohistan arc fall mostly within data fields 1 and 2, corresponding to a mantle fractionate or a pre-collisional setting. The data for the Aillik domain (Barr et al., 2001) lie along the boundary between 2 and 3, but mostly fall within section 6, indicating a syn-collisional environment. In contrast, the data from the current study lie along fields 3 and 4, (with a few samples in 6), consistent with a post-collisional or late-orogenic setting, or a post-collisional ensialic arc. This suggests that few of the analyzed samples come from original accreted arc crust, but instead represent re-melting of this primitive accreted arc crust by Makkovikian age ensialic arc plutonism.

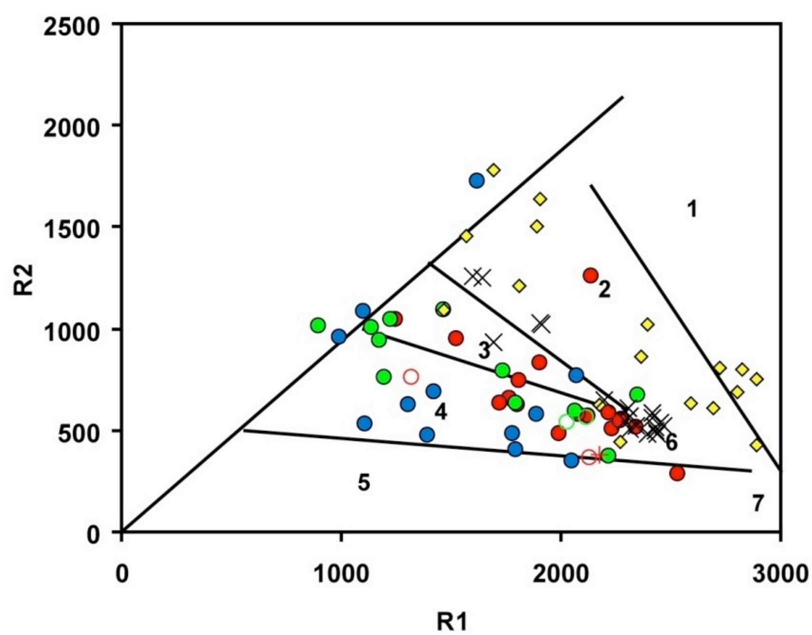
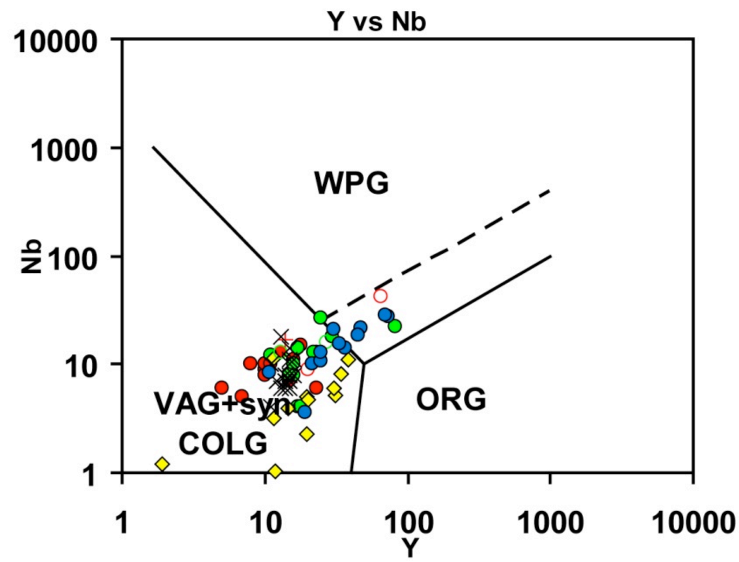
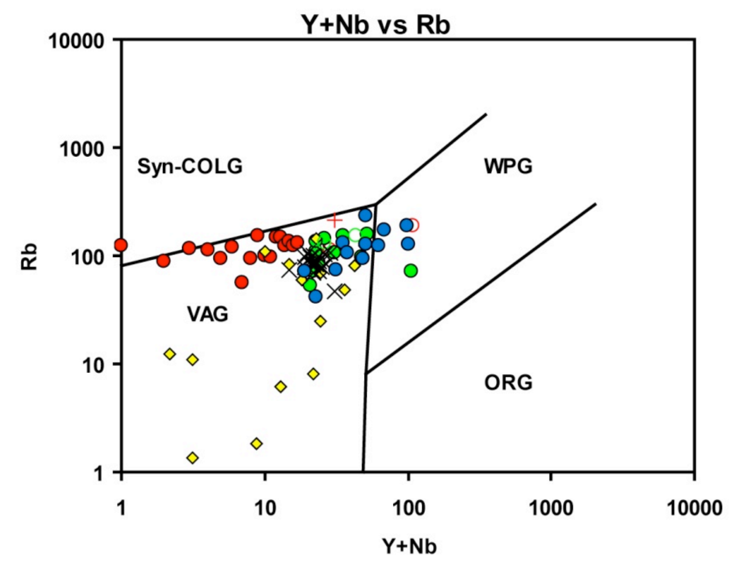


Figure 2.9. R1-R2 plot of the study area data as well as samples from Barr et al., 2001 (Aillik domain), Kerr et al., 1994 (Cape Harrison West) and Jagoutz et al., 2009 (Kohistan arc) for comparison. Symbols are the same as Fig. 2.7. Data fields for tectonic setting: 1 = mantle fractionates, 2 = pre-plate collision, 3 = post-collision uplift, 4 = late-orogenic, 5 = anorogenic, 6 = syn-collision, 7 = post-orogenic.

The sample set is also plotted on discrimination diagrams utilizing Y versus Nb, and Y+Nb versus Rb by Pearce et al. (1984), which aim to subdivide granitoid rocks according to four tectonic settings, namely ocean ridge granites, volcanic arc granites, within plate granites, and collisional granites.



(a)



(b)

Figure 2.10. (a) Y–Nb diagram; and (b) Y + Nb–Rb diagram after Pearce et al. (1984). VAG, volcanic arc granites; syn-COLG, syn-collisional granites; WPG, within plate granites; ORG, orogenic granites.

In both plots (Figs 2.10 a,b), the Cape Harrison and Kohistan samples lie almost entirely within the volcanic-arc granite field, but can be separately distinguished. In Figure 2.10b, the Cape Harrison suite lies near the boundary with the syn-collisional field, consistent with a continental arc setting.

2.9. Discussion

Previous Nd isotopic data taken in conjunction with the new data reported here point to a relatively simple model for the Makkovik orogeny. There are two key elements. The first is the clear break between reworked Archean crust and juvenile Makkovik crust at the Aillik – Cape Harrison domain boundary, as previously established by Kerr and Fryer (1993, 1994) and Kerr et al. (1996). The second is the flat trend in T_{DM} model ages (Fig. 2.5) across the Cape Harrison domain, which is taken to indicate juvenile Makkovik Province crust (except for small remnants of pre-Makkovikian crust). The uniform T_{DM} model ages across the Cape Harrison domain do not encourage models involving accretion of two separate outboard arcs.

One way of reconciliation between U-Pb geochronological data (which have been interpreted to indicate two major arc-accretionary events) and Nd isotopic data (which offer no support for the two-arc model) is to envisage magma separation from the mantle at the same time (around 2.0 Ga) in two separate arcs, which subsequently accreted to pre-Makkovikian Laurentia at different times (1.86 and 1.81 Ga). However, it needs to be demonstrated that the more complex model is essential to explain the data.

Based on Nd isotope data for the Ketilidian Mobile Belt, (Patchett and Bridgwater, 1984; Kalsbeek and Taylor, 1985), a Border Zone of reworked Archean crust can be defined, adjacent to which is a zone of isotopically homogeneous but geochemically heterogeneous orthogneisses having Paleoproterozoic T_{DM} ages (referred to as the Julianehaab Batholith). The U-Pb data for the Julianehaab Batholith records plutonic activity at 1.84-1.87 Ga, and 1.80-1.82 Ga (Garde et al., 2002), similar to the two dominant plutonic episodes recorded in the Makkovik Province.

A comparison between the U-Pb distributions for the Makkovik and Ketilidian orogens is presented as histograms in Figure 2.11. The data indicate that plutonic activity peaked twice at approximately similar times in both segments of the orogen during this period, and that both regions experienced a period of quiescence around 1.83 Ga. It is important to note that although the period of deformation at 1.86 Ga (or earlier?) can be explained by the plutonic activity in the histogram during the first peak, the second period of deformation at 1.80 Ga occurs after the gap of activity. This indicates that the period of inactivity at 1.83 Ga does not support a secondary accretion event, but rather a brief pause in plutonic activity.

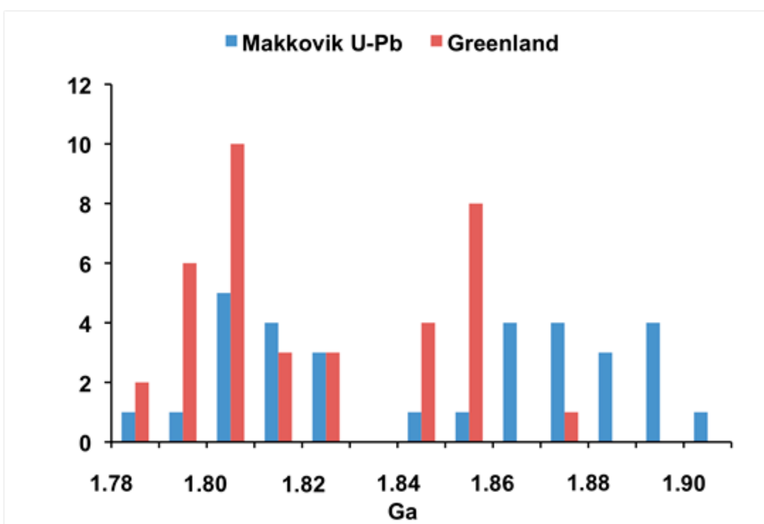


Figure 2.11. Histogram of U-Pb data for the Makkovik orogeny (blue shading) and the Ketilidian orogeny (red shading) in Greenland.

The tectonic model proposed by Ketchum et al. (2002), developed from earlier models by Kerr et al. (1997), also suffers from severe geometrical problems. This model implies that the first accreted arc gave rise to the Aillik domain, whereas the second generated the Cape Harrison Domain. However, the large amount of Archean crustal material demonstrated to exist within and under the Aillik domain makes it extremely unlikely that this very narrow crustal zone (< 30 km wide) represents an accreted arc terrane, in comparison with the >150 km width of juvenile crust in the Cape Harrison domain. Therefore a model of double arc accretion would require an arc-arc boundary within the Cape Harrison Domain, which has not been found.

The alternative model for the Makkovik orogeny proposed here begins with an outboard arc approaching the continental margin around 2.0 Ga (Fig 2.12a). The attempt to subduct the old continental margin under the accreted arc explains the preservation of older passive margin supracrustal rocks on the Archean side of the suture (Beaumont et al., 1996). Arc accretion led to a subduction flip towards the north-west, resulting in continental arc magmatism (Fig 2.12b), with plutons dated at 1.9-1.87 Ga.

Deposition of supracrustal units, comprising Paleoproterozoic metavolcanic and metasedimentary rocks from the Aillik Group, occurred at 1.86-1.85 Ga (Fig 2.12c). It is notable that the vast majority of Aillik Group rocks are found within the area of Archean basement to the NW of the suture (Figure 2.2). This is consistent with the formation of a retro-arc foreland basin, which is the typical result of arc accretion onto a continental margin. The accreted arc would have caused loading of the margin that depressed the back-arc region. This is similar to the retro-arc basin developed behind the accretionary margin of the Canadian cordillera, forming the Alberta foreland basin (Cant and

Stockmal, 1989). At the same time, the continent-ward subduction that resulted from the subduction flip would have caused a temporary reduction in compressive stress across the arc, thus allowing the development of rift-related magmatism within the basin (Sinclair et al, 2002).

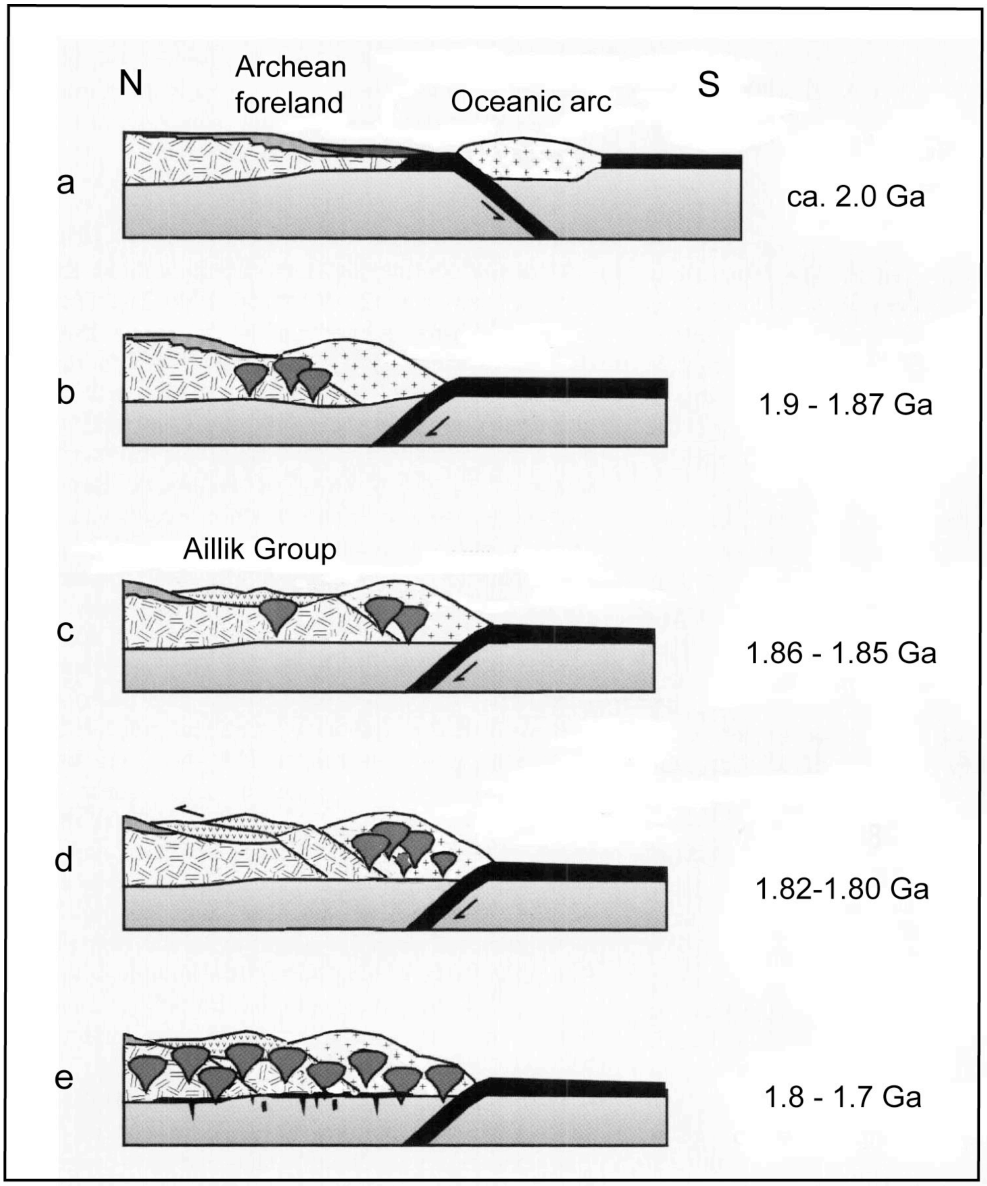
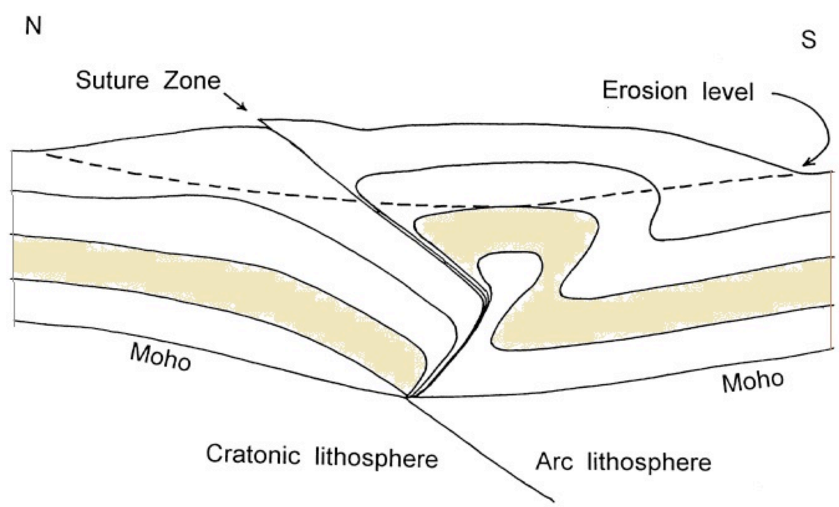


Figure 2.12. Revised tectonic model proposed based on data from the current study.

The intensification of magmatic activity around 1.80 Ga can be explained by phenomena such as changes in subduction angle that are seen within the modern Andean arc system. This would have caused additional uplift of the continental margin, and hence back-thrusting into the foreland basin (Fig 2.12d). Finally, diminishing quantities of magmatism continued to 1.72 Ga, well after the Makkovik orogeny (Fig 2.12e).

A reproduction of the modelled crustal section that can result from an arc accretion event is shown in Fig. 2.13 after Beaumont (1996). This section shows the uneven effects of crustal exhumation on the two sides of the suture, with the preservation of supracrustal rocks in the foreland zone of the craton, which could include retro-arc basin sediments. It also shows how the suture zone can be folded back on itself by back-thrusting in the accreted arc, hence no longer preserving the simple oceanward-dipping suture assumed in previous tectonic models of the Makkovik Province.



2.13. Modeled crustal section resulting from arc accretion, after Beaumont (1996). The upper part of the lower crust is shaded to convey the effects of variable exhumation.

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Chapter 3: The Grenville Province-southeast Labrador

3.1. Introduction

The Grenville Province represents a mid-Proterozoic orogenic belt that forms the youngest geologic province of the Canadian Shield. Dickin (2000) subdivided the Grenville Province into several regions each characterized by its own particular Nd-isotopic signature. He concluded that these regions provide a record of a series of crust-formation events between 1.9 and 1.0 Ga, and suggested that these were due to accretion of island arcs (Figure 3.1).

In the eastern Grenville Province, two of these regions were named Makkovikia and Labradoria, suggested to represent reworked Makkovik-Province crust and juvenile Labradorian crust, respectively. Dickin's sampling was sparse, however, hence the boundary between these proposed accreted crustal blocks was poorly constrained.

The objective of the present investigation is to use Nd isotope analysis to refine the position of the boundary between these crustal regions and gain greater understanding of their character. The study incorporates previously published data (Prevec et al., 1990; Schärer, 1991; Dickin, 2000) and a large, formerly unpublished regional Nd-isotopic data resource acquired in conjunction with reconnaissance geological mapping by the Geological Survey of Newfoundland and Labrador (Gower, 2010; Nd-isotopic analysis by R.A. Creaser and J.S. Daly). Additional sampling was carried out in areas of interest, utilizing a recently created road network in the region.

The geological history of eastern Labrador is especially defined by four major orogenic events, the Makkovikian (1880-1790 Ma), Labradorian (1710-1600 Ma), Pinwarian (1520-1460 Ma) and Grenvillian (1085-985 Ma), as summarized by Gower et al. (2008a). The first three orogenies were accretionary, resulting in the creation of new continental crust and reworking of pre-existing crust. The Grenvillian orogeny was collisional, involving less juvenile-crust addition, but causing extensive metamorphism of variable severity.

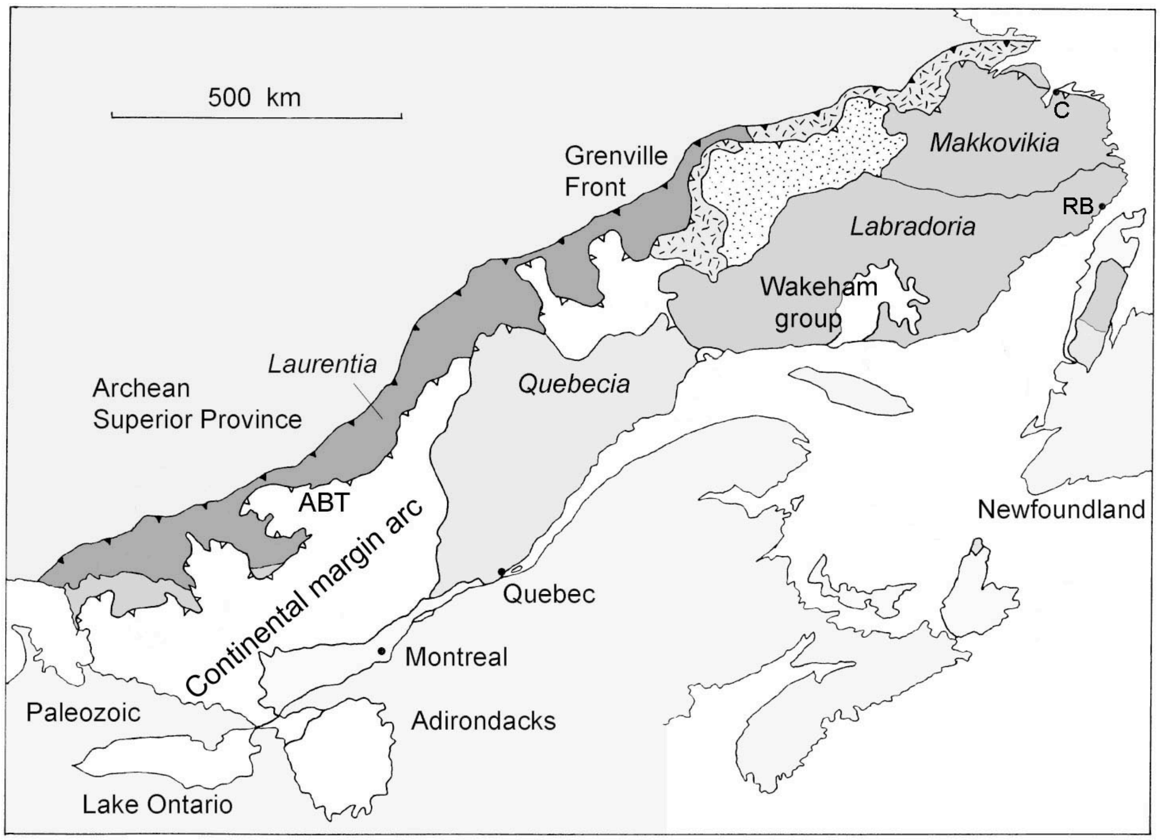


Figure 3.1. Major crustal terranes of the Grenville Province after Dickin (2000) and Thomson et al. (2011). Coarse stipple = Trans Labrador Batholith. Fine stipple = Paleoproterozoic metasedimentary terranes. The location of the study area is in eastern Labrador, between Cartwright (C) and Red Bay (RB).

Crust-formation-age maps can be used to demonstrate the extent of crust extracted from the mantle at various times. Nd model-age dating is an appropriate tool because Nd normally remains isotopically immobile during orogenic processes (Dickin, 2005). The method is extremely useful in the Grenville Province, where pre-Grenvillian history has been obscured by collisional tectonism and concomitant high-grade metamorphism. Hence Nd isotopic analysis can establish the time of mantle separation of juvenile crust and its regional extent. It may also be able to provide some constraints on magma-mixing processes that occur during crustal reworking.

3.2. Geological Context

The Grenville Province in southeast Labrador has been affected by Grenvillian age tectonism, resulting in a series of lithotectonic terranes that achieved their final configuration during Grenvillian orogenesis, but commonly also having distinct pre-Grenvillian geological histories. Any attempt to understand the Paleoproterozoic and early Mesoproterozoic geological history of the area must be made in the context of the recognized Grenvillian terranes, which are shown in Figure 3.2.

Periods of crustal growth and reworking are usually accompanied by igneous intrusion, which can be dated by U-Pb geochronological methods. Therefore, in order to properly interpret Nd isotope data in a region having a complex geological evolution, it is necessary to be aware of this history, as understood from igneous crystallization ages. Based on the work of Schärer et al. (1986) and Schärer and Gower (1988), the Labradorian event was seen to extend across the whole width of southeast Labrador, and to have occurred between 1710 and 1620 Ma. This evidence was also confirmed in a later study by Kamo et al. (1996), who studied the Hawke River and Groswater Bay terranes in detail, concluding that a major migmatizing event occurred at 1665 Ma. The effects of Labradorian plutonism extended as far north as the Trans-Labrador Batholith, which tapers out in an eastward direction along the northern fringe of Groswater Bay terrane.

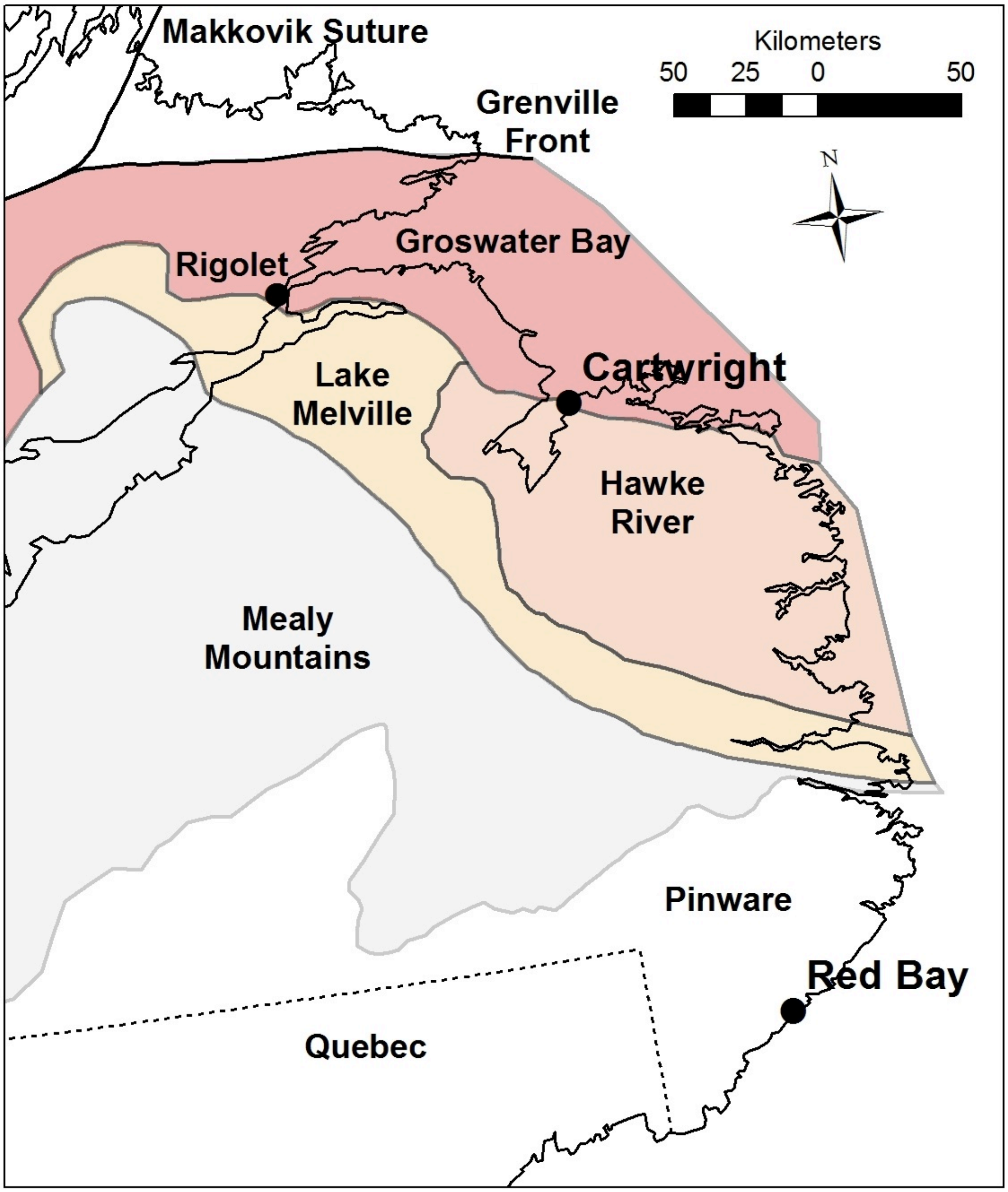


Figure 3.2. Nomenclature for Grenvillian lithotectonic terranes is illustrated: Groswater Bay Terrane, Hawke River Terrane, Lake Melville Terrane, Mealy Mountains Terrane, and the Pinware Terrane.

Kamo et al. (1996) interpreted their evidence to indicate that the Groswater Bay, Hawke River and Lake Melville terranes 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, hence showing that Labradorian plutonism occurred across the full north-south extent of the Grenville Province in eastern Labrador.

Gower and Krogh (2002) reviewed these and several other dating studies, and proposed a tectonic model for the evolution of the Labradorian orogeny, that was based on U-Pb ages from across the eastern Grenville Province. This model is broken into four main stages of development, spanning from 1680 Ma to 1600 Ma (Figure 3.3).

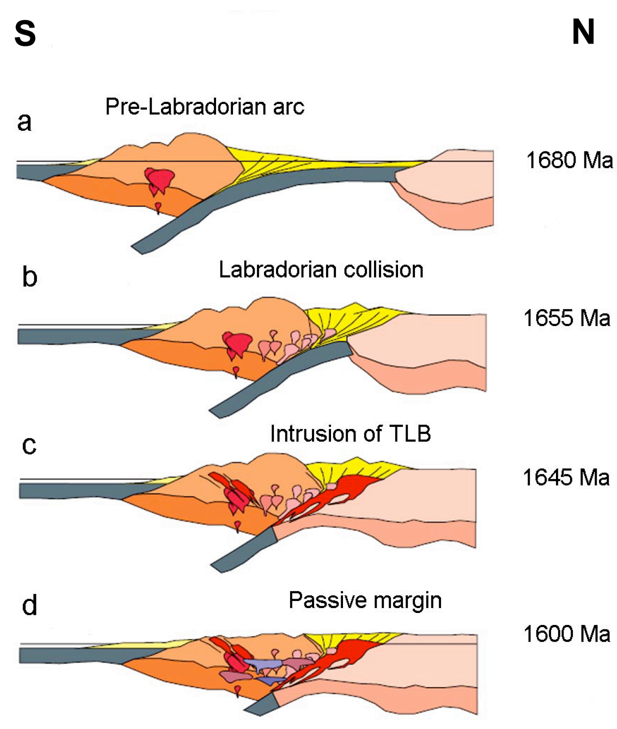


Figure 3.3. Gower and Krogh's (2002) tectonic model for the evolution of the Labradorian orogeny within the eastern Grenville Province.

From 1680 Ma to 1655 Ma, it was argued that calc-alkaline magmatic granitoid plutons were emplaced into a pre-Labradorian arc situated outboard (south) of the Laurentian margin. An apparent lack of early Labradorian (pre-1655 Ma) magmatism in pre-Labradorian Laurentia (north of the present-day Grenville Front) was used as one line of evidence to infer that subduction was directed away from Laurentia. Around 1655 Ma, it was proposed that the pre-Labradorian arc, augmented by early Labradorian magmatic products, collided with the craton. It was proposed that crustal thickening in the region of the suture zone initiated melting in the mid-crust, which resulted in Trans-Labrador batholith magmatism between 1654 and 1646 Ma. This was succeeded by 'trimodal' mafic-anorthositic-monzogranitic magmatism between 1650 and 1620 Ma, followed by a transition to a passive continental margin, which developed by about 1600 Ma.

3.2.1 The Extent of Pre-Labradorian Crust in the Grenville Province

Schärer (1991) presented Pb, Nd and Sr isotopic data for a selection of dated Labradorian orthogneisses from the Grenville Province in eastern Labrador. His results showed that U-Pb crystallization ages were in broad agreement with a Nd-Sm isochron age of 1711 ± 66 Ma and an Rb-Sr isochron age of 1617 ± 21 Ma, and that T_{CHUR} Nd ages were also in agreement with U-Pb crystallization ages. This consistency led Schärer to conclude that juvenile granitoid magma formed in less than 70 million years by primary melting of a chondritic-type mantle source to produce a basaltic crust, followed by melting of the basaltic material to yield the granitoid rocks. Thus, according to Schärer's interpretation, very little pre-Labradorian crust existed in the Grenville Province in eastern Labrador, although a granitoid sample from the Mealy Mountains terrane (Schärer and Gower, 1988; sample CG-317) gave pre-Labradorian $^{207}Pb/^{206}Pb$ ages, suggesting at least some involvement of a pre-Labradorian crustal source.

The first substantive evidence for pre-Labradorian crust within the eastern Grenville Province was delivered through U-Pb dating by Philippe et al. (1993). They reported U-Pb ages of 1775, 1754 and 1712 Ma for rocks from the Goose Bay area (Mealy Mountains terrane), although they assigned the ages to early Labradorian crustal development, rather than defining them as pre-Labradorian.

The results of Philippe et al. (1993), combined with Nd-Sm data from farther afield in the Grenville Province (Dickin and Higgins, 1992; Emslie and Hegner, 1993), led Gower (1996) to suggest that pre-Labradorian, post-Makkovikian crust might be present in the eastern Grenville Province, although its extent was acknowledged to be very uncertain. Further evidence for the presence of pre-Labradorian crustal material (although possibly representing assimilated metasedimentary rocks rather than granitoid basement) was provided by inherited ca. 2.0 Ga zircon ages in younger granitoid rocks from the Pinware terrane (Scott et al., 1993; Wasteneys et al., 1997).

A challenge to Schärer's (1991) interpretation that most of the Grenville Province in eastern Labrador comprised juvenile Labradorian crust was mounted by Dickin (2000). One objection addressed was the pooling of mineral data (two titanite results) with 12 whole-rock analyses to produce a composite Sm-Nd isochron age of 1711 Ma, which Schärer interpreted to be the age of crust formation. Dickin regressed the whole-rock data without the titanite analyses, obtaining an age of 1599 ± 236 Ma, which he regarded as too imprecise to infer a meaningful crust formation age. He also argued that the derivation of a large suite of Labradorian calc-alkaline plutons in subduction-related setting from a chondritic lower mantle source was very unlikely.

Hence Dickin proposed that most samples from the Groswater Bay and Hawke River terranes were derived from remelted Makkovik crust, based on the calculation of 2.0 Ga T_{DM} ages. He then proposed a terrane boundary between pre-Labradorian crust of the Makkovikian orogeny (≈1.9 Ga), and juvenile Labradorian crust (≈1.7 Ga), as shown in Figure 3.1. This proposed boundary separated the Mealy Mountain terrane and the rest of the Grenville lithotectonic terranes to the north as being Paleoproterozoic crust (termed Makkovikia), and the Pinware terrane as being juvenile Proterozoic crust (Labradoria).

From a U-Pb geochronological perspective, however, the extent of pre-Labradorian crust still remained unclear. Despite the fact that Krogh et al. (2002) obtained a Makkovik U-Pb age of 1799 +3/-2 Ma for a location immediately south of the Grenville Front, the first U-Pb evidence of pre-Labradorian crust was obtained for Makkovik plutonic rocks within the Mealy Mountain terrane (Gower et al., 2008). Therefore, although the presence of Makkovikian crust within the Grenville Province of eastern Labrador was well established by 2008, its extent was not.

3.2.2 The Pinwarian Orogeny

The Pinwarian orogeny, which affected a large area of the Grenville Province in southeast Labrador, was first termed the ‘Pinwarian event’ by Tucker and Gower (1994). Granitoid plutonism was dated by the U-Pb method, which gave ages of 1490 ±5 Ma, 1479±2 Ma, and 1472 ±3 Ma.

The Pinwarian event was upgraded to an orogeny by Wasteneys et al. (1997), a status endorsed by Heaman et al. (2004), both justifying the upgrade on the basis of evidence for significant deformation and amphibolite- to granulite-facies metamorphism accompanying granitoid magmatism. The Pinwarian orogeny affected much of the eastern Grenville Province, but especially its southern region. A continental-margin arc tectonic setting was first suggested by Tucker and Gower (1994), although Heaman et al. (2004) concluded that no evidence for juvenile Pinwarian crust existed within the eastern Grenville Province. Such is not the case farther west, in the central Grenville Province, where, on the basis of Nd-Sm data, Dickin (2000) interpreted a large region (termed Quebecia) as having a crust-formation age of 1.5 Ga.

3.2.3. The Grenvillian Orogeny

The Grenville Province in Labrador is defined as the series of events that, orogeny-wide, collectively led to the creation of the Grenville Province in its final structural configuration. These events occurred between 1085 to 985 Ma (Gower et al., 2008b and references therein).

Gower (2005) reconstructed the tectonic events of the Grenville orogeny in part of southeast Labrador by investigating the displacement of lithotectonic terranes using structural kinematic data. The Lake Melville terrane (Figure 3.2) is a highly sheared zone that Gower *et al*. (1987) termed the Gilbert River shear belt - alternatively named the Gilbert River belt by Hanmer and Scott (1990).

Gower et al. (2008b) has argued that Grenvillian orogenesis in eastern Labrador can be explained in terms of an ‘indentor’ model for the eastern Grenville Province. In this model, the dextral motion of the Lake Melville terrane is attributed to transpression (lateral ramp), whereas west of the indentor corner at Rigolet (Figure 3.2), the system becomes a series of north-verging thrusts (frontal ramp).

Of relevance to this study is recognition that the northwest regional strike of this shear zone must be considered when interpreting the trajectory of pre-Grenvillian boundaries that may have been important during Labradorian and/or Pinwarian orogenesis. This issue will be discussed further in relation to the isotopic results presented below.

3.3. Sampling and Analytical Methods

Fifty-four igneous whole rock powders were analyzed for the current study, including samples provided by the Geological Survey of Newfoundland and Labrador (collected by C.F. Gower). Sampling locations are indicated in Figures 3.4 a) and b), within the Grenville Province. Sm-Nd analysis followed the procedure of Dickin and McNutt (1989). After dissolution using HF and HNO3, samples were split and one aliquot spiked with a mixed ^{150}Nd-^{149}Sm spike. Analysis by this technique yielded Sm/Nd = 0.2280 ± 0.0002 for BCR-1, in agreement with Thirlwall (1982). Standard cation and reversed-phase column separation methods were used.

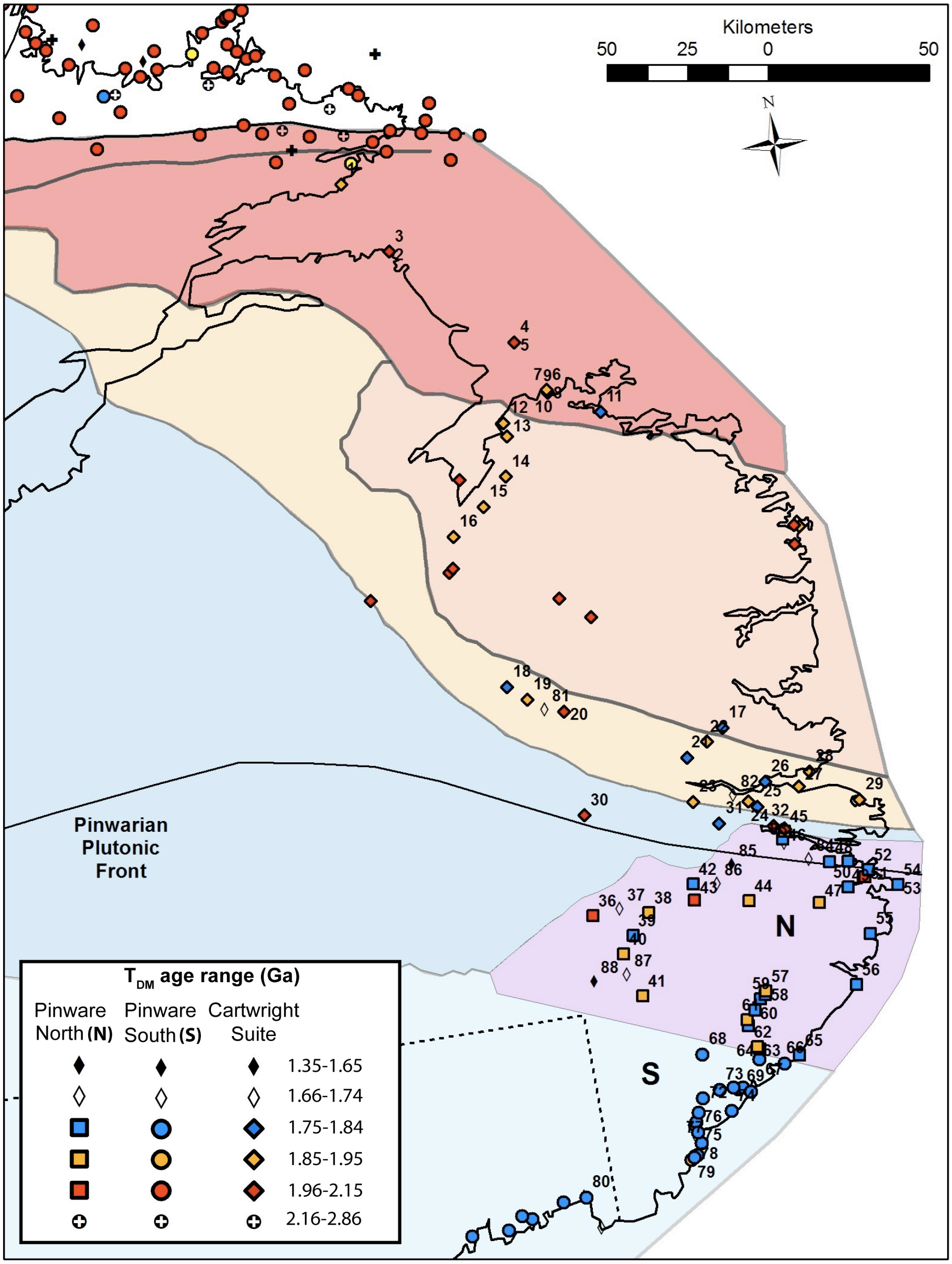
Nd isotope analyses were performed on a VG isomass 354 mass spectrometer at McMaster University using double filaments and a four-collector, peak-switching algorithm, and were normalized to a ^{146}Nd/^{144}Nd ratio of 0.7219. Average within-run precision on the samples was ±.000014 (2 sigma), and an average value of 0.511856 ± 0.000020 (2 sigma population) was determined for the La Jolla standard during this work, in agreement with Thirlwall (1991). The reproducibility of $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ is estimated at 0.1% and 0.002% (1 sigma), respectively, leading to an average uncertainty on each model age of 20 million years (2 sigma) that is based on empirical experience over several years of analyzing duplicate dissolutions.

An additional thirty-five samples were analyzed by J. Stephen Daly and Robert A. Creaser (samples denoted by an asterisk (Daly) and caret (Creaser) in Table B.1, Appendix B). Samples analyzed by Creaser used methods similar to those described above. Nd isotope analyses were performed on a VG 354 mass spectrometer at the University of Alberta using double filaments and a four-collector, peak-switching algorithm, and were normalized to a $^{146}Nd/^{144}Nd$ ratio of 0.7219. (Creaser et al., 1997). Average within-run precision on the samples was ± 0.000008 (2 sigma).

Samples analyzed by Daly used a semi-automated VG Micromass 30 mass spectrometer at University College, Dublin. $^{143}Nd/^{144}Nd$ ratios were determined on spiked samples. $^{143}Nd/^{144}Nd$ ratios are normalized to $^{146}Nd/^{144}Nd = 0.7219$. Average within-run precision on the samples was ±0.000015 (2 sigma). Reproducibility of $^{143}Nd/^{144}Nd$ ratios is about 0.00002. Reproducibility of Sm and Nd concentrations is 2% and of $^{147}Sm/^{144}Nd$ ratios is 0.1% (Menuge and Daly, 1990).

Major- and trace- element analysis was carried out by the Geological Survey of Newfoundland and Labrador (Table B.2, Appendix B).

a)


Kilometers
50 25 0 50
N
Pinwarian
Plutonic
Front
N
S
T_{DM} age range (Ga)
Pinware North (N)
Pinware South (S)
Cartwright Suite
1.35-1.65
1.66-1.74
1.75-1.84
1.85-1.95
1.96-2.15
2.16-2.86

b)

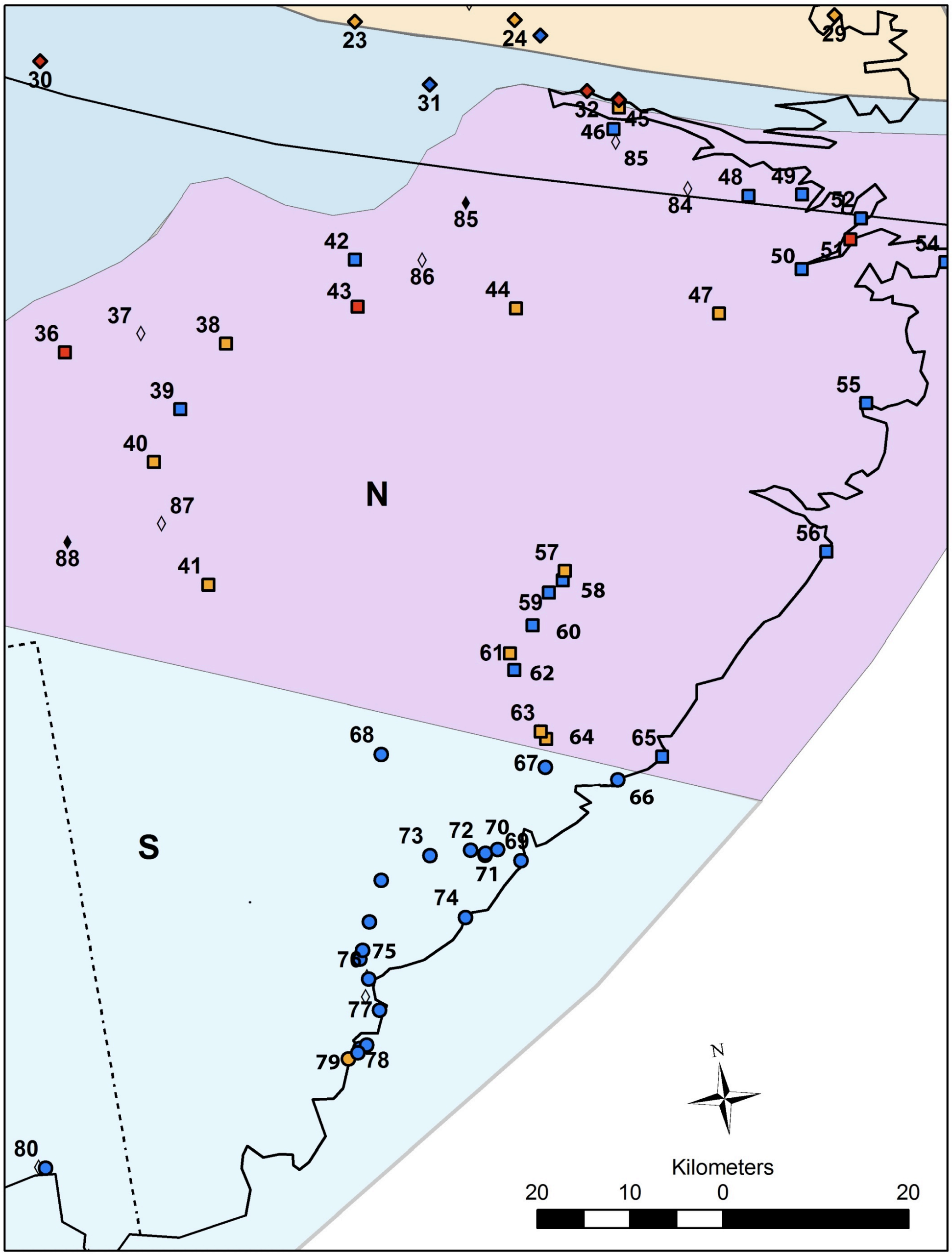


Figure 3.4.(a) Map of the study area within the Grenville Province, illustrating the sample locations for published (unnumbered samples), and new Nd data (numbered samples**)** **(b)** Map of sample locations within Pinware North and Pinware South. Symbols the same as 3.4 a). Published Nd data from Prevec et al. (1990), Schärer (1991) and Dickin (2000). Makkovik Province data included in the north for comparison.

3.4. Nd Isotope Results

New Nd isotope data from the current study are presented in B.1, Appendix B, and are used to calculate depleted mantle model ages (T_{DM}) using the model of DePaolo (1981). Sample localities are represented in Figs. 3.4 a) and b) by numbered points, along with locations for published data (not numbered).

Symbols plotted in Figures 3.4 a) and b) are subdivided by colour according to T_{DM} model ages. The northerly terranes (Groswater Bay, Hawke River, Lake Melville and the narrow eastern part of the Mealy Mountains terrane) have broad but overlapping ranges of model ages. They have been grouped together in this study and referred to as the Cartwright suite. In contrast, the Pinware terrane is subdivided into two crustal segments, since the northerly part contains several T_{DM} ages over 1.85 Ga , whereas the southerly segment only has T_{DM} ages less than 1.85 Ga. The boundary between these two segments appears to have a WNW-ESE trend near the Labrador coast (Fig. 3.4), but apparently cuts across the Pinware terrane. Therefore, the northerly and southerly segments of this terrane will be referred to here as Pinware North and Pinware South.

The majority of samples in the Cartwright suite have T_{DM} ages over 1.85 Ga, indicating that the bulk of the crust within these terranes has a Makkovikian or older character. However, the spread in model ages implies significant reworking by the Labradorian orogeny. Samples within the Pinware North group also display some Makkovikian T_{DM} ages, but also contain a spread of younger ages that may result from magma mixing in the Labradorian and possibly Pinwarian events. In contrast, samples from the Pinware South region consistently have T_{DM} ages below 1.85 Ga, and this crustal segment is therefore interpreted as juvenile Labradorian arc crust.

Both new and published data are plotted on a Sm-Nd isochron diagram in Figure 3.5, with symbols designating samples from the geographically defined suites identified above. On this diagram, samples from the Pinware South area plot close to published data from the coast of southern Labrador (black diamonds), which lie along a 1.75 Ga reference line (Dickin, 2000). This suggests that the Pinware South area represents part of the same juvenile Labradorian arc as the rocks further south. On the other hand, samples from the Cartwright suite and Pinware North block lie between the 1.75 Ga and 1.95 Ga reference lines. This suggests that these samples represent Makkovik crust that has been variably reworked by mixing with juvenile mantle-derived magmas during the Labradorian orogeny. Finally, samples shown by open diamonds are believed to contain a larger fraction of young mantle-derived Nd, which will be discussed further below.

Based on these groupings, the WNW-ESE trending boundary between the Pinware North and Pinware South segments is postulated to be a crustal-formation age boundary separating crustal blocks created in different orogenic events. This boundary is relatively well constrained by sample locations between the coast and the southern Labrador highway, but less well constrained to the west. However, we conjecture that it continues west-northwest. It coincides with a change from ill-defined structural trends in rocks to the north versus more pronounced west-northwest structural trends to the south. The boundary appears to be sub-parallel with the Gilbert River belt discussed above and

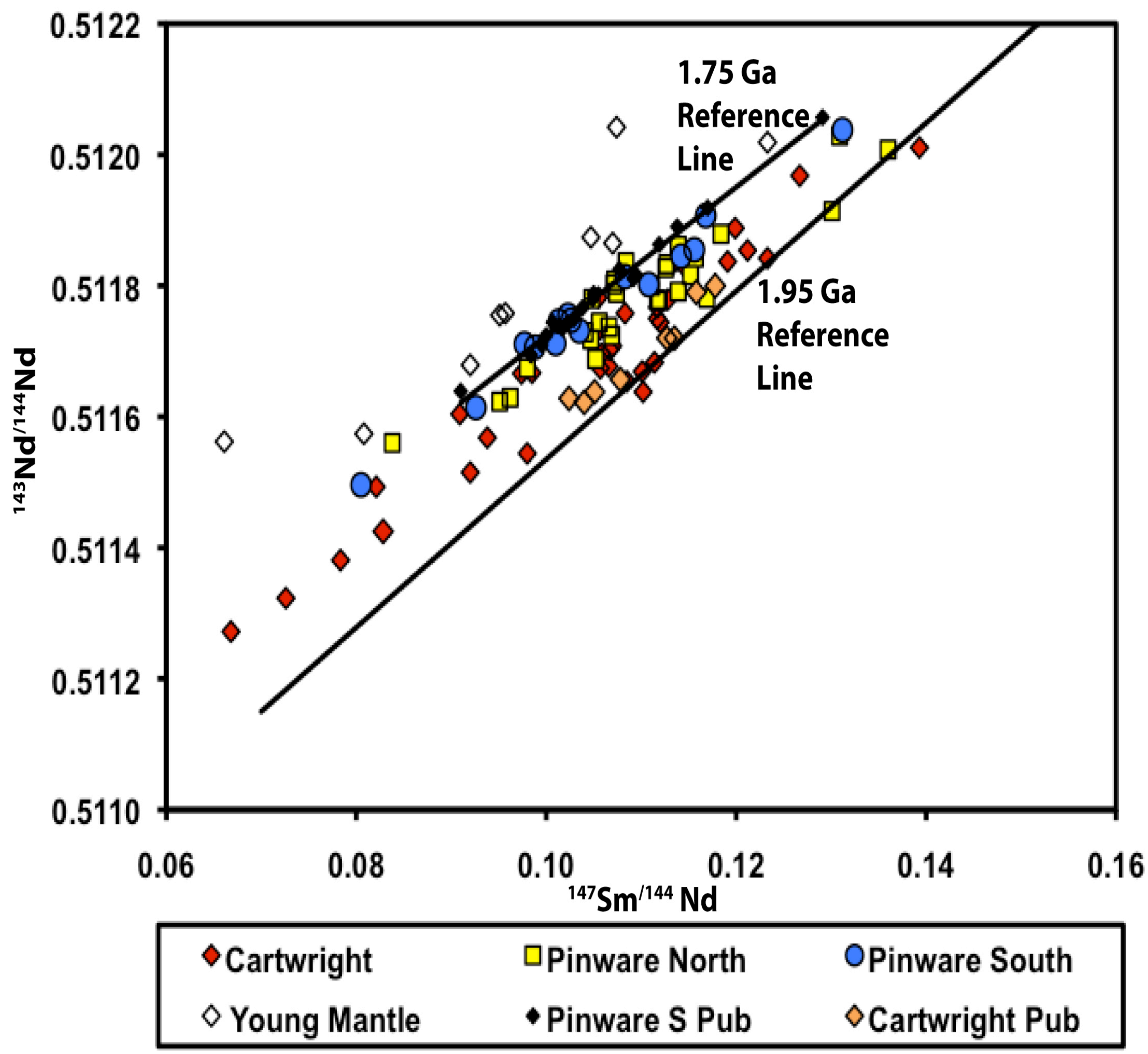


Figure 3.5. Sm–Nd isochron diagram for data from southeast Labrador. Reference lines of 1.75 Ga (Labradoria), 1.95 Ga (Makkovikia) are shown for comparison. Pinware South published data from Dickin (2000) and for the Cartwright suite by Prevec et al. (1990) and Schärer (1991).

therefore with the general structural fabric of the Groswater Bay - Hawke River - Lake Melville terranes to the north. This facilitates the construction of a north – south transect across the crust of Eastern Labrador, as will be discussed below.

3.5. Nd Isotope Profile

To test whether the isotopic mixing relationship proposed above has a spatial dimension, T_{DM} ages are plotted in Figure 3.6 against the north-south distance (km) from the proposed crustal-formation age boundary. Samples from the Makkovik Province (Moumblow et al., 2014), are also shown for comparison. Separate linear regressions were carried out for the Makkovik, Cartwright—Pinware North, Pinware South and Pinware South Pub (published) suites.

All of the data, except the Pinware South Pub suite, display correlations of increasing T_{DM} age northward. However, there are two age steps. The more northerly is believed to mark the northern boundary of major Labradorian plutonism within the pre-Labradorian Makkovik margin, whereas the southerly is believed to mark the southerly limit of Makkovikian crust, previously identified as a possible crustal boundary. Such a crustal age boundary is implied if an older continental margin is reworked by either ensialic arc magmatism, or by accretion of an oceanic arc. The sharpness of the boundary and its geological significance will be discussed below.

A possible complication to this model of a Makkovik – Labradorian crustal boundary is subsequent reworking of the crust during the Pinwarian event. In fact, Gower et al. (2008a) proposed a northern limit of major Pinwarian plutonism that forms a line sub-parallel to Labradorian-Makkovikian boundary proposed here, but shifted slightly to the north (Fig. 3.4). To test whether Pinwarian reworking has affected the Nd signatures of analysed samples, those with Pinwarian U-Pb ages have been identified with square boxes in Figure 3.6.

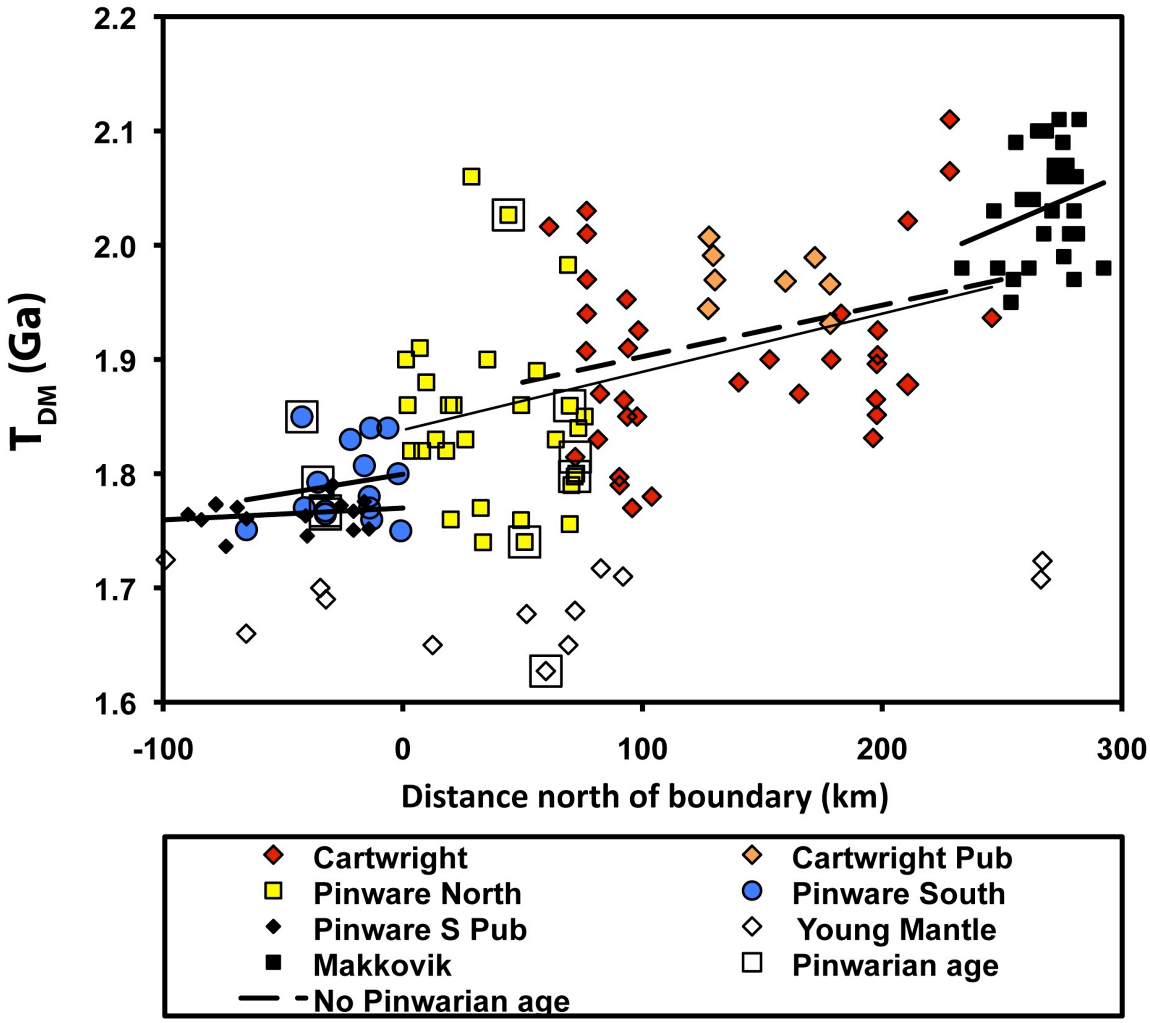


Figure 3.6. Plot of T_{DM} model age *versus* distance in km from the proposed crustal age boundary. Previously published data from Schärer (1991) and Dickin (2000). Pinwarian-age plutons are represented by open square boxes.

Pinwarian samples have more scattered T_{DM} ages than most other samples in the data set, but it appears that Pinwarian magmatism has only introduced minor amounts of juvenile material into the crust. This is in accord with the suggestion of Dickin (2000), supported by Heaman et al. (2004), that the Pinwarian event in southern Labrador was largely a crustal reworking event. Juvenile mantle mixing would be much greater for Grenvillian-age plutons, but the late- to post-tectonic plutons, at least, can be recognized with a fairly high degree of certainty by their relatively undeformed appearance. Hence, all such samples have been excluded from the present study to avoid such extra complications.

To further test the possible effect of Pinwarian magmatism on T_{DM} ages (for samples without U-Pb ages) a separate regression line across the Cartwright—Pinware North segments was calculated using U-Pb dated Labradorian samples only (dashed line in Figure 3.6). It can be seen that this line does have a slightly shallower slope than the (solid) regression line through all samples, but the effect is fairly limited. This shows that, although dated samples are to be preferred, undated samples can serve to identify Nd-isotopic boundaries (at lower analytical cost). For example, there is a sampling gap between U-Pb dated samples in the vicinity of the age boundary, which has been effectively filled with undated samples.

Figure 3.6 also includes 'Young Mantle' samples, which yield model ages below 1.75 Ga. One of these samples is a dated Pinwarian-age intrusion, but as noted above, most Pinwarian samples do not contain a large fraction of young mantle-derived Nd. Instead, the 'Young Mantle' suite is interpreted as granitoid rocks that contain a large fraction of direct mantle-derived differentiates. In contrast, all other samples are attributed to crustal melting, whether of juvenile mafic arc crust or older continental crust. This is in accord with the model of Chappell and White (1974) for granite petrogenesis, which attributed most I-type granites to melting of igneous crustal material, in contrast with the more rare M-type granites showing a component with direct mantle derivation.

To further test the model that the Cartwright and Pinware North suites represent a mixture of Nd from Makkovikian crust and juvenile Labradorian plutonism, Nd isotope data (in the form of epsilon values at 1.65 Ga) are plotted against Nd concentration in Figure 3.7. When comparing epsilon Nd values in this way, it is important to calculate all data at the same age, even though the intrusive ages of the samples vary. Using a single time minimizes any bias arising from the variable age of the samples. A value of 1.65 Ga was chosen because this is the major plutonic event that affected most samples. However, using different values of T has little effect on the distribution, except to move all points up and down, because of the relatively limited variation of Sm/Nd ratio in most samples. This causes Nd isotope compositions of most samples to evolve along sub-parallel evolution paths.

The Cartwright suite and the Pinware North suite generally fall between the distributions of the Makkovik and juvenile Labradorian (Pinware South) suites in Figure 3.7, which is consistent with the model proposed above that they represent Makkovik crust reworked by the Labradorian orogeny. In particular, the increasing degree of mixing with younger Labradorian magmas in the Pinware North suite is reflected by their increased Nd contents, which closely resemble the range in the juvenile Labradorian crust from Southern Labrador.

The higher Nd contents in samples of known Pinwarian-age plutons (square boxes) reflect the effects of two stages of crustal reworking in these samples, leading to increased scatter of the data, but not to a consistent increase in epsilon Nd values, as would be expected if Pinwarian crustal reworking had introduced new mantle-derived Nd. On the other hand, the latter effect is seen in samples of the 'Young Mantle' suite, which have high epsilon Nd values but very variable Nd contents.

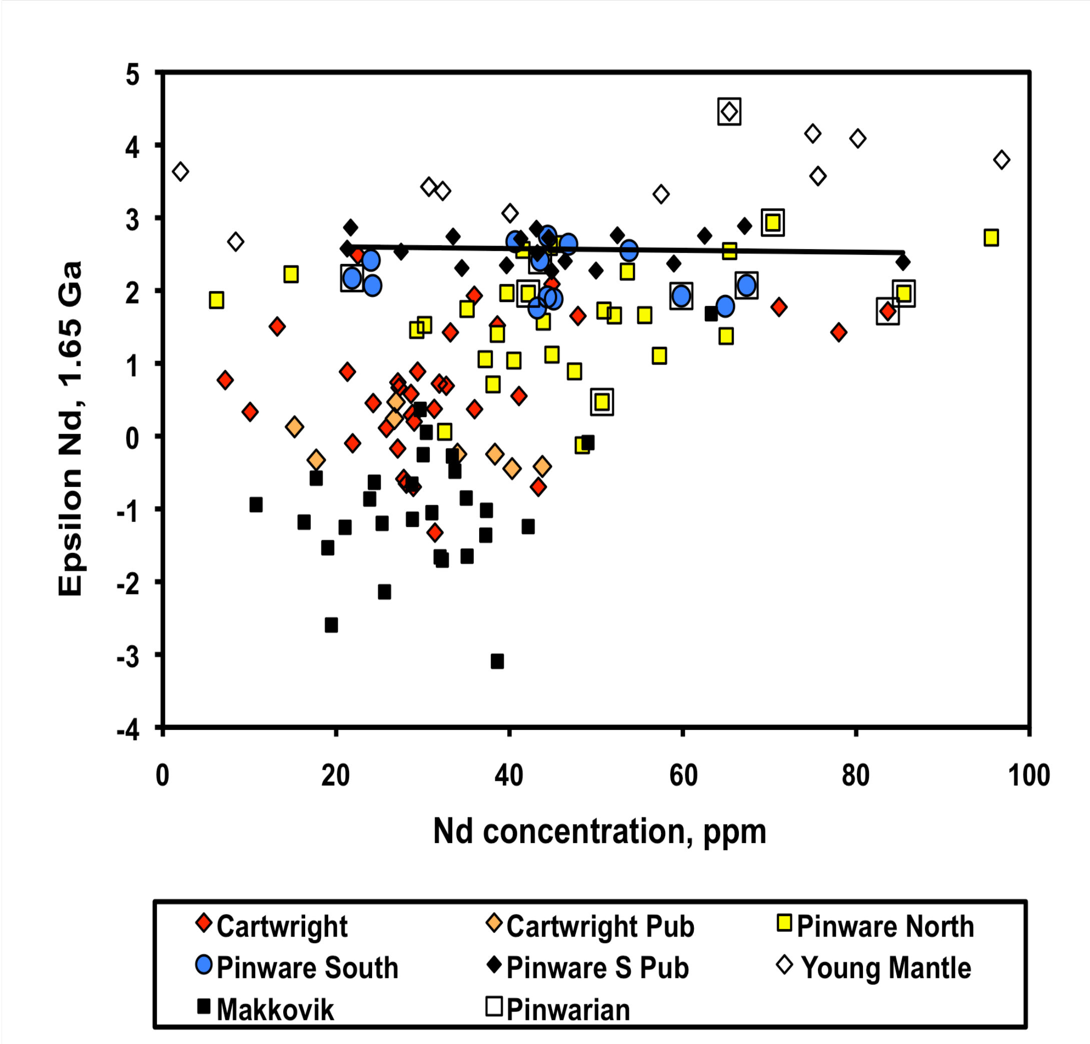


Figure 3.7. Plot of epsilon Nd calculated at 1.65 Ga against Nd concentration. Symbols as in Figure 3.6. Pinwarian-age plutons represented by open square boxes.

3.6. Petrochemical Data

Additional information regarding the possible tectonomagmatic setting of the analyzed suites was sought by utilizing major- and trace-element whole-rock geochemical data. To geochemically evaluate these suites, they are first plotted on variation diagrams against SiO_2 in Figure 3.8.

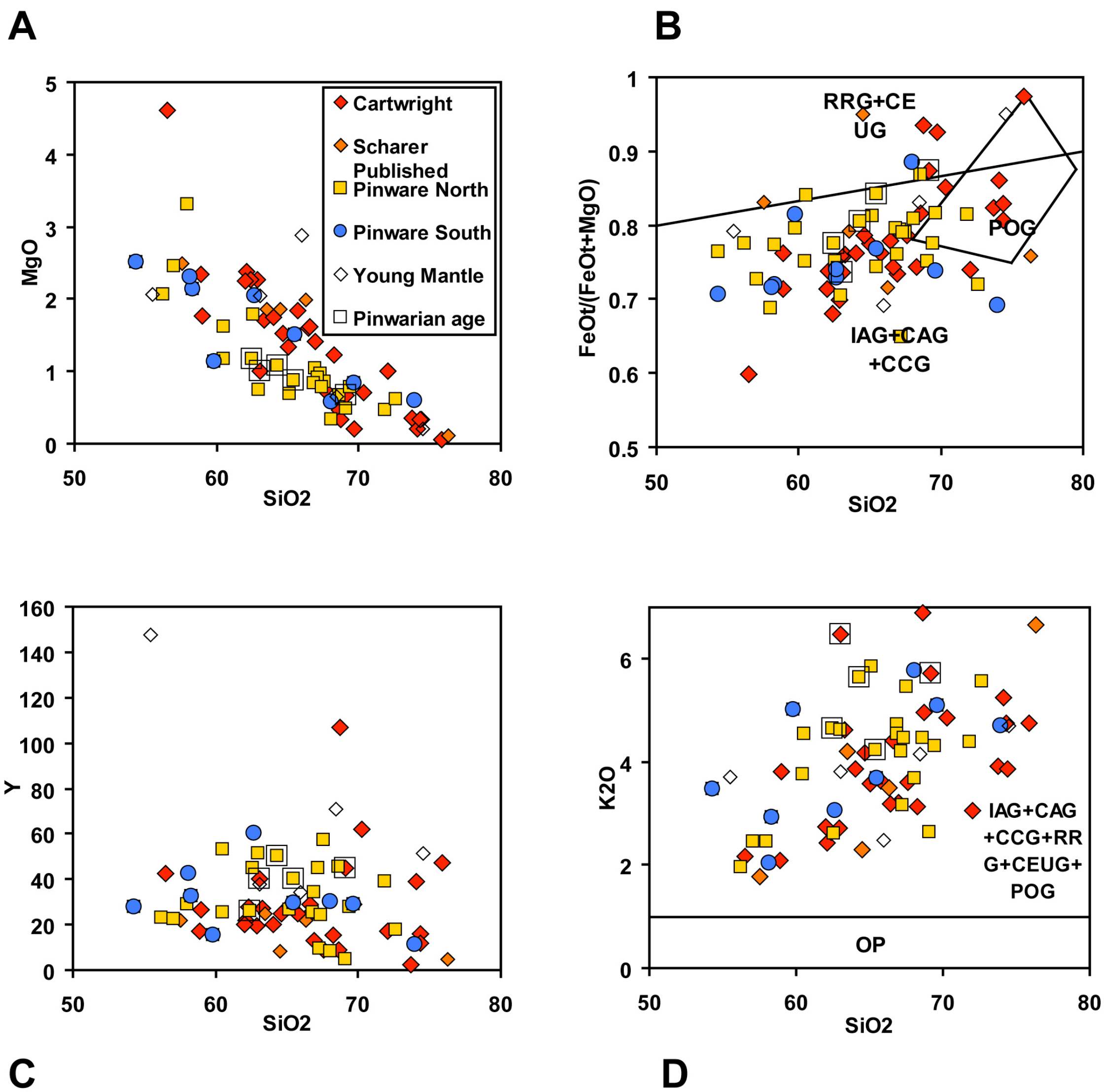


Figure 3.8. Plots of SiO_2 vs. MgO, Y, FeOt/(FeOt+MgO) and K_2O are presented for rocks of the study area. Data are expressed in weight percent. . IAG= Island arc granite, CAG=continental arc granitoids, CCG= continental collision granitoids, RRG= rift-related granitoids, CEUG= continental epeirogenic uplift granitoids, POG= postorogenic granitoids.

These diagrams show that all of the analysed suites have similar ranges of SiO_2 as well as other elements, although there are small differences in relative elemental abundances. For example, the Pinware North suite has generally lower MgO relative to the other suites. This may reflect the presence in this suite of a greater proportion of

Pinwarian-age samples, which mostly seem to have undergone two stages of crustal melting, which is likely to lead to lower MgO. This suite seems to have slightly higher Fe/Mg ratios, Y contents and K_2O concentrations than the other suites.

Discriminant plots that enhance relative elemental differences between suites are more useful as a guide to possible tectonomagmatic affinity. Figure 3.9 shows the Q (Quartz)–P (Plagioclase) diagram of Debon and LeFort (1983). This aims to classify granitoid rocks according to their whole-rock chemical compositions in a way that mimics the Streckeisen diagram. A notable feature revealed by the diagram is an almost complete lack of samples in the tonalite field, despite a potential sampling bias toward such material, as it is preferred in Nd-isotopic mapping studies (*e.g.,* Dickin et al., 2014). Tonalites are typically abundant in primitive oceanic arcs, such as Quebecia (Dickin and Higgins 1992), and Dickin (2000). Their absence in southeast Labrador points implies magma differentiation in thick crustal sections such as ensialic arcs.

Samples from the Cartwright suite trend from the quartz diorite to granite field, consistent with their emplacement in such an arc. This type of tectonic environment was also proposed for the Makkovik Province, which is shown for comparison. On the other hand, samples from the Pinware North suite trend to the right side of the figure. Several of these samples are U-Pb dated Pinwarian plutons (large square boxes), which supports the suggestion above that the Pinware North crustal segment contains a greater proportion of Pinwarian-age samples. Since these are believed to be crustal melts, this implies two stages of magma differentiation, leading to more alkaline compositions in quartz monzonite and quartz syenite fields.

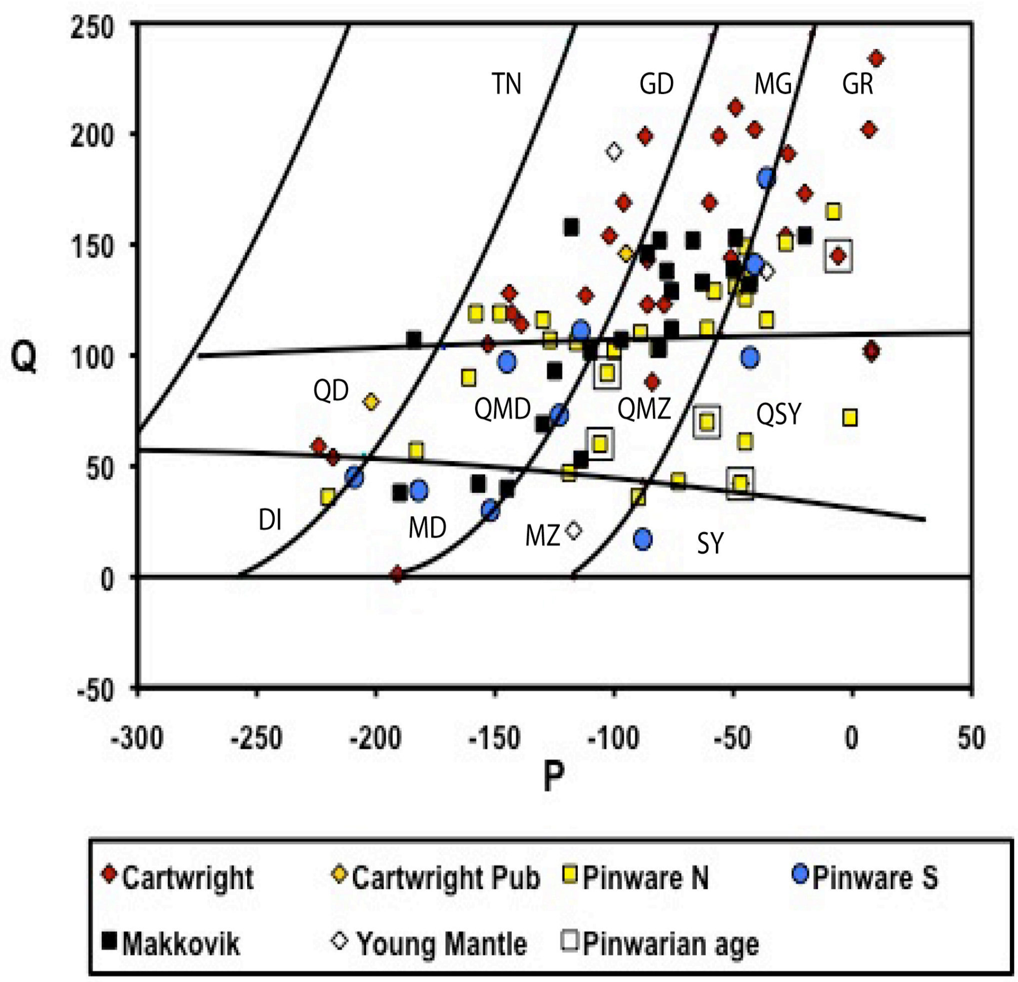


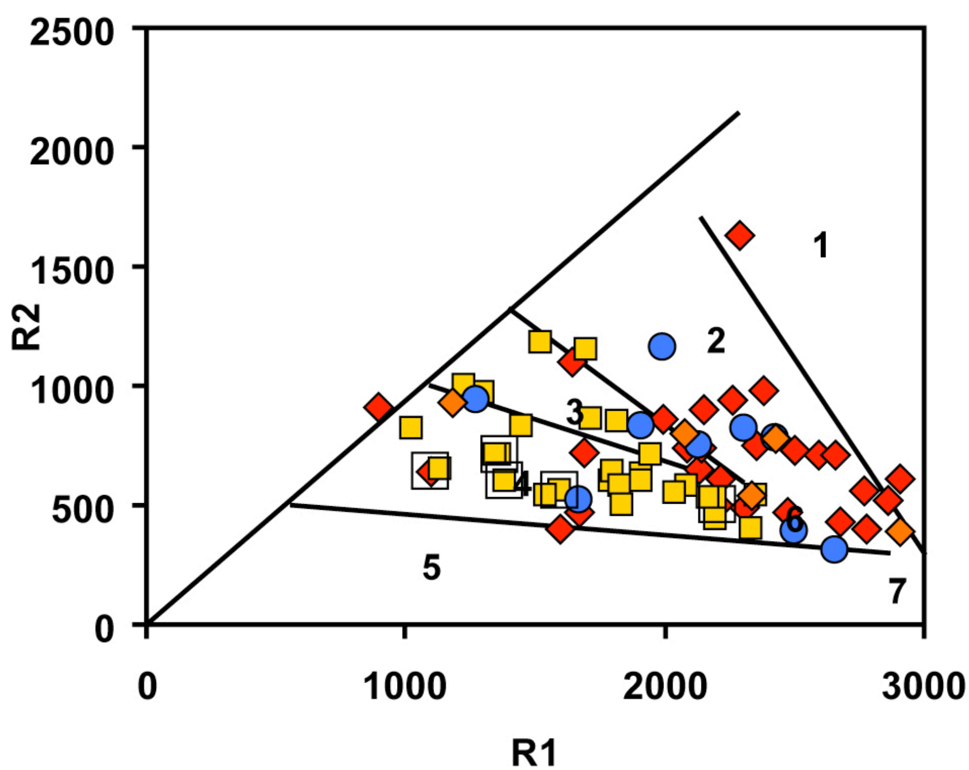
Figure 3.9. Samples from this study, along with previously published data for samples from Schärer (1991) and Moumblow et al. (2014), are plotted on the petrochemical grid of Debon and Le Fort (1983), a chemical classification of granitoid rocks that adopts Streckeisen's (1976) modal fields. Q is an index of quartz content, and P is an index of plagioclase vs. K-feldspar content. 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. See text for discussion.

Another major element discriminant diagram useful for assessing granitoid suites is the R1-R2 multi-cationic diagram (de la Roche et al., 1980; Batchelor and Bowden, 1985). This plot uses vectors to reflect the differences in magma composition during fractional crystallization and equilibrium, and hence to interpret the tectonic environment.

The R1-R2 diagram (Fig. 3.10a) demonstrates a separation between the data for the Cartwright suite and the Pinware North/South suites.

The samples from the Cartwright suite fall mostly within data field 2, possibly indicating a pre-plate-collisional setting. In contrast, the data from the Pinware North falls distinctly across fields 3 and 4, possibly suggesting a post-collisional uplift or late orogenic setting (or extra stages of magmatic differentiation in the case of Pinwarian samples). The Pinware South samples are somewhat intermediate between these two trends. The R1-R2 diagram from the Makkovik Province is plotted below for comparison (Fig. 3.10b, Moumblow et al. 2014). Most of these samples fall in fields 3 and 4, pointing to a post-collisional or mature ensialic arc setting, in contrast to the Kohistan arc of the Himalayas (Jagoutz et al., 2009) which is interpreted as a mature oceanic arc.

a)



b)

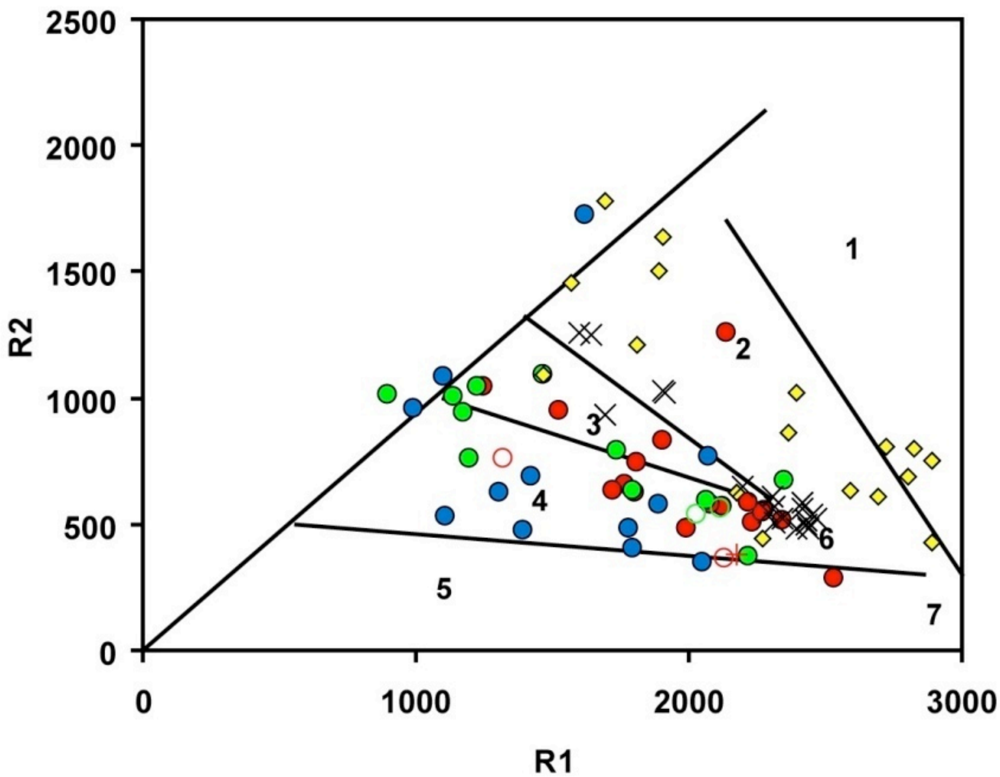
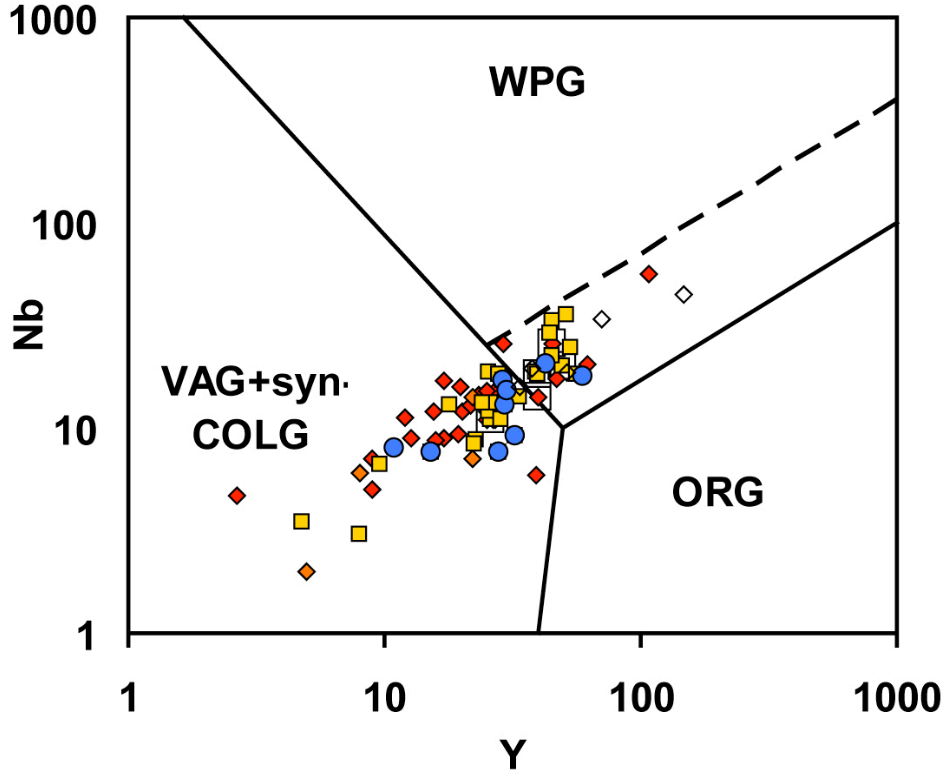


Figure 3.10 a). R1-R2 plot of the study area data, including previously published samples from Pinware South (Dickin, 2000) and the Cartwright suite (Schärer, 1991). **b)** Samples from the Makkovik Province (Moumblow et al., 2014) the Aillik domain (Barr et al., 2001), and the Kohistan arc (Jagoutz et al., 2009) are plotted for comparison. Symbols for 3.10 a) are the same as Fig. 8. Data fields for tectonic setting: 1 = mantle fractionates, 2 = pre-plate collision, 3 = post-collision uplift, 4 = late-orogenic, 5 = anorogenic, 6 = syn-collision, 7 = post-orogenic.

Finally, the sample set is also plotted on discrimination diagrams utilizing Y versus Nb, and Y+Nb versus Rb by Pearce et al. (1984), which aim to subdivide granitoid rocks according to tectonic setting (Figure 3.11). In Figure 3.11a, the Cartwright, Pinware North/South suites lie mostly within the volcanic-arc granite field, with the exception of a few samples that plot in the within-plate granite field. This signature can also be indicative of orogenic suites that underwent prolonged differentiation in thick crustal sections (Moumblow et al., 2014). Figure 3.11b displays a similar tectonic environment for all suites with the exception of the Pinware North suite, which has more samples that lie in the field of within-plate granites. Again, these samples may reflect further differentiation during Pinwarian magmatism.

a)



b)

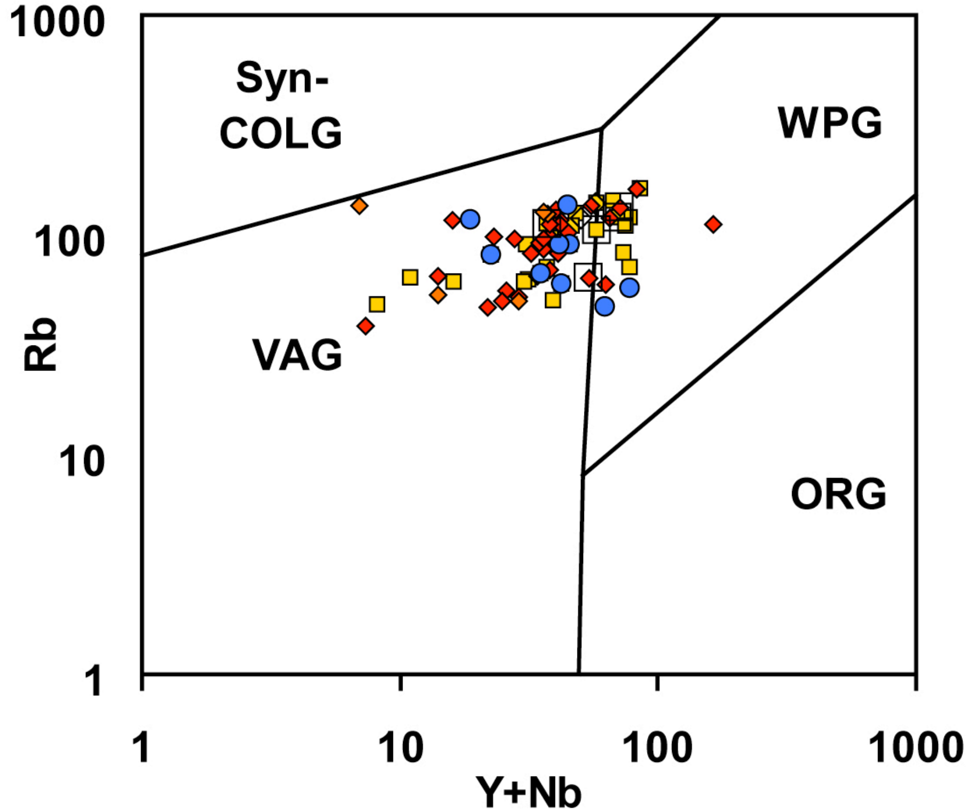


Figure 3.11.(a) Y–Nb diagram; and **(b)** Y + Nb–Rb diagram after Pearce et al. (1984). VAG, volcanic arc granites; syn-COLG, syn-collisional granites; WPG, within plate granites; ORG, orogenic granites.

3.7. Discussion

The Grenville Province of southern Labrador has a complex geological history, recording the effects of at least four major tectonic episodes; the Makkovikian, Labradorian, Pinwarian and Grenvillian orogenies. Although these events were established mostly through U-Pb geochronological studies, Nd-isotopic mapping can complement such conclusions by characterizing regions having distinct isotopic Nd-age signatures, identifying boundaries between them, and making inferences regarding crust-formation processes. The newly presented Nd isotopic data are now evaluated in the context of the U-Pb geochronological database.

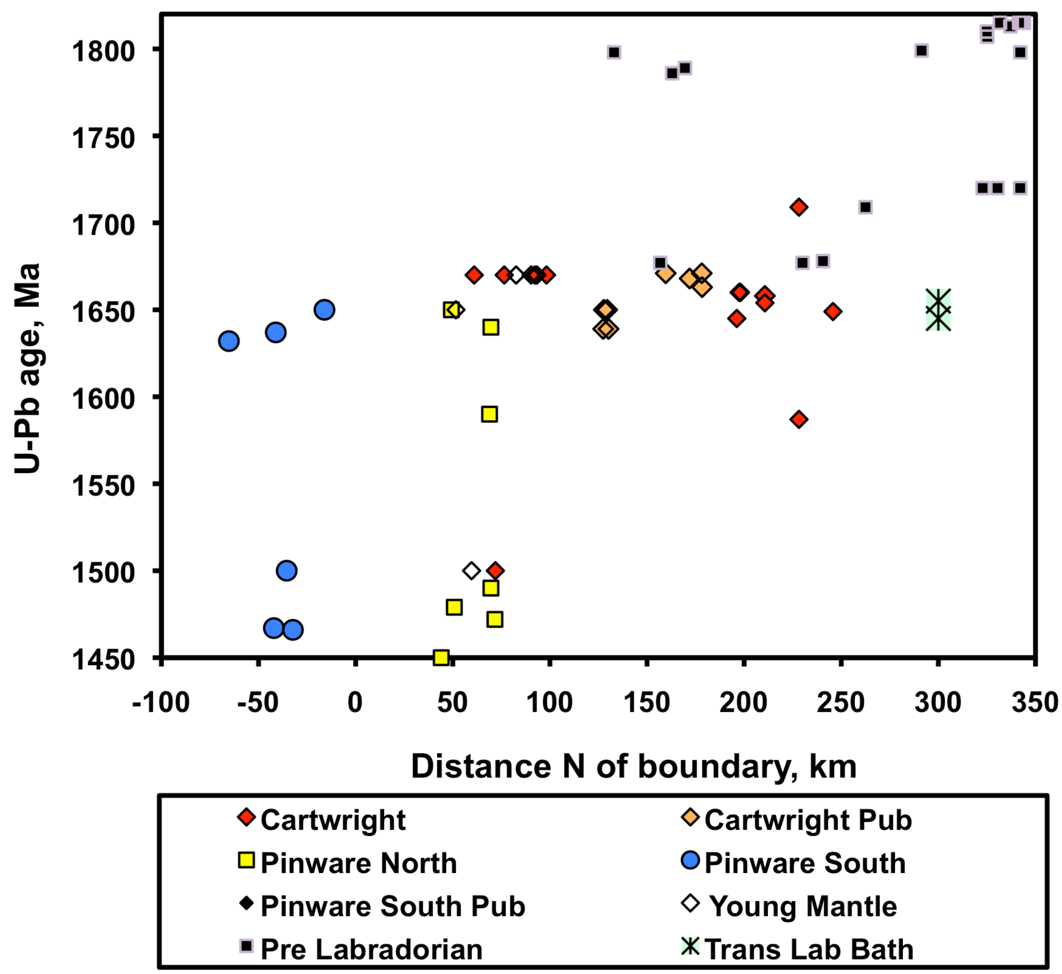


Figure 3.12. Plot of published U-Pb data against N-S distance from the Makkovik – Labradorian crustal boundary proposed above.

According to the tectonic model of Gower and Krogh (2002, 2003), summarized here in Figure 3.3, the boundary between an accreted Labradorian arc and Laurentia was located in the region of the Trans-Labrador batholith (TLB, stars in Figure 3.12). Observing that evidence for pre-collisional (>1.65 Ga) Labradorian magmatism was strong southeast of the TLB, but lacking to the northwest (Figure 3.12), Gower and

Krogh reasoned that this magmatism would not have been caused by northwest-directed subduction under the Laurentian margin, otherwise plutons of this age would be observed further north within pre-Labradorian Laurentia. They therefore proposed that pre-collisional, early Labradorian plutonism (1.71 - 1.65 Ga) was emplaced into a pre-Labradorian outboard arc.

Complications to Gower and Krogh's model arise if it is accepted that a 300 km-wide belt of Makkovikian crust existed in the eastern Grenville Province prior to Grenvillian orogenesis (as proposed here), having its southern boundary against juvenile Labradorian crust passing near Red Bay. If northwest-directed subduction was located outboard of such a wide Makkovik continental margin, it is less surprising that plutonism is not found north of the Trans-Labrador batholith, especially if it is assumed that this Makkovikian-age crustal section has been compressed by three subsequent orogenic events (Labradorian, Pinwarian and Grenvillian) and, hence, may originally have been even wider.

Assuming pre- and early-Labradorian northwest-directed subduction did occur beneath this 300-km wide zone, then provokes questions regarding the cause of the 1.65 Ga Labradorian deformational event and why the Trans-Labrador batholith was emplaced as a linear belt well inboard of the active margin. Perhaps the deformation event was caused by accretion of an off-shore juvenile arc, or maybe the northwest-directed juvenile Labradorian arc stepped offshore. However, any plausible model must satisfy another notable feature of the Labradorian orogeny, which is the relatively short duration of magmatism recorded in U-Pb ages (Figure 3.12), and the rapid waning of major magmatic activity after 1630 Ma, implying a lack of ongoing continentward subduction after collision.

If juvenile Labradorian crust was created by a north-dipping ensialic arc that stepped offshore, or by the accretion of an off-shore arc with the same subduction direction, the likely result would be a long-lived ensialic arc on the new margin. The extinction of such a subduction zone could have been caused by the attempt to subduct a mid-ocean ridge, as has been occurring on the west coast of the USA during the Tertiary (Cox and Hart, 1986). However, a more elegant model envisages a collision between two opposite-dipping subduction zones, as shown in Figure 3.13. This model explains the intensity of magmatism associated with the orogeny, since both margins were heated before collision by subduction-related magmatism. Hence when these two hot arcs collided, a modest amount of crustal thickening would lead to widespread intra-crustal melting.

Based on the geology of southern Labrador, it might appear that the accreted juvenile Labradorian arc was of modest size. Nd isotopic data suggest, however, that the Labradoria terrane extends westward into Quebec as far as Sept Iles, and has a N-S width reaching 300 km (Figure 3.1, and Dickin, 2000). The relatively large size of the accreted terrane could explain the intensity of the Labradorian orogenic event, and it also explains the longitudinal extent of the Trans Labrador Batholith (Figure 3.1).

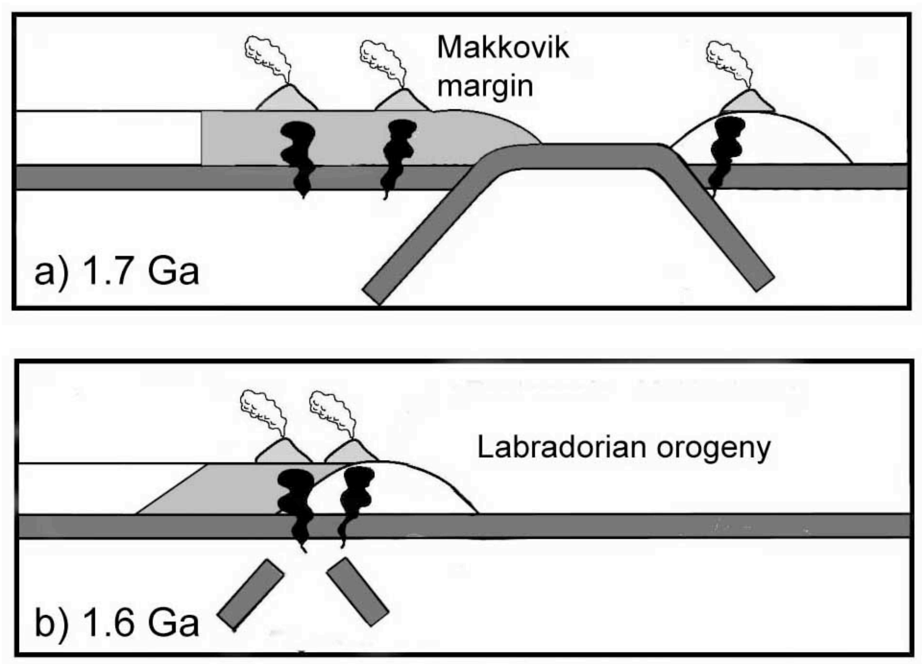


Figure 3.13. Simplified model for the Labradorian orogeny. Grey shading = Makkovikian crust previously accreted to the Laurentian margin. Off-shore arc = Labradoria.

This model can also explain the distribution of Paleoproterozoic metasedimentary terranes along the Makkovik-Ketilidian margin of Laurentia (Gower, 2012). These metasedimentary terranes could have a variety of origins, including passive-margin sequences developed on the earlier Makkovik margin, or fore-arc wedges associated with either of the subduction zones shown in Figure 3.13. These metasedimentary units are not equally well developed along the margin, possibly due to transpression during the collision.

It is notable that in the area north of Red Bay, metasedimentary units identified as the Pitts Harbour Group are abundant on the northern side of the proposed crustal boundary but rare to the south (Gower, 2010). This is consistent with this boundary representing a collisional suture between the two arc systems. In such a collision, one arc would eventually over-ride the other, leading to down-loading of one side of the collision zone, and the likely development of a foreland basin. If the offshore arc over-rode the older Laurentian margin, the Pitts Harbour Group may represent sedimentation in such a post-collisional foreland basin.

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Chapter 4: The Grenville Province-central-south Labrador

4.1. Introduction

The Grenville Province in Labrador experienced intense magmatism and regional metamorphism during collisional orogenesis (ca. 1085 to 985 Ma), and, earlier, experienced three major active-margin accretionary orogenic events, namely a pre-Labradorian event (1810-1770 Ma), Labradorian (1710-1600 Ma), and Pinwarian (1520-1460 Ma), resulting in a complex geological history.

Central-south Labrador has been subdivided into several terranes (Fig. 4.1), which acted as distinct lithotectonic units during the Grenville orogeny, but whose geological history may go back to the Paleoproterozoic. In the east, addressed here, are the Mealy Mountains terrane, containing the Labradorian-age Mealy Mountains Intrusive Suite; and the Pinware terrane, dominated by Labradorian and Pinwarian granitoids. In the west, there are several terranes dominated by Paleoproterozoic metasedimentary rocks (Lac Joseph, Churchill Falls and Wilson Lake terranes). To the north, lies the Trans-Labrador Batholith; while in the south is the Mesoproterozoic Wakeham Supergroup, plus a series of partially defined lithotectonic entities that are not depicted in Figure 4.1 (Lac-à-l'Aigle, Saint-Jean and Natashquan domains; Gobeil et al., 2003).

The objective of the present study is to provide a reconnaissance understanding of crustal development through Nd isotopic analysis performed on a suite of regional samples previously dated by U-Pb geochronological methods, and followed up by more detailed sampling in selected areas.

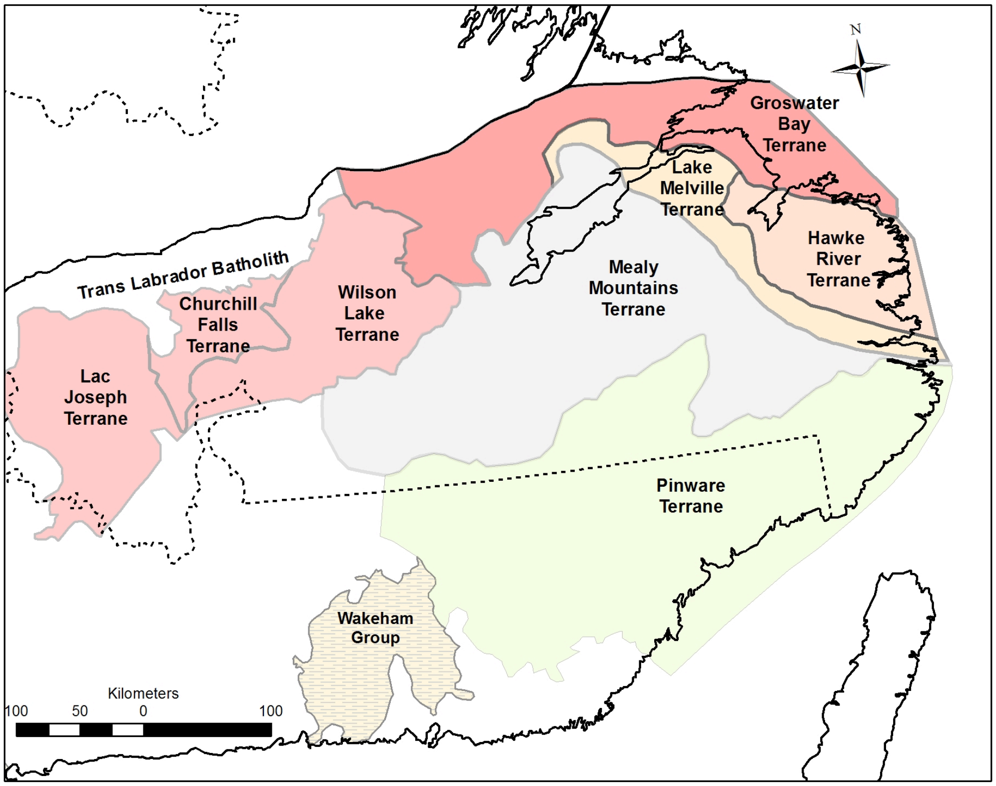


Figure 4.1. Map of the eastern Grenville Province showing major Grenvillian lithotectonic terranes.

4.2. Geological background

The major terranes that make up the study area have somewhat distinct geological histories. Therefore, to begin the description of the geological background, the major features of each terrane are described.

4.2.1. Mealy Mountains Terrane

The Mealy Mountains terrane has an outcrop width of only 5 km on the Labrador coast, but widens westwards to a N-S extent of up to 200 km. The terrane is dominated by the Mealy Mountains Intrusive Suite (MMIS, Fig. 4.2), which comprises large bodies of anorthosite, leuconorite and leucotroctolite, along with associated granitoid bodies emplaced between 1650 and 1630 Ma (Gower et al., 2008a; Bybee et al., 2014). It was emplaced into pre-Labradorian metasedimentary gneiss, and pre-Labradorian and Labradorian orthogneiss.

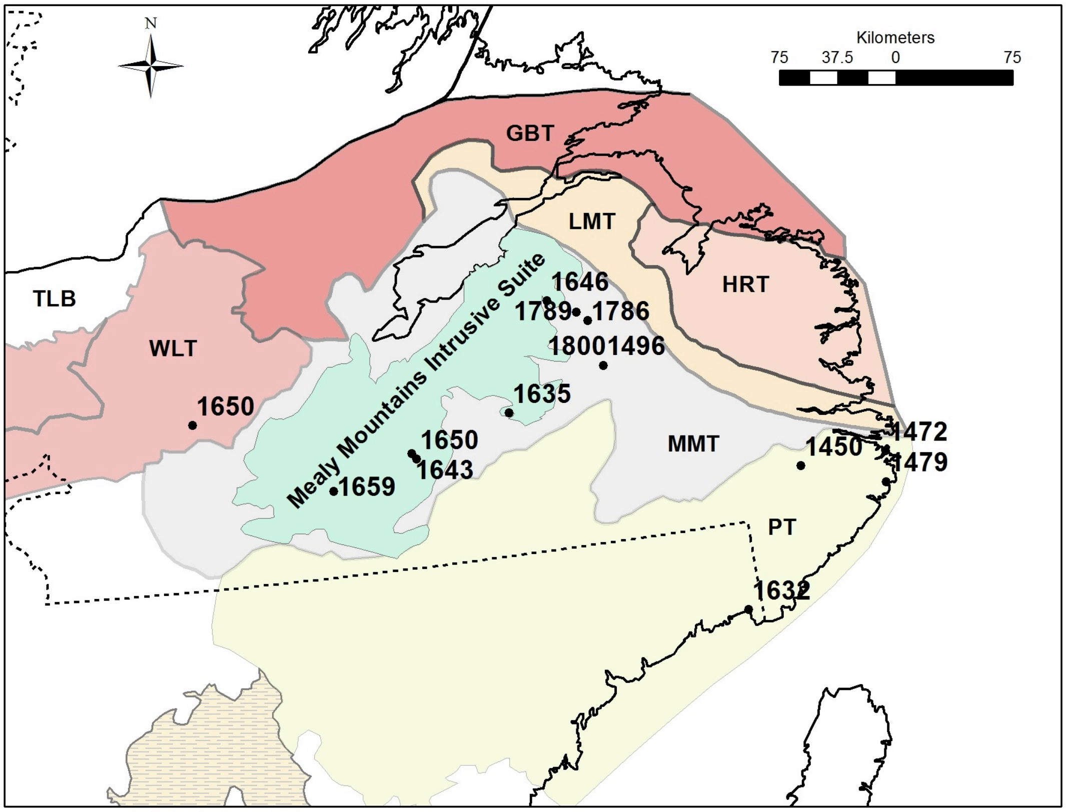


Figure 4.2. Map of southern Labrador showing locations for U-Pb ages discussed in the text. Data from Emslie and Hunt (1990), James et al. (2000), James et al. (2002), Gower et al. (2008a), Heaman et al. (2004), Tucker and Gower (1994), and Wasteneys et al. (1997). GBT=Groswater Bay Terrane, HRT=Hawke River Terrane, LM=Lake Melville Terrane, MMT= Mealy Mountains Terrane, PT=Pinware Terrane, WLT= Wilson Lake Terrane, and TLB= Trans-Labrador Batholith.

Nd isotopic analysis of MMIS anorthosite (Ashwal et al., 1986) yielded epsilon values around +3 at 1650 Ma, implying a largely mantle-derived source, possibly with minor involvement of Paleoproterozoic crust. A recent Nd isotope study on a suite of high-alumina orthopyroxene megacrysts (HAOMS) from the MMIS gave a good quality Sm-Nd isochron, yielding an age of 1765 ± 12 Ma and an initial epsilon value of +3

(Bybee et al., 2014). They interpreted the 100 million-year time difference between the crystallization of the HAOMS and the anorthosite emplacement (1646 Ma) to mean a very long-lived magmatic system in the base of the crust, probably in an Andean-type ensialic arc.

Until recently, the extent of pre-Labradorian crust in the Mealy Mountains terrane was uncertain, although its presence had been suspected since the early 1990s (*cf.* summary of accumulated evidence by Moumblow et al., 2014). Confirmation was provided by Gower et al. (2008a), who reported U-Pb ages of 1800 ± 40 Ma, 1789 ± 29 Ma, and 1786 ± 11/-5 Ma for a group of calc-alkaline plutons just east of the MMIS (Fig.4.2). These granitoid rocks intrude supracrustal rocks (which are probably only marginally older) containing Archean and early Paleoproterozoic inherited zircons (Gower, 2008a). The pre-Labradorian ages confirm indications from earlier U-Pb dating (Schärer and Gower, 1988; Philippe et al., 1993; Scott et al., 1993; Wasteneys et al., 1997); and Nd-isotopic studies by Dickin (2000), who concluded that at least the northeastern part of the terrane consists of juvenile Makkovik crust reworked in the Labradorian orogeny.

The Mealy Mountains terrane was also affected by the Pinwarian orogeny (1520-1460 Ma) (Gower and Krogh, 2002). In particular, Gower et al. (2008a) reported a U-Pb upper intercept age of 1496 ± 10Ma for pegmatitic inter-boudin material, the regression including a collinear monazite analysed from the adjacent quartzofeldspathic gneiss. Gower et al. (2008a) interpreted this date as support for a Pinwarian deformation and Pb-loss event. Due to poor exposure in the region and similarity of rock types between the

Mealy Mountains and the Pinware terranes, the boundary between the two remained ill defined (Gower et al., 2008a).

4.2.2. Pinware Terrane

The Pinware Terrane consists of Labradorian- and Pinwarian-age granitoid plutonic rocks, with minor gneiss of supracrustal origin (Tucker and Gower, 1994). Labradorian-age granitoid plutons were dated by Heaman et al., (2004) at 1632 ± 8 Ma for the Brador River granite, and at 1650 +18/-9 Ma and 1649 ± 7 Ma by Wasteneys et al. (1997).

Labradorian-age supracrustal rocks of the Pitts Harbour Group from southeast Labrador were dated by Wasteneys et al. (1997) and Tucker and Gower, (1994), yielding ages of 1637 ± 8 Ma and 1640 ± 7 Ma, respectively. U-Pb dating of a feldspathic quartzite from the southwest part of the present study area yielded three detrital zircons with upper intersection ages around 2.4 Ga (Gower et al., 2008a), implying contribution from an early Paleoproterozoic source. Gower et al., (2008a) also presented U-Pb ages for some enclaves in younger plutons. One enclave was interpreted to be have been derived from a sediment having a dominantly ca. 1800 Ma protolith, but the presence of Archean zircons implies that the source is unlikely to be local crustal basement.

Granitoid Pinwarian-aged plutons dated by the U-Pb method gave ages of 1479 ± 2 Ma, and 1472 ± 3 Ma (Fig. 2) (Tucker and Gower, 1994). High-grade metamorphism resulting from the Pinwarian orogeny was also recorded in a migmatitic quartz monzonite, with an age of 1450+15/-21 Ma (Wasteneys et al., 1997).

Sm-Nd data from the Pinware terrane were presented by Dickin (2000), yielding a mean T_{DM} age of 1.76 Ga. Since the difference between this T_{DM} age and the 1650 Ma

U–Pb ages of the Labradorian quartz monzonite plutons dated by Wasteneys et al. (1997) is only 110 Ma, Dickin (2000) agued that the magma could not have come from Archean crust. Instead, he proposed that the granitoid plutons were intruded into juvenile Paleoproterozoic crust that formed in a Labradorian off-shore arc.

4.2.3. Metasedimentary Terranes

The Wilson Lake terrane is the largest and the most easterly of the Paleoproterozoic metasedimentary terranes in the Grenville Province in southern Labrador. It is comprised of late Paleoproterozoic high-grade metasedimentary gneisses with a probable pre-Labradorian depositional age (ca. >1720 Ma) (Nadeau and James, 2002, James et al., 2002, Parsons and James, 2003). A minimum age for deposition of these meta-sedimentary gneisses is based on the emplacement of intrusions of variably deformed granitoid orthogneisses and minor gabbro units within the terrane, which are dated by U-Pb at 1650 ± 4 Ma (Figure 4.2) (James et al., 2002). To the north, the Wilson Lake terrane is bounded by the Trans Labrador Batholith, and to the south a set of ductile shear zones demarks the boundary with the Mealy Mountains terrane (James et al., 2001).

4.2.4. The Trans-Labrador Batholith

The Trans-Labrador Batholith (TLB) forms a 600-km-long belt of granitoid rocks that is situated near the Grenville Front (Kerr, 1989). It is not a product of the Grenville orogeny, but was emplaced as a result of magmatism during the Labradorian orogeny. Based on numerous U-Pb dates, its emplacement age range was given as 1654-1646 Ma by Gower and Krogh (2002). Note that the timing of the magmatism of the Trans-Labrador Batholith overlaps with the start of trimodal mafic-anorthositic-monzogranitic magmatism in the Mealy Mountains Intrusive Suite (Gower, 2012).

4.3. Geological history

To summarize, the principal accretionary orogenic episodes in southern Labrador were from ca. 1.8 to 1.5 Ga. Figure 4.3 reproduces a compilation of U-Pb data from Gower et al. (2008a). Based on these data, Gower et al. used the igneous crystallization ages of major plutonic bodies to define 'regional orogenic ages' for large crustal segments (identified by different shading densities in Fig. 4.3).

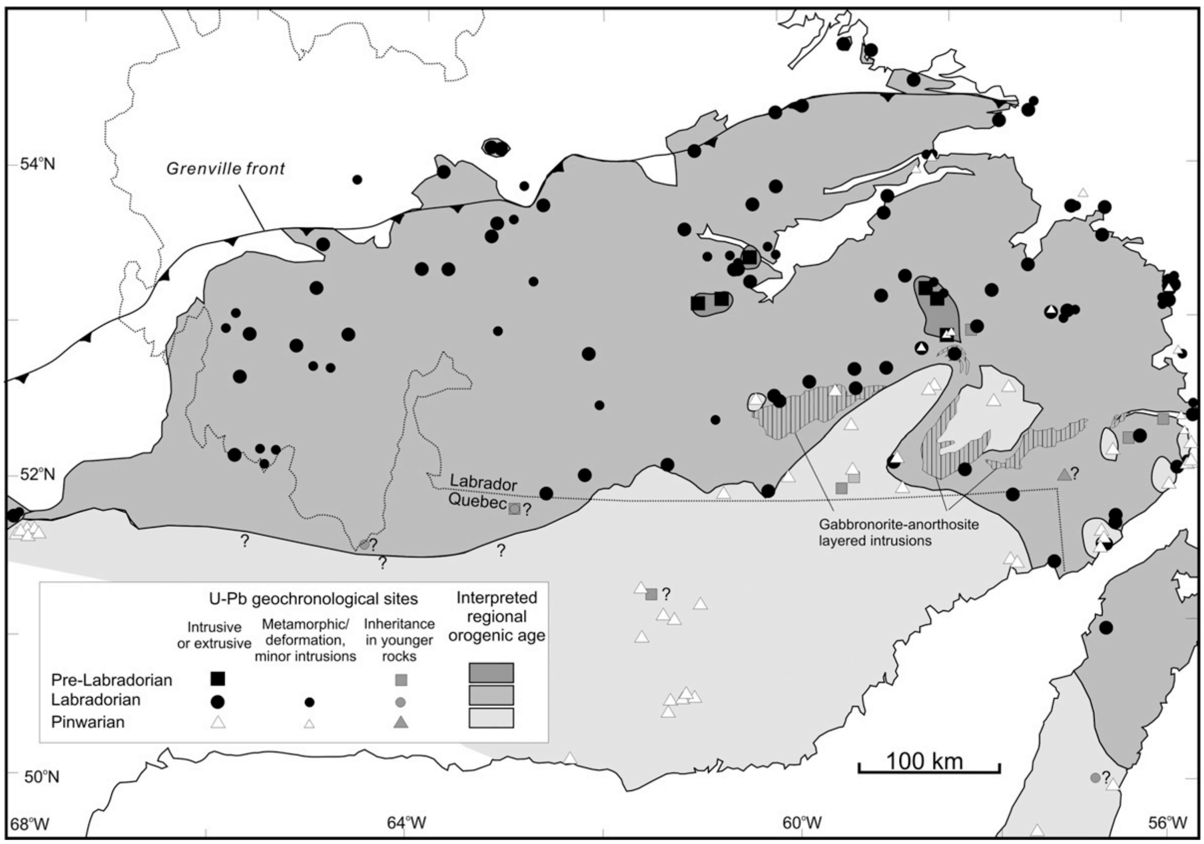


Figure 4.3. Gower et al. (2008a) distribution of pre-Labradorian, Labradorian and Pinwarian rocks based on U-Pb geochronology.

In this figure, pre-Labradorian crust is depicted as a few small pockets within the central portion of the map. Gower et al. (2008a) suggested that, based on enclaves and inherited zircon in younger rocks, that pre-Labradorian crust extended farther south than previously recognized, but that crustal additions from Labradorian and Pinwarian magmatic processes had obscured the earlier history. As noted above, the upper limit of these pre-Labradorian U-Pb ages (1800 Ma) defines this crust as coeval with late Makkovikian events. This crustal segment was inferred to be part of a juvenile accreted terrane, termed Makkovikia, by Dickin (2000).

The northern limit of Labradorian plutonism seems to be well constrained on the map, corresponding to the location of the Trans-Labrador Batholith near the later Grenville Front. Hence this indicates an overlap of at least 200 km between late Makkovikian and Labradorian plutonism. Furthermore, the 1765 Ma Sm-Nd isochron for MMIS megacrysts (Bybee et al., 2014) supports the idea that the Mealy Mountains terrane was a locus of major post-Makkovik magmatism, possibly as part of a long lived Andean-type margin.

The pattern of overlap between Makkovik and Labradorian plutonism in the north is repeated in the south by an overlap of over 100 km between Labradorian and Pinwarian plutonism, at least on the Labrador coast, where Labradorian and Pinwarian plutonism is intermingled. In the interior, this pattern is complicated by a large Grenvillian-age fold (Fig. 4.3). In this region, Gower et al. (2008a) drew a boundary between Labradorian- and Pinwarian-age plutons that was based on dated sample locations and regional structure. The boundary was not recognized in the field, but falls close to a Grenvillian metamorphic boundary that is marked by a zone of straight gneiss, adopted as the interface between the Mealy Mountains and Pinware terranes (Gower, 2012).

4.4 Sampling and Analytical Methods

One of the principal objectives of the present study is to enhance understanding of the distribution of pre-Labradorian (Makkovik-age) crust within the Grenville Province. This guided sampling in the southern part of the study area, but, in addition, reconnaissance sampling of plutonic rocks from the north-western part of the study area was undertaken along the Labrador Highway. The objective here was to test whether these rocks in these terranes, while largely sedimentary, also contain igneous components of Makkovik age, or, alternately, have older crustal sources.

Sixty-three orthogneissic samples were analyzed for the current study, including samples provided by the Geological Survey of Newfoundland and Labrador (collected by C.F. Gower). Sampling locations are indicated in Figure 4.4, and complement those from the southeast Labrador study (Moumblow et al., 2014).

Sm-Nd analysis followed the procedure of Dickin and McNutt (1989). After dissolution using HF and HNO3, samples were split and one aliquot spiked with a mixed ^{150}Nd-^{149}Sm spike. Analysis by this technique yielded Sm/Nd = 0.2280 ± 0.0002 for BCR-1, in agreement with Thirlwall (1982). Standard cation and reversed-phase column separation methods were used. Nd isotope analyses were performed on a VG isomass 354 mass spectrometer at McMaster University using double filaments and a four-collector, peak-switching algorithm, and were normalized to a ^{146}Nd/^{144}Nd ratio of 0.7219. Average within-run precision on the samples was ±0.000014 (2 sigma), and an average value of 0.511856 ± 0.000020 (2 sigma population) was determined for the La Jolla standard during this work, in agreement with Thirlwall (1991). The reproducibility of ^{147}Sm/^{144}Nd and ^{143}Nd/^{144}Nd is estimated at 0.1% and 0.002% (1 sigma), respectively, leading to an average uncertainty on each model age of 20 million years (2 sigma), based on empirical experience over several years of analyzing duplicate dissolutions.

An additional sixteen samples were analyzed by Stephen Daly and Robert A. Creaser (samples denoted by an asterisk (Daly) and caret (Creaser) in Table C.1, Appendix C). Samples analyzed by Creaser used methods similar to those described above. Nd isotope analyses were performed on a VG 354 mass spectrometer at the University of Alberta using double filaments and a four-collector, peak-switching algorithm, and were normalized to a $^{146}Nd/^{144}Nd$ ratio of 0.7219 (Creaser et al., 1997). Average within-run precision on the samples was ± 0.000008 (2 sigma). Samples analyzed by Daly used a semi-automated VG Micromass 30 mass spectrometer at University College, Dublin. $^{143}Nd/^{144}Nd$ ratios were determined on spiked samples. $^{143}Nd/^{144}Nd$ ratios are normalized to $^{146}Nd/^{144}Nd = 0.7219$. Average within-run precision on the samples was ±0.000015 (2 sigma). Reproducibility of $^{143}Nd/^{144}Nd$ ratios is about 0.00002. Reproducibility of Sm and Nd concentrations is 2% and of $^{147}Sm/^{144}Nd$ ratios is 0.1% (Menuge and Daly, 1990).

Major- and trace- element analysis was carried out by the Geological Survey of Newfoundland and Labrador (Table C.2, Appendix C).

4.5. Nd Isotope Results

New Nd isotope data from the current study are presented in C1, Appendix C and are used to calculate depleted-mantle model ages (T_{DM}) using the model of DePaolo (1981). Sample localities are represented in Fig. 4.4 by numbered points, along with locations for published data (not numbered).

Symbols plotted in Figure 4.4 are subdivided by colour according to their T_{DM} model ages. Sample ages from the Mealy Mountains terrane are largely concentrated between 1.75 Ga and 1.95 Ga. The relatively small range in model ages suggests that most of the Mealy Mountains terrane is comprised of Makkovik-age crust that has been reworked by mixing with juvenile mantle-derived magmas during the Labradorian orogeny. However, the northern part of the Pinware terrane displays a similar range of model ages, suggesting that Makkovikian crust may extend into this region, as was previously proposed for the coast of SE Labrador by Moumblow et al. (2014). Hence a segment of the northern Pinware terrane has been shaded a different colour in Fig. 4.4 to indicate a possibly older crustal formation age than the juvenile Labradorian-age crust in the southern part of the Pinware terrane. This evidence will be addressed in detail below.

Finally, the majority of samples within the Trans-Labrador Batholith (diamonds) and Wilson Lake terrane (squares) have T_{DM} ages between 1.95 and 2.15 Ga, implying that the bulk of the crust within these terranes has a Makkovik provenance and was not significantly affected by the Labradorian orogeny.

New sample data from the study area, along with previously published data, are plotted on a Sm-Nd isochron diagram in Figure 4.5, using symbols to distinguish samples from the geographically defined terranes and terrane segments discussed above. In this figure, samples from the Mealy Mountains terrane are widely distributed between 1.95 Ga and 1.75 Ga reference lines, attributed to mixing of Makkovik and Labradorian Nd components. Samples from the northern part of the Pinware terrane display a similar tendency, but generally with a reduced Makkovikian component.

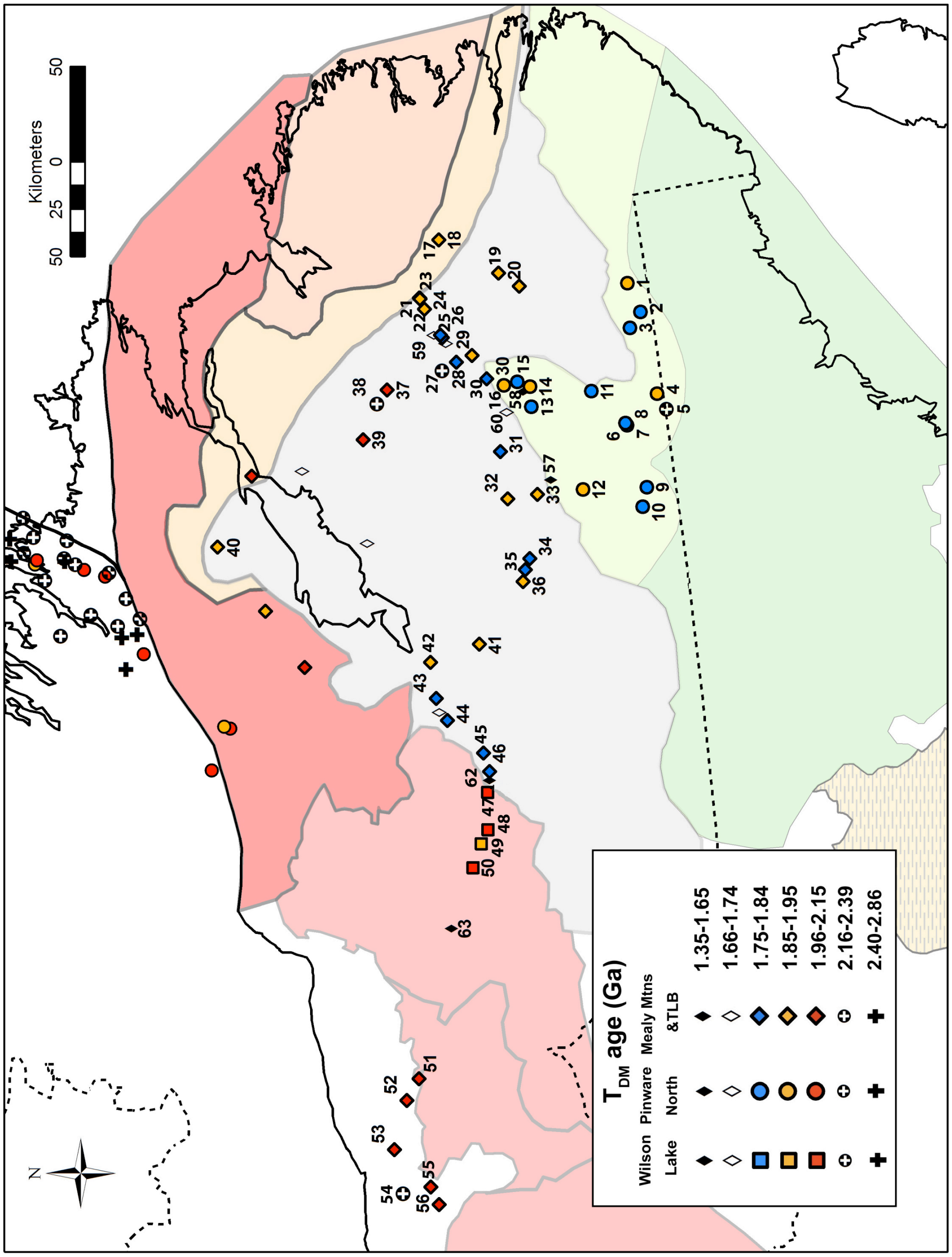


Figure 4.4. Map of the study area within the Grenville Provinces, illustrating the sample locations for published (unnumbered samples), and new Nd data (numbered samples). Published Nd data from from Kerr and Fryer (1994), Ketchum et al. (2002), Prevec et al. (1990), and Schärer (1991).

Data from the Wilson Lake terrane, Lake Melville and Groswater Bay Published data plot very close to the 1.95 Ga reference line, indicating a Makkovik provenance, although there is some minor evidence of magma mixing from a Labradorian source. Data from the Trans Labrador Batholith are entirely below the 1.95 Ga reference line, suggestive of Makkovik aged crust that has been unaffected by the Labradorian orogeny.

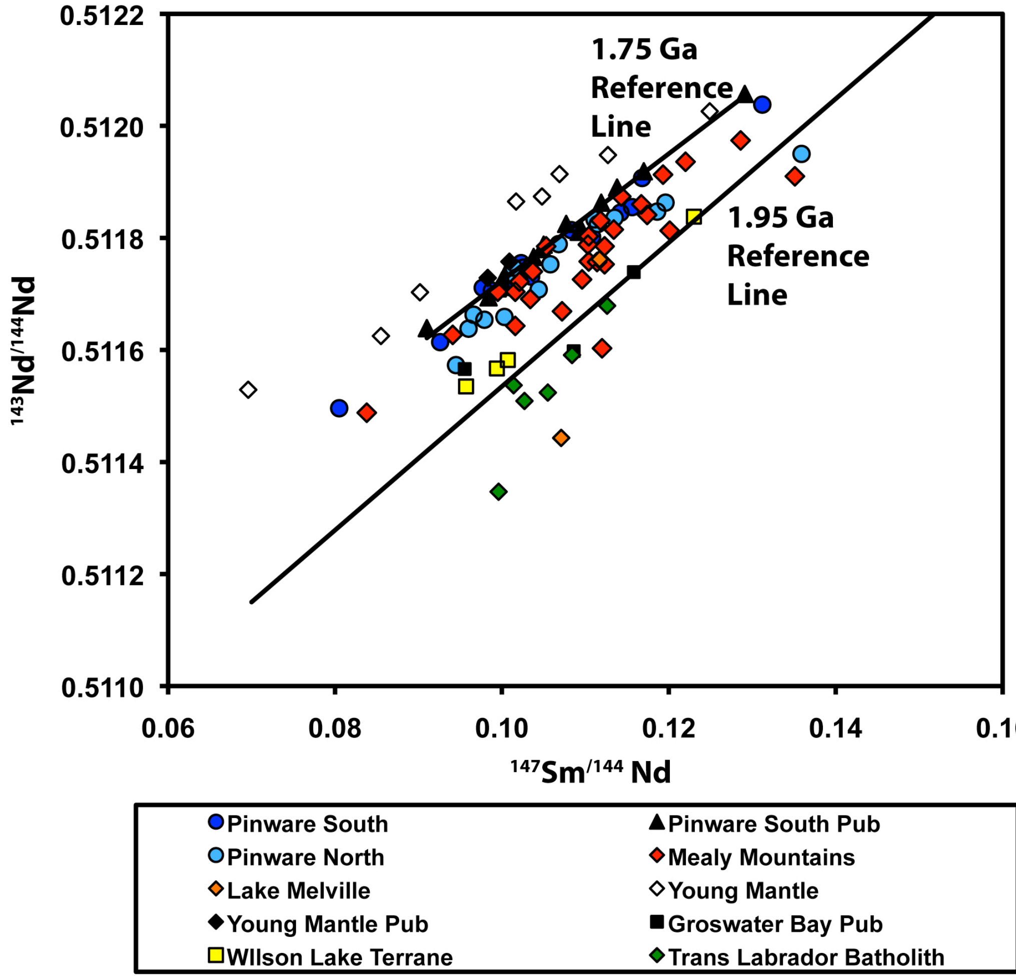


Figure 4.5. Sm–Nd isochron diagram for data from SW Labrador. Reference lines of 1.75 Ga (Labradoria), 1.95 Ga (Makkovikia) are shown for comparison. Pinware South data from Moumblow et al. (2014), and previously published data for Pinware South from Dickin (2000). Groswater Bay Pub by Prevec et al. (1990) and Schärer (1991).

4.6. Nd Isotope Profile

To test whether the isotopic mixing relationship proposed above has a spatial dimension, T_{DM} ages are plotted in Figure 4.6 against the distance north of the 52^{o} N latitude (km), which is used as a reference point to create a N-S transect. This is effective because it separates the juvenile Labradorian crust of the Pinware South segment (Moumblow et al., 2014) from the samples further north, which display evidence of mixing with older crust. Samples from the Makkovik Province (Moumblow et al., 2014), are also shown for comparison.

Separate linear regressions were determined for the Makkovik and Pinware South suites. There is a suggestion in the intervening samples of increasing T_{DM} age northward. However, the data are significantly scattered, with a few notable outliers that yield T_{DM} ages older than juvenile Makkovik samples (above 2.15 Ga). Some of this scatter of T_{DM} ages could be caused by outliers having low or high Sm/Nd ratios (Figure 4.5). When crustal isotopic growth curves for these outliers are projected onto the depleted mantle growth curve to calculate T_{DM} ages, increased scatter is produced in the data. To eliminate this effect, the data are plotted in Figure 4.7 in the form of epsilon Nd values calculated at 1.65 Ga.

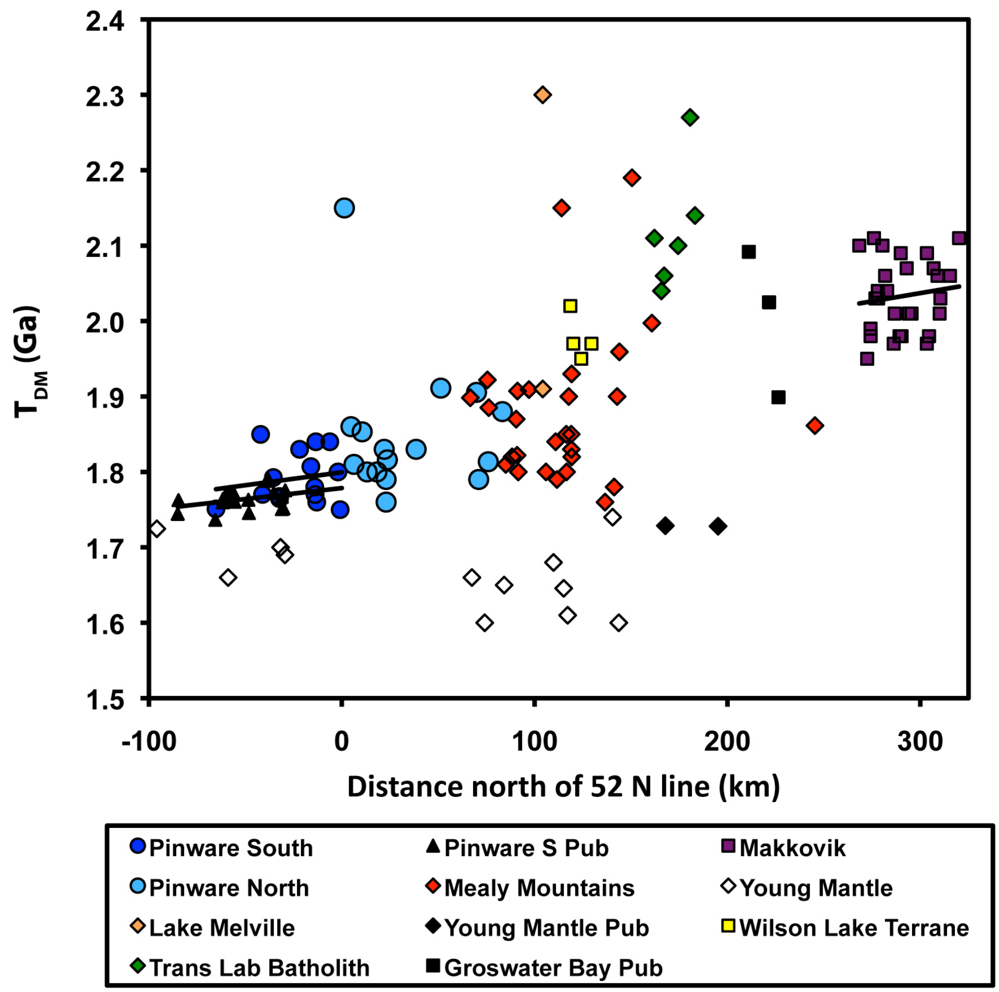


Figure 4.6. Plot of T_{DM} model age *versus* distance north of 52° N latitude (km). Previously published data for Pinware South Pub by Dickin (2000), Groswater Bay Pub by Prevec et al. (1990) and Schärer (1991). Data from Pinware South and the Makkovik Province from Moumblow et al. (2014).

When comparing epsilon Nd values in this way, it is important to calculate all data at the same value of T, even though the intrusive ages of the samples vary. Using a single time T minimizes any bias arising from the variable age of the samples. A value of 1.65 Ga was chosen because this is the age of the major plutonic event that affected most samples. However, using different values of T has little effect on the distribution, except to move all points up and down, because of the relatively limited variation of Sm/Nd ratio in most samples. This causes Nd isotope compositions of most samples to evolve along sub-parallel evolution paths.

It can be seen in Figure 4.7 that plotting epsilon values at 1.65 Ga has decreased the scatter of data points for the Pinware South segment, as expected for a juvenile Labradorian terrane. The scatter of the Makkovik data has increased, since this is a 1.9 Ga arc, but this is an acceptable trade-off to achieve greater certainty about the significance of old T_{DM} ages in younger Labradorian and Pinwarian plutons.

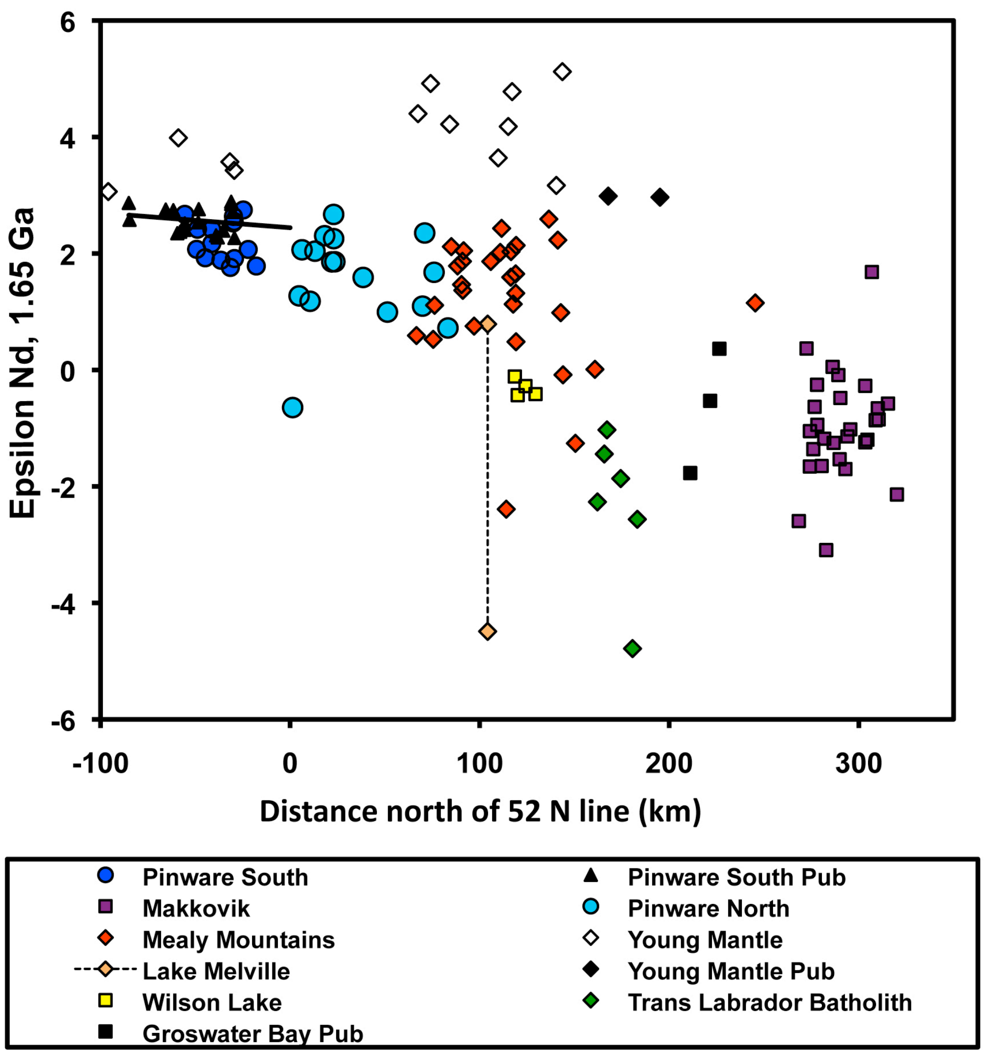


Figure 4.7. Plot of epsilon Nd calculated at 1.65 Ga *versus* distance north of the 52 N line (in km). Samples taken from the same location within the Lake Melville terrane are marked by the dashed line. Symbols as in Figure 4.6.

The Pinware North and Mealy Mountains suites generally fall between the distributions of the juvenile Makkovik and juvenile Labradorian suites in Figure 4.7, which is consistent with the model proposed above that they represent Makkovik crust reworked by the Labradorian orogeny. Two samples from Lake Melville (taken from the same location), show an extreme contrast in their Nd isotope signature (marked by the dashed line), indicating that one may be an enclave with uncertain provenance. However, the outlier with a low epsilon value in the Pinware North region is a Pinwarian pluton, and its Nd signature must therefore be taken seriously as an indicator of the presence of old crust in its source. This sample was replicated to eliminate the possibility of analytical error. Hence this sample provides strong evidence for a southerly extension of Makkovik crust to near the Quebec-Labrador border in this region.

A suite of samples with epsilon (1.65 Ga) values above +3 in Fig. 4.7 is attributed to young mantle-derived components introduced into older crustal terranes. It will be remembered that this value (+3) is the Nd signature of the Mealy Mountains anorthosites (Ashwal et al., 1986), which is attributed largely to juvenile Labradorian magmas emplaced into older (Makkovik) crust. In figure 4.6, most of these samples have T_{DM} ages below 1.7 Ga that marks them as not being crustal melts. Since the purpose of Nd isotope mapping is to use granitoid plutons to sample the formation age of the regional crustal protolith, these 'young mantle' samples are excluded as not being representative of regional crustal formation ages.

4.7. Petrochemical Data

In order to acquire additional information about the possible tectonomagmatic context of the analysed suites, major- and trace-element data were evaluated on the majority of samples using analytical data obtained by the Geological Survey of Newfoundland and Labrador, as presented in Table C.2 (Appendix C). To obtain an overall picture of the geochemistry of these suites, they are first plotted on variation diagrams against SiO_2 in Figure 4.8.

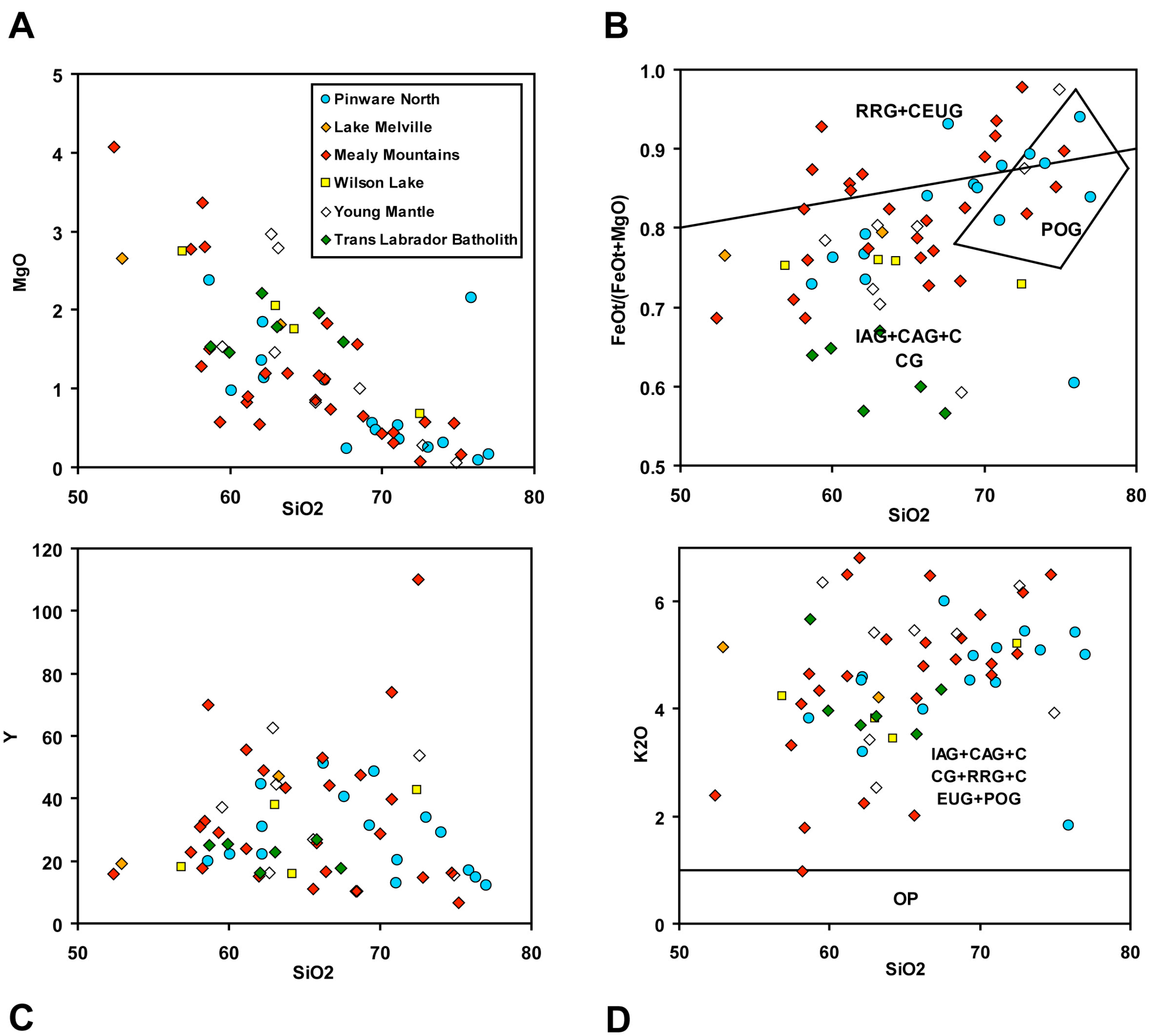


Figure 4.8. Plots of SiO_2 vs. MgO, FeOt/(FeOt+MgO), Y, and K_2O are presented for rocks of the study area. Data are expressed in weight percent. . IAG= Island arc granite, CAG=continental arc granitoids, CCG= continental collision granitoids, RRG= rift-related granitoids, CEUG= continental epeirogenic uplift granitoids, POG= postorogenic granitoids.

These diagrams show that all of the analysed suites have similar ranges of SiO_2 as well as other elements, although there are small differences in relative elemental abundances. Orthogneiss samples from the Wilson Lake terrane plot within the range of data for the other suites. This is important because these plutons are emplaced into largely metasedimentary terranes. The geochemical data suggest that these Wilson Lake samples are not derived from a sedimentary protolith, but are normal I-type granites (Chappell and White, 1974). Hence these samples suggest that these crustal terranes contain a significant component of magmatic arc material, in comparison with possible accretionary prism components in the sedimentary gneiss.

Discriminant plots that enhance relative elemental differences between suites are more useful as a guide to possible tectonomagmatic affinity. The first of these is the Q (Quartz)–P (Plagioclase) diagram of Debon and LeFort (1983), which aims to classify granitoid rocks using their whole-rock chemistry in a way that mimics the Streckeisen diagram (Figure 4.9).

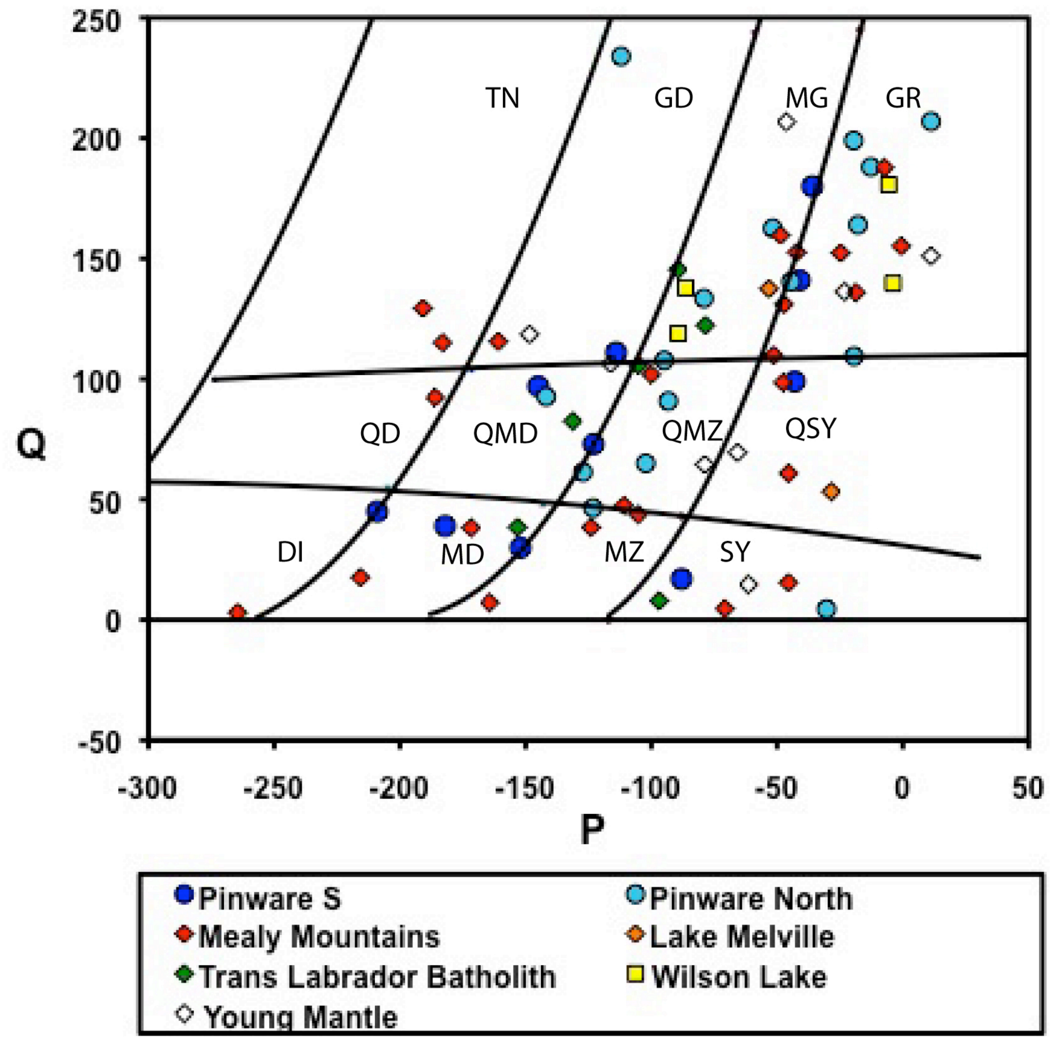


Figure 4.9. Samples from this study, along with previously published samples from Dickin (2000) are plotted on the petrochemical grid of Debon and Le Fort (1983), a chemical classification of granitoid rocks that adopts Streckeisen's (1976) modal fields. Q is an index of quartz content, and P is an index of plagioclase vs. K-feldspar content. 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. See text for discussion.

A notable feature revealed by this diagram is the small number of samples in the tonalite field, despite our previously stated preference to sample such material (*e.g.* Dickin et al., 2014). Tonalites are typically abundant in primitive oceanic arcs, and are a significant rock type in the Quebecia arc terrane, as reported by Dickin (2000). Their absence in southeast Labrador points to the importance in this region of magma differentiation in thick crustal sections such as ensialic arcs.

Another major element discriminant diagram useful for assessing granitoid suites is the de la Roche R1-R2 multi-cationic diagram (Batchelor and Bowden, 1985), after de la Roche et al. (1980). This plot (Figure 4.10) uses vectors to reflect the differences in magma composition during fractional crystallization and equilibrium, and hence to interpret the tectonic environment.

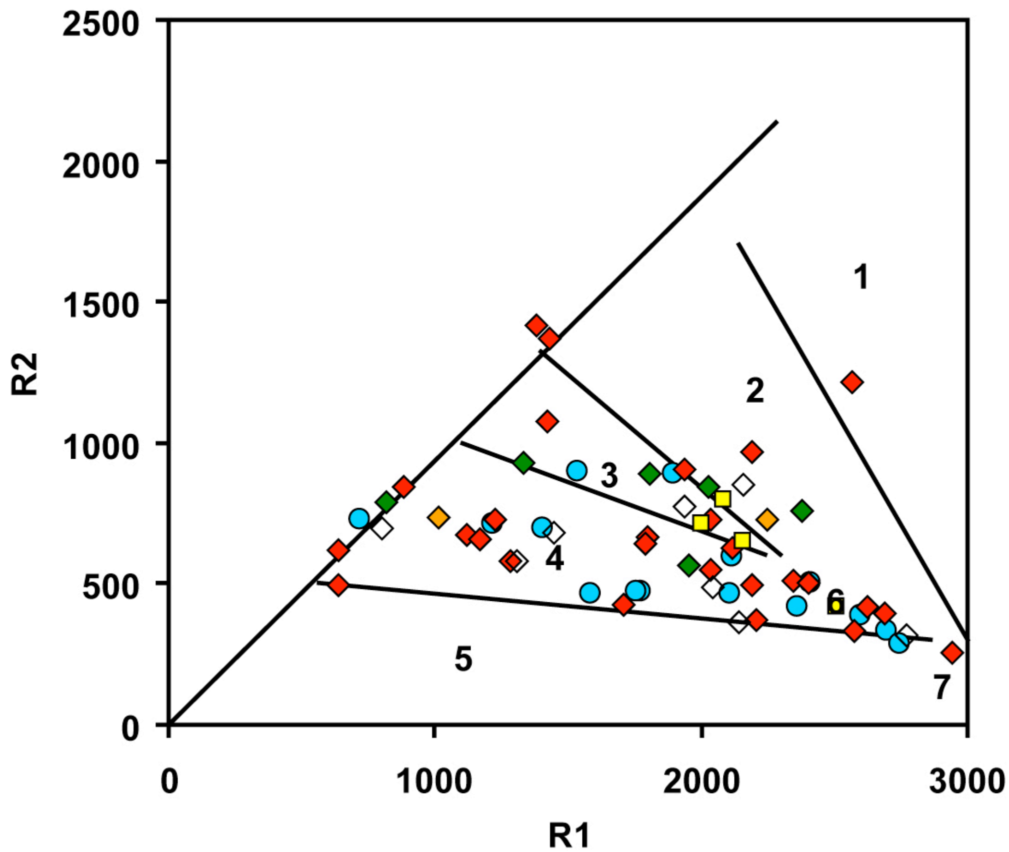
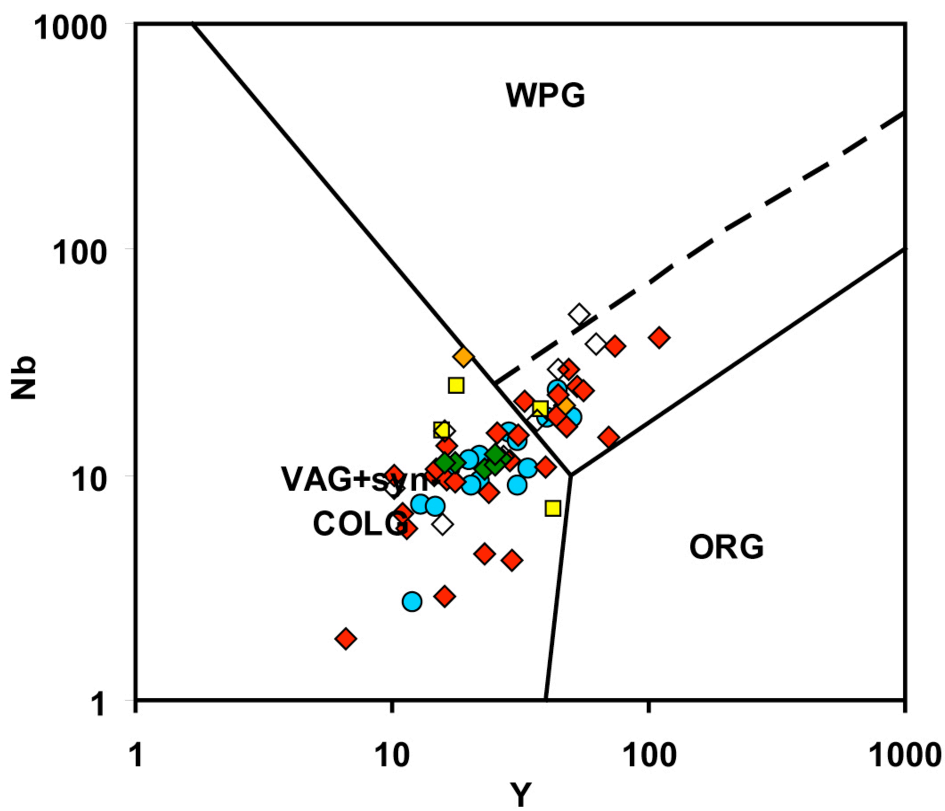


Figure 4.10. R1-R2 plot of the study area. Symbols are the same as Fig. 4.7. Data fields for tectonic setting: 1 = mantle fractionates, 2 = pre-plate collision, 3 = post-collision uplift, 4 = late-orogenic, 5 = anorogenic, 6 = syn-collision, 7 = post-orogenic.

It is notable that in this diagram (Fig. 4.10) most samples from the Mealy Mountains and Pinware North crustal segments plot in field 4 (late orogenic), which is also indicative of crust that has been strongly reworked in an ensialic arc. In contrast, most samples from the Wilson Lake and Trans Labrador Batholith plot in fields 2-3, indicative of more pristine accreted (Makkovik) arc crust, largely unaffected by Labradorian magmatism.

Finally, the sample set is also plotted on discrimination diagrams utilizing Y versus Nb, and Y+Nb versus Rb by Pearce et al. (1984) (Figure 4.11). In these figures, the samples from the TLB lie completely within the volcanic-arc field, while Wilson Lake samples are nearly so. This is in contrast with the Pinware North and the Mealy Mountains suite, which straddle the volcanic-arc and within plate fields. As argued above, this is consistent with strong magmatic reworking in the Labradorian ensialic arc and collision zone.

a)



b)

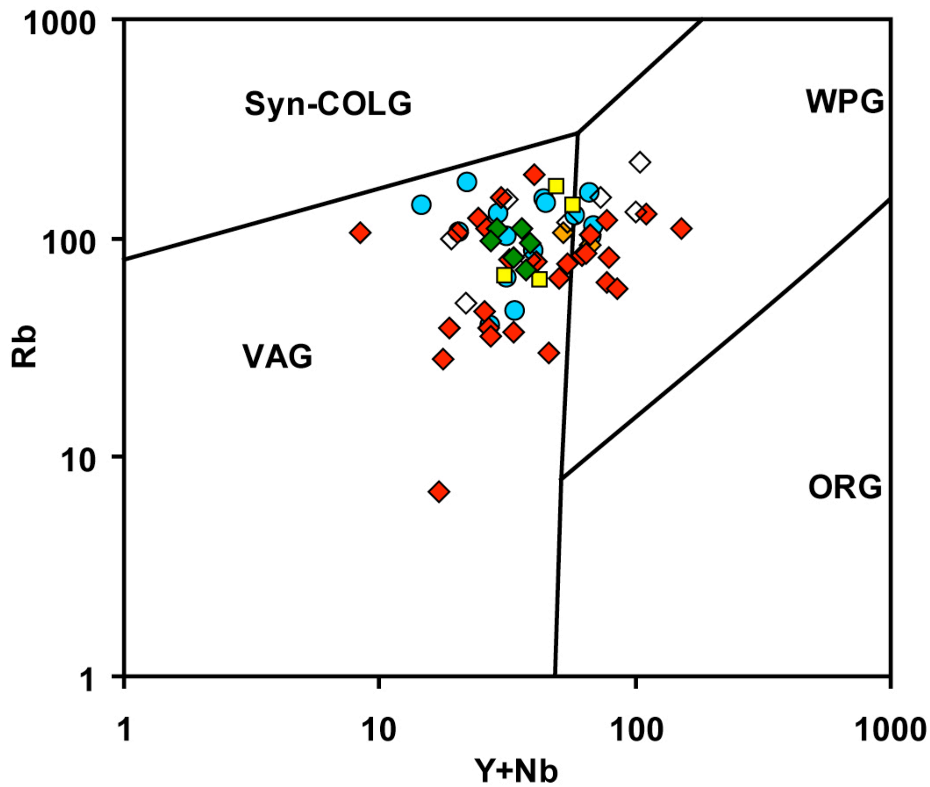


Figure 4.11. (a) Y–Nb diagram; and **(b)** Y + Nb–Rb diagram after Pearce et al. (1984).VAG, volcanic arc granites; syn-COLG, syn-collisional granites; WPG, within plate granites; ORG, orogenic granites.

4.8. Discussion

New Nd evidence presented here, coupled with published U-Pb ages (Gower et al., 2008a) suggest that most of the Mealy Mountains terrane consists of Makkovik crust reworked during the Labradorian orogeny. New evidence from MMIS megacrysts (Bybee et al., 2014) extends this model by suggesting that the Makkovik continental margin was involved in a long-lived Andean-type ensialic arc between the Makkovik and Labradorian accretionary events (Figure 4.12a).

The wide extent of the 1.9 Ga Makkovik margin (grey shading in Figure 4.12a, with a width of at least 300 km) explains why post-Makkovik pre-Labradorian ensialic arc magmatism was largely confined to the present extent of the Grenville Province, and did not extend significantly north of the TLB into Archean crust (white in Figure 4.12a). Late pre-Labradorian plutons located on either side of the TLB, based on U-Pb dates around 1720 Ma, indicate that the Makkovik continental margin was intact and undergoing northwest-directed subduction during this period.

The Labradorian orogeny was intense but of short duration, with a rapid decrease in magmatic activity after 1630 Ma. This is best explained by the accretion of an oceanic arc with an opposed sense of subduction, as shown in Figure 4.12a. The intense magmatism of the Labradorian orogeny is consistent with this model, as the crust on both margins would have already been heated by subduction-related magmatism prior to the collision. Moumblow et al. (2014) identified a WNW-ESE boundary between Makkovik crust and juvenile Labradorian crust within the northern part of the Pinware terrane near Red Bay. However, the trajectory of the boundary further west was not established.

In order to determine the extension of the boundary to the west, we expanded the sample set for the current study to include the region south of the Pinware-Mealy Mountains terrane boundary (Figure 4.4). In agreement with the observations of Moumblow et al. (2014), an area of reworked Makkovik crust (TDM ages > 1.85 Ga) is present within the regional fold of the western Pinware terrane, indicating that Makkovik basement continues westwards in the northern part of the Pinware terrane.

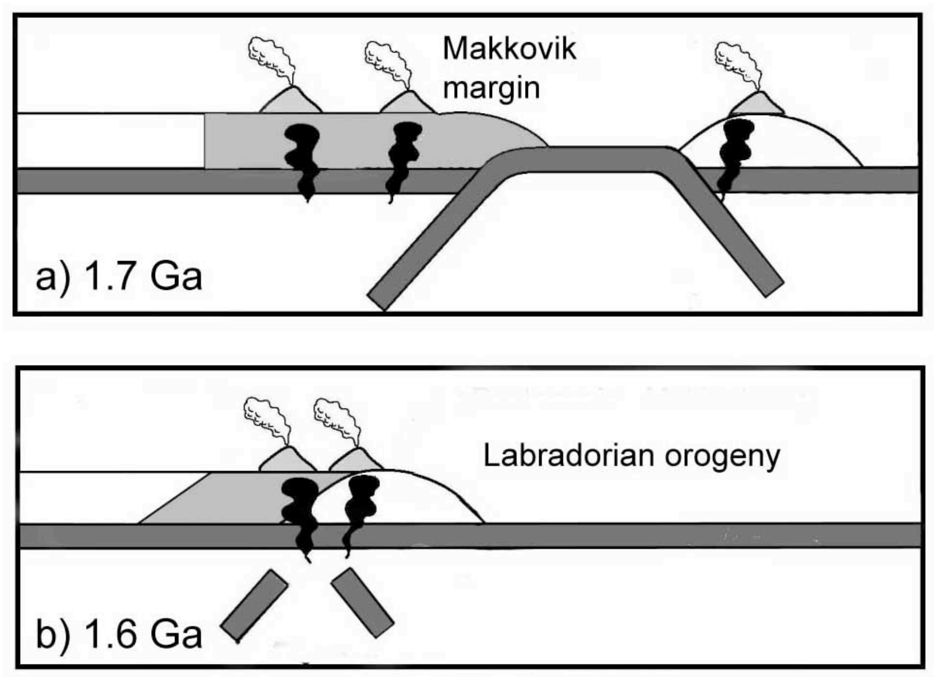


Figure 4.12. Moumblow et al., (2014) simplified model for the Labradorian orogeny. Grey shading = Makkovikian curst previously accreted to the Laurentian margin. Off-shore arc = Labradoria.

This feature is notably demonstrated by sample #5 (Fig. 4.4) with a T_{DM} age of 2.15 Ga in a Pinwarian pluton (Fig. 4.6). The slightly high T_{DM} age relative to normal Makkovik crust can be explained by the relatively high Sm/Nd ratio of this sample (Fig. 4.5). However, the epsilon Nd (1.65 Ga) of -0.7 confirms its Makkovik affinity (Fig. 4.7). The lack of samples from further west in the vicinity of the provincial boundary (Fig. 4.4) prevents tracing the crustal boundary further west, but detailed mapping and sampling for U-Pb ages within the regional Grenvillian fold may allow more detailed geological reconstruction in this area (Figure 4.13).

A group of metasedimentary units shown within the southern part of Fig. 4.13 (yellow shading) were provisionally mapped by Gower (2010a) as correlatives of the Pitts Harbour group, a belt of psammitic gneisses located within the southeastern Pinware terrane (Gower, 2010b). Moumblow et al. (2014) observed that the Pitts Harbour Group is almost entirely confined to the north of the isotopic age boundary in SE Labrador, interpreted by them as a collisional suture between old Makkovik crust and a juvenile Labradorian arc. If the two groups of rock are correlative, then the crustal boundary may be located on the south side of these psammitic metasedimentary units, as shown in Figure 4.13.

These metasediments may have been deposited in a foreland basin that was created during the collision of the accreted arc. On the other hand, another group of metasedimentary units is located to the north of Figure 4.13, within the Mealy Mountains terrane. These rocks are pelitic in nature, probably representative of sedimentation on the pre-Labradorian Makkovik margin.

In an attempt to understand possible details of the collision, a cross section of the only modern example of this type of collision is shown in Fig. 4.14 after Moore et al. (1981). In this case, the collision between the two arcs has only just begun, but it is clear that the convergence between them is uplifting the two intervening fore-arc wedges. This material will almost certainly be removed by erosion as the collision proceeds, until the plutonic basement of the two arcs meets directly. This model may offer an analogue for what happened in the deep crust of the Labradorian orogeny, so that the collisional suture runs between granitoid orthogneisses having very similar petrological character.

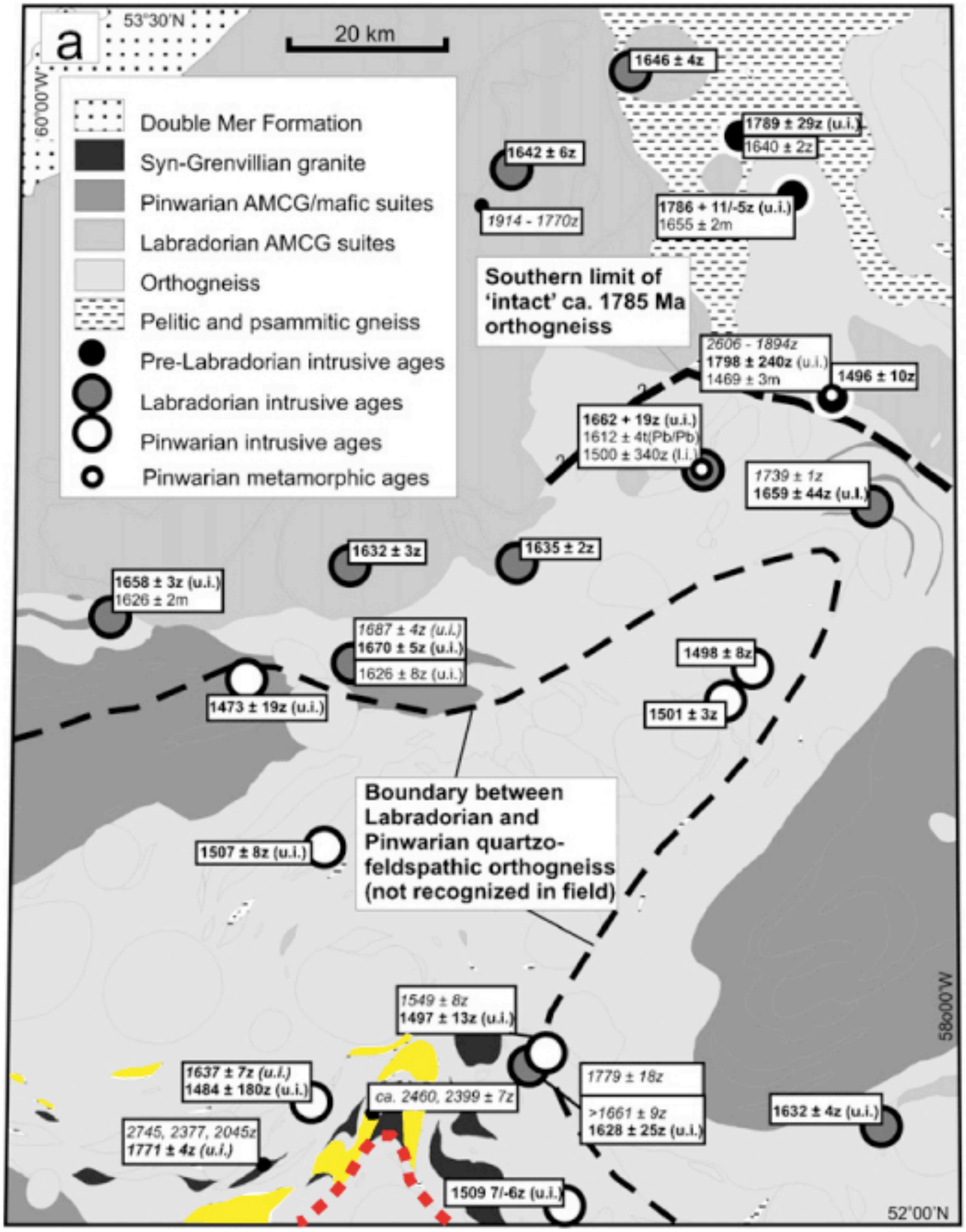


Figure 4.13. Location of the proposed crustal boundary (dashed red line) between juvenile Labradorian to the south and reworked Makkovik crust to the north. Metasedimentary units highlighted in yellow. Modified after Gower et al. 2008a). (Italicized = inherited age, bold = emplacement age, and normal font = metamorphic age).

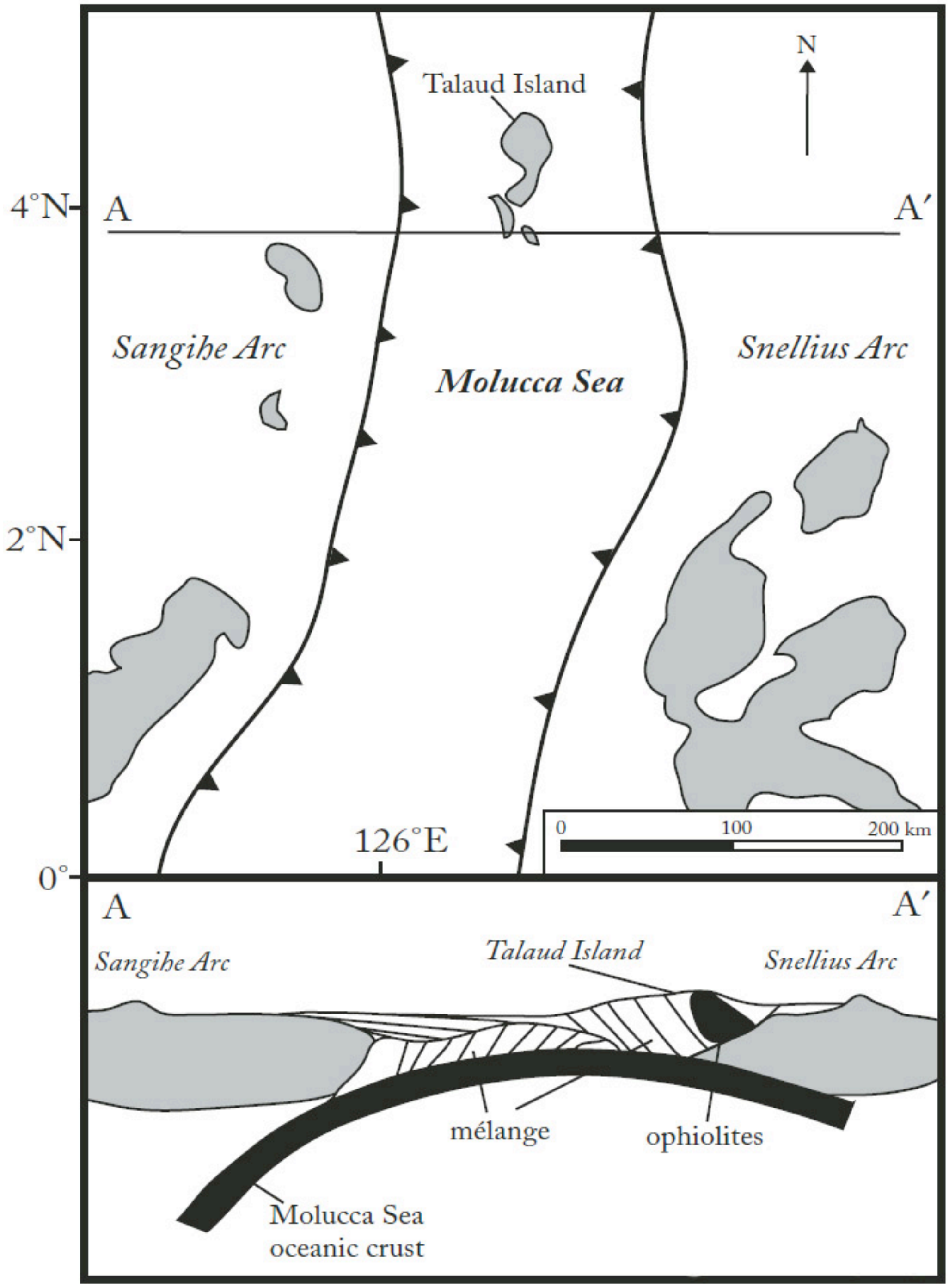


Fig. 4.14. Map and cross-section of the Talaud orogeny after Moore et al. (1981) and Schwartz et al. (2010).

As the collision between the two arc terranes proceeds, one of the colliding terranes must eventually over-ride the other, causing the over-ridden terrane to be depressed. At this point, a foreland basin is likely to develop, which will receive a mixture of the collisional arc detritus and preexisting recycled sedimentary material. This may be the origin of the Pitts Harbour Group of southern Labrador.

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Chapter 5: Conclusions

5.1 Conclusions

The overall objective of this thesis was to improve the understanding of crustal development in the eastern Grenville and Makkovik Provinces by integrating results of previous Nd studies with those of a new suite of samples. In order to provide a comprehensive analysis of the geological history of southern Labrador, the thesis was separated into three regions, and is summarized below.

5.2 Chapter Summary

In Chapter 2, Nd isotope data was presented for the eastern Makkovik Province that suggested that accreted juvenile Makkovik crust was generated in the Cape Harrison domain during a single crust-forming event around 2.0 Ga. An accretion event around 1.9 Ga is proposed to have triggered subduction-zone reversal and the development of an ensialic arc on the composite margin. After the subduction flip, a temporary release of compressive stress around 1.87 Ga led to the development of a retro-arc foreland basin on the downloaded Archean continental edge, forming the Aillik Group. Unlike previous models, a second arc is not envisaged. Instead, a compressive regime around 1.82 Ga is attributed to continued ensialic arc plutonism on the existing margin. The tectonic model for the Paleoproterozoic Makkovikian orogeny proposed here is similar to that for the Ketilidian orogeny.

In Chapter 3, Nd isotope data was presented within the eastern Grenville Province, just south of the Makkovik Province. A WNW-ESE boundary was proposed between Makkovik crust and juvenile Labradorian crust within the northern part of the

Pinware terrane near Red Bay. This boundary separates the Pinware terrane into Pinware North (containing some T_{DM} ages with Makkovik provenance, and some younger ages resulting from magma mixing in the Labradorian) and Pinware South (T_{DM} ages below 1.85 Ga). The resulting model suggests a collision between two opposite-dipping subduction zones to explain the intensity of magmatism associated with the orogeny. This model also attempts to explain the distribution of Paleoproterozoic metasedimentary terranes along the Makkovik-Ketilidian margin of Laurentia as either passive-margin sequences developed on the earlier Makkovik margin, or fore-arc wedges associated with subduction zones. Since these metasedimentary units (identified as the Pitts Harbour Group) are abundant on the northern side of the proposed crustal boundary but rare to the south, they may represent sedimentation in the post-collisional foreland basin.

Lastly, in Chapter 4, the region to the west that was considered in Chapter 3, was examined within the eastern Grenville Province. Nd isotope data was presented to determine if the WNW-ESE boundary seen in Chapter 3 extends to the west. As suspected, an area of reworked Makkovik crust (TDM ages > 1.85 Ga) is present within the regional fold of the western Pinware terrane, indicating that Makkovik basement continues westwards in the northern part of the Pinware terrane. Metasedimentary units that correlate with the Pitts Harbour group (north of the isotopic age boundary in SE Labrador), suggest that the crustal boundary may be located on the southern side of these psammitic metasedimentary units.

5.3 Tectonic Model for the eastern Grenville and Makkovik Provinces

By integrating all of the Nd data acquired, a tectonic model is proposed for the eastern Grenville and Makkovik Provinces. (Figure 5.1). At approximately 2.0 Ga, an arc was formed offshore of the Archean craton (5.1a) The accretion of the arc initiated a subduction flip, which resulted in continental arc magmatism (Fig 5.1b), with plutons dated at 1.9-1.87 Ga. Between 1.85-1.81 Ga (Fig. 5.1c), the supracrustal units of the Aillik Group were deposited in a retro-arc foreland basin, due to loading of the margin from the accreted arc. Subsequently, the continent-ward subduction (due to the subduction flip) caused an intensification of ensialic arc magmatism, causing uplift of the crust. This additional uplift along the continental margin led to gravitational collapse and back thrusting of the foreland basin. Magmatism continued after the Makkovik orogeny in an ensialic arc between 1.8-1.7 Ga (Fig 5.1d).

At 1.7-1.65 Ga a juvenile oceanic arc was formed offshore of the Makkovik continent. Eventually continent ward subduction brought this arc into proximity with the Laurentian margin. The resulting collision (as a result of two opposite-dipping subduction zones) (Fig 5.1e), initiated intense magmatism as both margins were heated before the collision by subduction-related magmatism. By 1.65-1.60 Ga, a foreland basin developed as one of the two colliding terranes rode over the other. This foreland basin contained a mixture of collisional arc detritus and preexisting recycled sediments, now seen as the Pitts Harbour Group (Fig 5.1f). Once the collision was complete, the Laurentian craton became a passive margin.

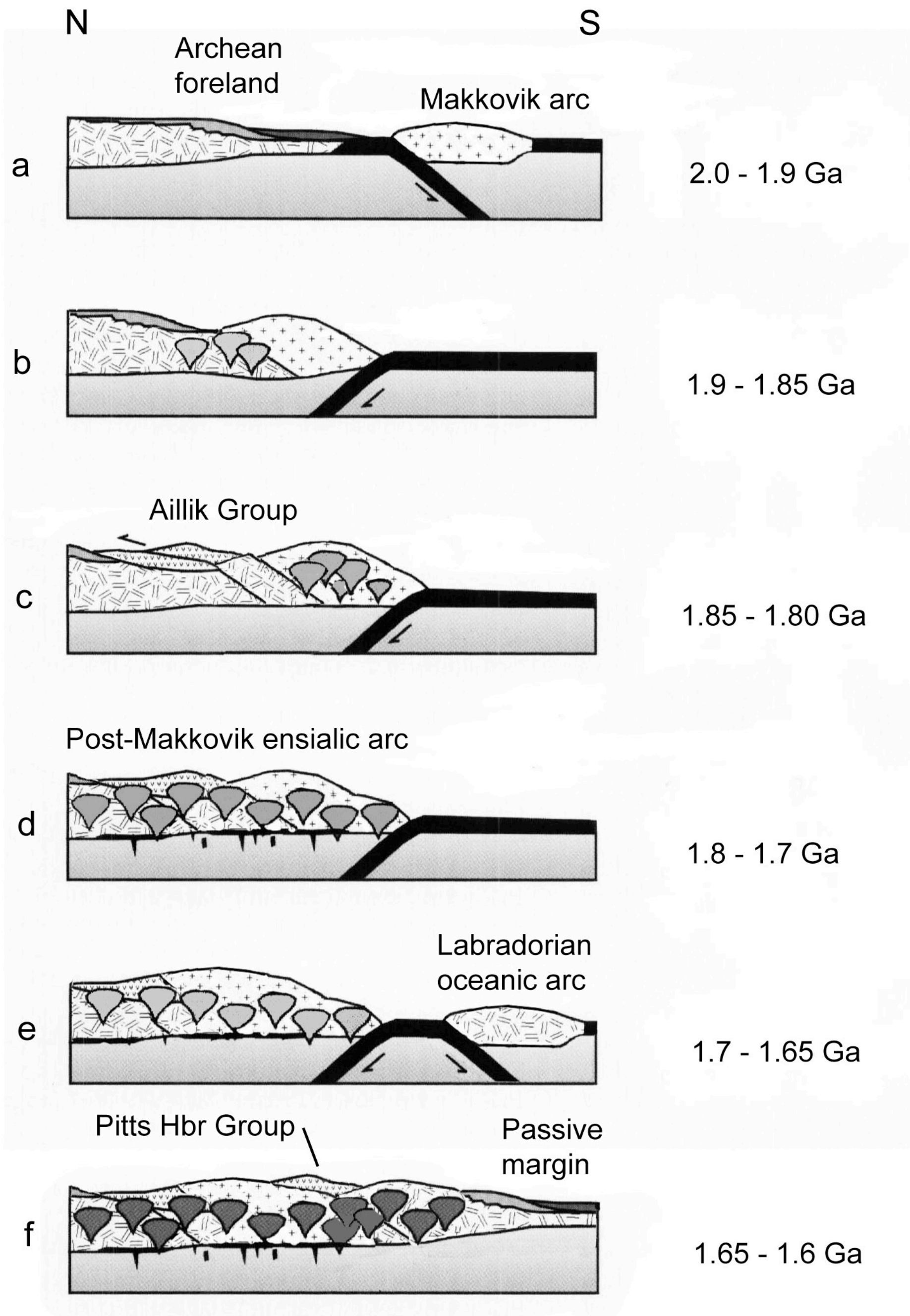

Figure 5.1. Proposed tectonic model for the eastern Grenville and Makkovik Provinces.

Appendix A

Table A.1. Nd-Isotope data for the Makkovik Province

Map #	Sample #	UTM N NAD 27	UTM E NAD 27	Rock type	Suture km	Nd ppm	Sm ppm	147 Sm / 144 Nd	143 Nd / 144 Nd	E Nd (T)	TDM Ga	Q	P
	Cape	**Harrison**	**East**										
1	CG79-130	6081113	426109	MG	53	25.6	4.40	0.1046	0.511536	2.0	2.11	146	-86
2	CG79-493	6069921	427649	MG	60	23.9	4.60	0.1158	0.511722	2.8	2.06	112	-76
3	CG79-201	6067912	431835	QM	66	63.3	17.20	0.1639	0.512371	3.2	2.07	107	-97
4	CG79-500	6076392	433075	GD	62	17.7	3.58	0.1226	0.511810	2.7	2.06	158	-118
5	CG79-198A	6071034	438274	QMD	69	28.8	5.10	0.1064	0.511631	3.4	2.01	93	-125
6	CG79-196	6071431	441216	QMD	72	35.0	6.40	0.1099	0.511659	3.0	2.03	69	-130
7	CG79-180	6064428	445896	GD	80	42.2	8.10	0.1162	0.511707	2.4	2.09	ND	ND
8	CG79-545	6055014	448758	ND	87	28.8	4.69	0.0984	0.511520	3.3	2.01	ND	ND
9	CG79-251A	6064380	455290	ND	86	33.4	5.75	0.1042	0.511627	3.9	1.97	ND	ND
10	CG79-269	6056502	467782	GR	102	37.3	6.20	0.1006	0.511550	3.3	2.01	ND	ND
11	CG79-273	6053945	470242	MD	105	32.3	5.40	0.1017	0.511527	2.6	2.07	38	-190
12	CG79-578R	6065530	477730	MG	105	25.3	3.53	0.0843	0.511365	3.8	1.98	133	-63
13	CG79-316	6042764	489499	QM	128	16.3	3.00	0.1110	0.511654	2.7	2.06	152	-81
14	CG79-308	6047705	491525	MG	127	21.0	3.30	0.0954	0.511482	3.3	2.01	152	-67
	East	**older**											
15	CG79-484	6064971	425293	MG	89	101.1	16.40	0.0981	0.511345	-0.1	2.25	153	-49
16	CG79-571	6051234	460997	ND	62	33.8	6.19	0.1106	0.511538	0.5	2.23		
	Cape	**Harrison**	**South**										
17	CG79-407	6051275	387947	ND	40	33.7	5.72	0.1025	0.511598	3.7	1.98	ND	ND
18	CG79-530	6050201	420027	QM	66	49.1	8.90	0.1100	0.511699	3.8	1.98	53	-114
19	CG79-535	6050870	433781	MG	76	19.0	3.50	0.1110	0.511636	2.3	2.09	129	-76
20	CG79-554	6047206	439090	ND	83	30.4	5.65	0.1123	0.511731	3.8	1.97	ND	ND
21	CG79-629	6037702	441757	ND	90	24.4	4.59	0.1136	0.511710	3.1	2.03	ND	ND
22	CG79-579	6043785	453307	ND	91	38.6	4.40	0.0688	0.511101	2.6	2.04	ND	ND
23	CG79-753	6033425	464589	ND	112	29.7	5.52	0.1122	0.511746	4.2	1.95	ND	ND
24	CG79-611	6038950	472163	MD	118	30.0	6.10	0.1233	0.511834	3.0	2.04	40	-145
25	CG79-383	6035226	475994	MG	123	31.0	4.60	0.0900	0.511434	3.7	1.98	103	-81
26	CG79-613	6041387	478200	MD	121	35.1	6.40	0.1109	0.511629	2.2	2.10	42	-157
27	CG79-320	6039116	487472	MG	131	10.8	1.90	0.1069	0.511622	3.1	2.03	ND	ND
28	CG79-349	6029356	494992	MG	141	19.5	3.10	0.0948	0.511407	2.0	2.10	138	-78
29	CG79-339	6036974	497682	TN	140	37.3	7.30	0.1188	0.511729	2.1	2.11	107	-184
30	CG79-344	6035178	505163	QMD	147	32.0	4.20	0.0799	0.511294	3.6	1.99	102	-110
	South	**older**											
31	CG79-564	6047171	445460	GR	107	33.2	6.98	0.1268	0.511787	1.2	2.21	132	-43
32	CG79-591	6042204	463732	MG	99	19.3	3.83	0.1193	0.511647	0.4	2.26	139	-50
	East	**Archean**											
33	CG79-594	6040510	447257	GR	93	12.7	2.86	0.1313	0.511621	-3.2	2.64	154	-20

The reproducibility of $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ is estimated at 0.1% and 0.002% (1 sigma). Average within-run precision on the samples was ± 0.000014 (2 sigma). Value of T = 1.85 Ga. Q= [Si/3-(K+Na+2Ca/30)], P=[K-(Na+Ca)], expressed as grams-atoms x10^3 of each element in 100g of rock. 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; ND, not determined.

Table A.2. Major and trace element data.

Sample #	CG79-130	CG79-180	CG79-196	CG79-198A	CG79-201	CG79-251A	CG79-269	CG79-273	CG79-308	CG79-316	CG79-320	CG79-339	CG79-344
SiO2	67.5	58.5	72.2	70.9	71.4	65.70	58.1	65.9	70	66.9	72.2	66.6	68.2
TiO2	0.64	0.7	0.24	0.3	0.18	0.69	0.74	0.42	0.27	0.43	0.23	0.53	0.49
Al2O3	16.3	19.5	15.2	15	15.3	16.45	16.4	17.5	15.9	16.7	15.05	15.8	14.95
FeO	2.48	3.38	1.21	1.55	0.87	3.27	4.18	1.91	1.54	2.09	1.21	2.93	2.65
Fe2O3	0.66	2.36	0.65	0.68	0.8	1.01	3.09	1.59	0.4	1.15	0.45	0.61	1.1
Fe2O3t	3.42	6.12	1.99	2.4	1.77	4.64	7.74	3.71	2.11	3.47	1.79	3.87	4.04
MnO	0.05	0.1	0.04	0.05	0.03	0.07	0.15	0.06	0.03	0.06	0.04	0.09	0.07
MgO	1.05	2.18	0.43	0.7	0.48	1.98	4.71	0.94	0.57	0.91	0.44	1.16	1.71
CaO	2.69	5.19	1.76	2.13	2.09	3.85	6.53	3.28	2.13	2.46	1.87	2.41	2.76
Na2O	4.23	4.99	4.1	4.01	4.05	4.14	3.18	4.29	4.11	4.28	4.4	4.07	3.99
K2O	4.8	3	4.53	4.07	4.28	3.70	1.65	4.08	4.36	4.76	3.63	4.61	2.81
P2O5	0.01	0.07	0.01	0.07	0.05	0.02	0.33	0.13	0.05	0.15	0.05	0.13	0.09
LOI	0.46	0.95	1.03	0.93	0.9	0.95	1.25	0.76	0.75	1.04	0.85	0.74	0.93
Total	101	101	101	100	100	101.83	100	101	100.1	101	100.4	99.68	99.75
Cr	88	4	-1	22	15	29	237	-1	8	-1	-1	17	131
Ni	5	4	-1	2	-1	7.0	27	2	2	2	2	3	11
Rb	122	89	116	112	95	120.0	57	94	152	101	97	149	152
Ba	1253	1494	1169	985	1533	974	436	1884	1393	1131	1039	1057	437
Th	4	2	9	4	-1	9.0	-1	6	5	8	10	18	15
U	4.1	4.1	2.1	1.8	0.9	3.6	1.5	0.7	2.2	1.5	2.2	4.7	4
Ce	97	83	62	49	34	80	81	86	59	92	34	62	64
Cu	10	13	27	5	2	10	2	3	2	7	2	13	12
F	811	1080	336	480	252	1084	1520	424	760	716	460	1160	2920
Ga	27	19	16	11	14	25	32	21	17	29	20	28	22
La	43	43	31	22	17	41	36	47	28	48	11	23	27
Li	23.7	30.4	16.9	15.2	8	31.0	21.5	26.6	26.9	20.3	25.6	29.6	88.8
Mo	4	5	5	4	4	4.0	5	3	5	5	3	7	4
Nb	15	7	9	12	5	10.0	6	6	10	8	10	11	13
Pb	14	18	20	15	18	14.0	5	13	19	14	15	46	12
Sr	472	917	440	495	588	650.0	858	813	584	603	529	535	211
V	39	86	12	25	18	60	130	33	23	37	12	42	43
Y	18	15	10	11	7	16	23	5	8	10	10	16	22
Zn	56	82	46	56	34	73	104	69	52	68	41	297	92
Zr	329	315	181	150	133	189	156	255	210	222	143	213	188

A.2. Continued

Sample #	CG79-349	CG79-383	CG79-403	CG79-407	CG79-493	CG79-500	CG79-530	CG79-535	CG79-545	CG79-554	CG79-578	CG79-611
SiO2	60.8	70.3	70.7	73.80	71.1	61.2	65.3	67.8	77.10	56.40	69.6	58.7
TiO2	1.09	0.34	0.43	0.30	0.37	0.67	0.67	0.49	0.08	0.75	0.21	1
Al2O3	16.4	16.2	15.05	13.65	15.7	16.1	16.7	15.95	12.35	20.00	15.35	18.6
FeO	4.09	1.03	1.15	1.28	1.61	4.11	2.7	1.78	1.61	3.58	1.06	4.02
Fe2O3	1.28	0.32	1.56	0.70	0.86	1.4	1.24	1.03	0.63	2.84	0.59	1.86
Fe2O3t	5.83	1.46	2.84	2.12	2.65	5.97	4.24	3.01	2.42	6.82	1.77	6.33
MnO	0.13	0.02	0.05	0.04	0.06	0.11	0.06	0.07	0.02	0.14	0.04	0.1
MgO	1.52	0.47	0.79	0.32	0.65	2.99	1.58	0.9	0.05	2.08	0.51	1.85
CaO	3.41	2.33	2.37	0.86	2.19	4.55	3.62	2.55	0.34	4.84	1.49	4.56
Na2O	4.6	4.16	4.07	4.23	4.6	4.11	4.44	4.5	3.37	5.32	4.22	4.59
K2O	4.48	4.69	4.12	4.83	4.03	3.94	3.91	4.42	5.75	3.33	4.68	3.95
P2O5	0.4	0.04	0.07	0.05	0.02	0.02	0.01	0.01	0.00	0.38	0.05	0.34
LOI	0.46	0.49	0.68	0.67	0.84	1.06	0.81	1.23	0.85	0.97	0.94	1.16
Total	98.7	100	101.04	100.73	102	100	101	100.72	102.15	100.63	98.74	101
Cr	202	-1	41	2	19	89	32	14	3	-1	-1	17
Ni	3	3	4	2.0	2	20	3	-1	5.0	2.0	3	5
Rb	97	108	147	156.0	125	136	144	72	122.0	53.0	130	105
Ba	1548	1488	803	767	589	688	878	1020	1033	1721	1175	1644
Th	8	17	24	23.0	16	12	11	5	12.0	4.0	10	3
U	3.8	5	5.6	8.1	3.2	4	6	1.9	5.8	1.7	2.4	3.6
Ce	105	46	65	94	109	86	71	88	73	68	66	56
Cu	12	7	2	20	5	21	10	6	17	10	9	15
F	1160	296	920	368	560	1480	1640	652	880	860	372	1220
Ga	23	13	10	23	26	21	25	22	19	19	20	24
La	52	20	37	40	58	41	36	31	39	31	37	17
Li	18.1	16.3	26.2	9.3	35.8	30.2	34.1	17.7	30.7	12.1	20.4	18.6
Mo	6	4	4	5.0	4	6	6	4	6.0	3.0	4	7
Nb	18	12	10	27.0	11	13	10	22	13.0	4.0	12	14
Pb	14	20	26	28.0	18	14	14	16	17.0	7.0	21	10
Sr	425	501	449	192.0	251	480	577	309	615.0	816.0	464	711
V	63	11	25	11	23	97	55	13	43	88	15	64
Y	30	11	11	25	23	23	16	83	13	17	9	17
Zn	105	30	68	45	79	88	81	93	63	94	42	96
Zr	474	221	164	278	201	211	186	223	158	312	174	352

Sample #	CG79-613	CG79-629	CG79-753	CG79-564	CG79-484	CG79-591	CG79-594	CG79-571
SiO2	57	57.40	57.50	70.7	72.2	69.4	73.1	61.40
TiO2	0.83	0.91	0.69	0.36	0.31	0.41	0.2	0.55
Al2O3	18.15	18.20	16.95	14.75	12.6	15.3	13.9	17.40
FeO	4.11	4.35	4.38	1.6	1.31	1.59	0.96	2.75
Fe2O3	2.66	2.17	1.98	0.93	1.12	0.68	0.4	1.57
Fe2O3t	7.23	7.00	6.85	2.71	2.58	2.45	1.47	4.63
MnO	0.11	0.11	0.13	0.05	0.07	0.02	0.04	0.09
MgO	3	2.40	3.08	0.61	0.26	0.77	0.26	1.63
CaO	5.05	4.95	5.69	2.02	0.98	2.07	0.89	3.12
Na2O	4.36	4.18	4.18	3.78	4.16	3.64	3.8	4.72
K2O	3.49	4.28	2.94	5.4	4.82	4.89	5.57	4.12
P2O5	0.3	0.23	0.30	0.09	0.03	0.14	0.1	0.14
LOI	0.66	0.95	0.77	0.71	1.04	0.7	0.46	0.95
Total	99.72	100.13	98.59	101	98.9	99.61	99.7	98.44
Cr	39	107	115	63	33	29	79	75
Ni	10	6.0	12.0	2	-1	2	3	5.0
Rb	85	134.0	72.0	151	191	132	211	114.0
Ba	1378	2062	1123	719	250	1030	386	1275
Th	-1	9.0	-1.0	10	16	10	32	9.0
U	1.7	3.4	3.3	3.3	5.9	5.3	6.2	3.1
Ce	78	62	67	87	282	68	48	77
Cu	23	28	37	2	2	4	2	15
F	1220	1040	660	740	3400	480	336	1640
Ga	29	16	24	26	29	17	22	25
La	33	27	35	24	141	19	13	37
Li	19.5	20.6	17.6	29.2	1.9	20	8	31.0
Mo	7	7.0	5.0	3	5	4	5	6.0
Nb	8	8.0	4.0	16	42	13	17	9.0
Pb	7	10.0	8.0	22	10	18	22	10.0
Sr	819	676.0	754.0	308	45	450	112	683.0
V	120	107	133	23	6	33	9	66
Y	16	15	18	27	66	13	14	20
Zn	97	77	81	63	153	40	32	65
Zr	279	313	83	196	1004	226	199	197

Values of -1 are below detection limits

Appendix B

Table B.1. Nd-Isotope data for the Grenville Province in southeast Labrador

Map #	Sample #	UTM N NAD 27	UTM E NAD 27	Rock type	Suture km	Nd ppm	Sm ppm	147 Sm / 144 Nd	143 Nd / 144 Nd	E Nd (T)	TDM Ga	Q	P
	Cartwright												
1*	CG84-469	6027550	460400	GD	246	32.7	11.40	0.1191	0.511837	0.7	1.94	42	-47
2*	CG84-468A	6004486	471486	QMZ	228	27.1	6.46	0.1393	0.512011	-0.2	2.11	88	-84
3*	CG84-468B	6004486	471486	QMZ	228	31.4	5.74	0.1102	0.511638	-1.3	2.06	ND	ND
4*	CG84-172A	5970254	504835	DI	211	28.9	6.78	0.1114	0.511683	-0.7	2.02	54	-218
5*	CG84-172B	5970254	504835	GD	211	28.8	3.94	0.0828	0.511425	0.3	1.88	127	-112
6*	VO81-021A	5954071	512092	GD	198	10.1	1.72	0.1057	0.511674	0.3	1.93	ND	ND
7*	VO81-021B	5954071	512092	GD	198	27.3	4.71	0.1067	0.511702	0.7	1.90	ND	ND
8*	VO81-539A	5953596	512301	GD	198	27.1	4.65	0.1058	0.511696	0.7	1.90	ND	ND
9*	VO81-539C	5953596	512301	GD	198	24.3	2.86	0.0726	0.511323	0.5	1.85	ND	ND
10*	VO81-540A	5953219	512370	GD	197	31.3	3.98	0.0783	0.511381	0.4	1.87	ND	ND
11^	CG81-429	5944530	527372	QSY	196	148.7	16.44	0.0668	0.511272	0.7	1.83	101	8
12	RH 1	5946177	497367	GD	183	29.0	5.12	0.1066	0.511677	0.2	1.94	119	-143
13	RH 2	5941903	497721	GD	179	21.3	3.93	0.1117	0.511767	0.9	1.90	154	-102
14	RH 3c	5929707	495224	MG	165	7.2	1.11	0.0938	0.511568	0.8	1.87	199	-56
15	RH 4a	5921581	486903	MG	153	31.9	5.64	0.1070	0.511708	0.7	1.90	212	-49
16	RH 6	5914021	476200	GR	140	47.9	10.04	0.1267	0.511968	1.7	1.88	173	-20
17	RH 20	5841835	548043	MG	104	44.9	6.75	0.0909	0.511604	2.1	1.78	202	-41
18	RH 17	5865394	484563	GR	96	22.5	3.92	0.1055	0.511782	2.5	1.77	202	7
19	RH 18	5860481	490277	GR	94	78.0	13.98	0.1083	0.511758	1.4	1.85	234	10
20*	CG86-285	5854970	500706	MG	93	28.6	5.74	0.1212	0.511854	0.6	1.95	143	-86
21	RH 24a	5834517	535874	GD	90	71.1	9.65	0.0821	0.511493	1.8	1.79	199	-87
22	RH 22	5838376	542680	GR	98	13.2	2.31	0.1057	0.511734	1.5	1.85	191	-27
23*	SN86-023	5820793	535405	QSY	76	25.8	3.93	0.0920	0.511515	0.1	1.91	103	8
24	RH 27b	5818135	552256	DI	82	38.6	7.65	0.1199	0.511888	1.5	1.87	59	-224
25	RH 28	5816050	554680	GR	81	133.0	25.02	0.1137	0.511838	1.9	1.83	154	-28
26*	CG86-053B	5823217	558203	GR	90	35.9	5.79	0.0974	0.511666	1.9	1.80	123	-86
27*	CG86-746A	5820114	568254	GR	92	33.2	6.30	0.1147	0.511827	1.4	1.86	123	-79
28*	MN86-224	5824056	572379	GR	98	41.1	7.59	0.1117	0.511750	0.6	1.93	144	-51
29	RM12-005	5812962	585960	MD	94	29.4	5.49	0.1128	0.511779	0.9	1.91	1	-191
30*	CG86-344	5822227	501582	GD	61	43.3	7.89	0.1101	0.511669	-0.7	2.02	169	-60
31*	CG87-312	5812851	542156	QMZ	72	83.7	13.63	0.0985	0.511667	1.7	1.81	145	-6
32	RH 30e	5809378	558609	GD	77	21.9	4.47	0.1233	0.511842	-0.1	2.03	128	-144
33	RH 37b	5807935	561726	GD	77	27.8	4.51	0.0980	0.511544	-0.6	1.97	169	-96
34	RH 35 A	5807843	561802	QMD	77	36.0	6.66	0.1120	0.511744	0.4	1.94	105	-153
35	RH36d	5807876	561801	GD	77	28.1	5.04	0.1085	0.511654	-0.7	2.01	114	-139
	Pinware	**North**											
36	RM12-004	5791096	499004	QSY	29	48.4	10.43	0.1301	0.511914	-0.1	2.06	61	-45
37	RM12-003	5791757	507346	QMZ	33	95.6	13.26	0.0838	0.511560	2.7	1.74	102	-100
38	RM12-002	5789178	516139	GD	35	57.3	10.91	0.1152	0.511816	1.1	1.90	119	-148
39	RM12-006	5783051	510142	QMD	26	29.3	4.67	0.0962	0.511629	1.5	1.83	106	-116
40	RM12-007	5777966	506446	MG	19	55.6	10.88	0.1184	0.511879	1.7	1.86	131	-49
41	RM12-009	5764080	510002	MG	7	47.5	8.94	0.1139	0.511791	0.9	1.91	110	-89
42*	CG87-265	5795707	531172	GR	49	45.3	8.03	0.1072	0.511808	2.6	1.76	103	-82
43*	CG87-262	5790718	530631	QMZ	44	50.7	11.41	0.1360	0.512008	0.5	2.03	60	-106
44	RM12-001	5787751	547279	ND	49	65.0	11.46	0.1066	0.511737	1.4	1.86	ND	ND
45	RH 31b	5807059	561649	MG	76	38.6	6.69	0.1047	0.511718	1.4	1.85	149	-45

	Pinware	North	Cont'd										
46	RH38c	5804868	560681	GR	73	52.1	9.58	0.1111	0.511800	1.7	1.84	151	-28
47	RH 84	5783600	568530	QMD	56	44.9	8.29	0.1117	0.511779	1.1	1.89	90	-161
48	RH 39a	5795474	573731	GD	70	14.8	2.63	0.1074	0.511789	2.2	1.79	116	-130
49	RH 80c	5794660	579360	QSY	72	53.6	10.11	0.1139	0.511861	2.3	1.80	43	-73
50	RH 40c	5786814	577987	GD	64	6.2	1.16	0.1126	0.511827	1.9	1.83	119	-158
51*	CG87-461	5789085	583666	GD	69	32.5	6.29	0.1169	0.511781	0.1	1.98	107	-127
52*	CG87-469	5791116	585145	QSY	72	85.5	13.86	0.0980	0.511674	2.0	1.80	42	-47
53*	CG87-445A	5785005	593253	QMZ	70	42.2	9.13	0.1309	0.512029	2.0	1.86	92	-103
54*	CG87-445B	5785005	593253	GR	70	41.6	6.77	0.0985	0.511710	2.6	1.76	165	-8
55*	CG87-426A	5771571	582445	MG	51	70.4	12.63	0.1084	0.511836	2.9	1.74	70	-61
56	VN93-662E	5756653	575599	GR	32	65.4	11.58	0.1071	0.511802	2.5	1.77	116	-36
57	RH 43	5759233	547764	MG	21	40.5	7.51	0.1119	0.511777	1.0	1.86	129	-58
58	RH 88b	5758300	547370	QMZ	20	44.7	7.76	0.1048	0.511780	2.6	1.76	47	-119
59	RH 44	5757261	545688	DI	18	35.1	6.04	0.1041	0.511729	1.7	1.82	36	-220
60	RH 91c	5754100	543400	QSY	14	50.9	8.90	0.1056	0.511744	1.7	1.83	72	-1
61	RH 45	5751528	540546	MG	10	37.2	6.58	0.1069	0.511724	1.1	1.88	112	-61
62	RH 93	5749700	540720	GR	8	43.9	6.90	0.0951	0.511623	1.6	1.82	126	-45
63	RH 46a	5742768	542414	QMD	2	30.2	5.79	0.1157	0.511843	1.5	1.86	57	-183
64	RH 96	5741900	542840	GR	1	38.1	6.64	0.1052	0.511688	0.7	1.90	135	-43
65	RH 101e	5738000	554740	MZ	3	39.7	7.41	0.1127	0.511833	2.0	1.82	36	-90
	Pinware	**South**											
66	RH 104c	5736300	549670	MD	-1	44.4	7.18	0.0977	0.511711	2.7	1.75	39	-182
67	RH 98c	5738900	542260	SY	-2	24.2	4.04	0.1010	0.511712	2.1	1.80	17	-88
68	CG93-698	5743163	525211	GR	-6	64.9	12.42	0.1156	0.511855	1.8	1.84	141	-41
69	RH 108	5729500	538050	QMD	-13	43.2	7.93	0.1108	0.511802	1.8	1.84	73	-123
70	RH 111	5731100	535800	MD	-13	46.8	7.92	0.1023	0.511755	2.6	1.76	30	-152
71	112aTTR	5730900	534450	GD	-14	38.1	6.84	0.1083	0.511814	2.5	1.77	111	-114
72	RH113a	5731500	532920	QMD	-14	53.8	10.40	0.1168	0.511907	2.5	1.78	97	-145
73^	CG93-027A	5731649	528574	QSY	-16	44.4	7.59	0.1035	0.511731	1.9	1.81	99	-43
74	RH 110 a	5724500	531210	DI	-22	45.1	8.52	0.1142	0.511845	1.9	1.83	45	-209
75^	RC97-006	5719704	519941	ND	-32	21.8	2.91	0.0805	0.511496	2.2	1.76	ND	ND
76^	RC97-007	5719704	519941	ND	-32	43.5	7.11	0.0988	0.511706	2.4	1.77	ND	ND
77^	RC97-005	5716234	520526	ND	-36	59.8	9.17	0.0926	0.511614	1.9	1.79	ND	ND
78^	CG93-268A	5712120	517524	MG	-41	24.0	4.07	0.1026	0.511747	2.4	1.77	180	-36
79^	RC97-004	5711680	516400	ND	-42	67.4	14.61	0.1312	0.512038	2.1	1.85	ND	ND
80^	RC97-001	5705449	482579	ND	-65	40.7	6.81	0.1013	0.511746	2.7	1.75	ND	ND
	Young	**Mantle**											
81	RH 19	5856516	494720	ND	92	57.5	8.75	0.0920	0.511679	3.3	1.71	ND	ND
82*	CG86-005	5820709	547789	DI	83	32.3	6.59	0.1233	0.512019	3.4	1.72	192	-100
83	RH32c	5803486	560713	MZ	72	96.8	17.13	0.1070	0.511865	3.8	1.68	21	-117
84	RH 33b	5797301	567479	GR	69	80.2	12.69	0.0957	0.511758	4.1	1.65	138	-36
85*	CG87-304A	5799732	543880	GR	60	65.4	11.33	0.1047	0.511874	4.5	1.63	ND	ND
86*	CG87-105A	5794495	538258	GD	52	2.0	0.27	0.0808	0.511574	3.6	1.68	ND	ND
87	RM11-008	5771341	506165	ND	12	75.0	11.80	0.0951	0.511755	4.2	1.65	ND	ND
88	CG86-697B	5771042	495929	ND	7	52.3	5.72	0.0661	0.511562	6.5	1.53	ND	ND
89	CG03-029B	5742869	542216	ND	2	22.8	4.05	0.1074	0.512042	7.2	1.43	ND	ND

Denotes samples analyzed by Daly. ^Denotes samples analyzed by Creaser. V081 sample suite analyses by Brooks, C. 1983: Fourth Report on the Geochronology of Labrador. Newfoundland Department of Mines and Energy, Mineral Development Division. Unpublished Report, 41 pages. The reproducibility of $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ is estimated at 0.1% and 0.002% (1 sigma). Average within-run precision on the samples was ± 0.000014 (2 sigma). Value of T= 1.65 Ga. Q= [Si/3-(K+Na+2Ca/30)], P=[K-(Na+Ca)], expressed as grams-atoms x10^3 of each element in 100g of rock. 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

Table B.2. Major and trace element data

Sample #	CG87-469	CG84-468A	CG84-172A	CG84-172B	CG81-429B	RH 001
SiO2	63.05	63.30	58.90	67.60	69.70	62.90
TiO2	0.83	0.51	0.62	0.31	0.29	0.618
Al2O3	17.07	16.19	18.83	15.86	15.50	16.12
FeO	2.30	3.55	3.52	1.44	1.40	3.19
Fe2O3	1.69	1.48	1.90	1.12	0.91	1.75
FeOt	2.80	5.43	5.81	2.72	2.47	5.30
MnO	0.12	0.14	0.15	0.06	0.08	0.103
MgO	1.00	1.71	2.34	0.74	0.20	2.28
CaO	2.38	2.95	5.74	2.87	0.85	4.73
Na2O	4.40	4.02	4.98	4.27	3.92	3.60
K2O	6.48	4.63	2.10	3.61	7.05	2.72
P2O5	0.27	0.36	0.32	0.12	0.03	0.215
LOI	0.62	0.73	0.64	0.58	0.67	0.46
Total	100.11	99.57	100.04	98.58	100.60	99.03
Cr	-1.00	2.00	66.00	-1.00	3.00	22
Ni	-1.00	-1.00	10.00	-1.00	-1.00	12
Rb	64.00	117.00	56.00	65.00	137.00	53
Ba	1955.00	996.00	1132.00	2726.00	530.00	1194
Th	-1.00	-1.00	-1.00	2.00	13.00	2.0
U	1.00	0.90	1.20	1.00	1.60	0.3
Ce	189.00	48.00	58.00	85.00	481.00	69.8
Cu	11.00	48.00	9.00	33.00	4.00	38
Ga	22.00	22.00	26.00	18.00	22.00	20
La	98.00	20.00	28.00	49.00	292.00	34.2
Li	11.00	16.60	12.90	12.80	5.00	10.1
Mo	3.00	3.00	4.00	3.00	3.00	-2
Nb	14.00	15.00	9.00	5.00	26.00	9
Pb	19.00	9.00	8.00	15.00	22.00	20
Sr	308.00	482.00	1387.00	1086.00	68.00	684
V	26.00	40.00	94.00	35.00	-1.00	105
Y	40.00	27.00	17.00	9.00	29.00	19
Zn	95.00	94.00	77.00	41.00	46.00	64
Zr	794.00	286.00	142.00	168.00	488.00	175

Sample #	RH 002	RH 003	RH 004	RH 006	RH 020	RH 017
SiO2	66.93	73.72	74.40	70.30	66.46	74.11
TiO2	0.461	0.156	0.184	0.562	0.651	0.136
Al2O3	15.06	14.17	13.70	13.74	15.86	13.62
FeO	2.10	1.00	0.73	2.06	1.45	0.92
Fe2O3	1.57	0.57	0.58	1.73	4.03	0.29
FeOt	3.90	1.68	1.39	4.02	5.64	1.31
MnO	0.082	0.031	0.022	0.074	0.107	0.063
MgO	1.41	0.36	0.33	0.70	1.60	0.21
CaO	3.45	2.06	2.13	1.52	1.55	1.18
Na2O	3.36	3.17	2.91	2.99	2.51	2.60
K2O	3.21	3.92	3.88	4.86	3.19	5.26
P2O5	0.162	0.044	0.044	0.151	0.103	0.099
LOI	0.64	0.54	0.58	0.53	0.38	0.47
Total	98.66	99.86	99.56	99.44	98.05	99.06
Cr	7	3	2	3	51	2
Ni	6	2	-1	5	19	-1
Rb	47	38	50	160	69	103
Ba	1288	2711	2062	801	1191	972
Th	0.6	0.9	4.9	15.1	16.8	5.1
U	0.2	0.2	0.6	3.4	1.8	0.5
Ce	46.8	19.5	49.9	109.6	130.7	53.7
Cu	4	4	2	11	5	3
Ga	19	13	14	23	25	17
La	24.9	11.0	25.0	50.0	64.8	27.9
Li	9.2	4.5	5.6	16.3	12.7	4.3
Mo	3	-2	-2	-2	-2	-2
Nb	9	5	9	20	14	6
Pb	22	23	22	35	23	28
Sr	569	633	589	112	418	154
V	72	27	16	28	61	9
Y	13	3	16	62	23	39
Zn	50	26	26	59	60	19
Zr	167	109	115	422	304	101

Sample #	RH 018	CG86-285	RH 024	RH 022	SN86-023	RH 027
SiO2	75.88	65.00	72.03	74.34	68.60	56.53
TiO2	0.263	0.49	0.583	0.345	0.38	0.716
Al2O3	11.56	16.39	14.41	13.97	15.75	14.94
FeO	1.41	3.10	1.53	0.75	1.13	4.53
Fe2O3	0.81	1.16	1.15	0.77	0.78	1.81
FeOt	2.38	4.61	2.85	1.60	2.04	6.84
MnO	0.034	0.08	0.076	0.037	0.04	0.144
MgO	0.06	1.34	1.00	0.33	0.46	4.60
CaO	0.76	3.38	2.56	1.31	1.28	10.34
Na2O	2.41	3.15	3.28	3.25	3.60	2.66
K2O	4.76	3.59	3.05	4.75	6.90	2.18
P2O5	0.013	0.16	0.043	0.030	0.09	0.163
LOI	0.21	0.66	0.29	0.16	0.50	1.16
Total	98.32	98.50	100.16	100.12	99.51	100.28
Cr	1	15.00	13	1	2.00	54
Ni	1	3.00	8	3	-1.00	31
Rb	118	98.00	64	98	117.00	59
Ba	666	997.00	601	1389	900.00	493
Th	21.9	-1.00	38.0	3.4	-1.00	10.8
U	1.0	1.00	1.3	1.0	0.30	5.5
Ce	186.6	66.00	219.9	38.1	68.00	90.6
Cu	2	2.00	6	8	4.00	83
Ga	25	24.00	22	13	18.00	25
La	90.4	32.00	111.7	21.8	38.00	42.4
Li	8.9	8.20	6.7	7.6	14.80	17.4
Mo	-2	3.00	-2	-2	2.00	24
Nb	18	11.00	17	11	7.00	21
Pb	31	12.00	33	27	16.00	32
Sr	74	307.00	171	143	262.00	261
V	-5	49.00	27	15	14.00	100
Y	47	27.00	17	12	9.00	43
Zn	62	59.00	41	25	38.00	127
Zr	407	234.00	332	319	326.00	212

Sample #	RH 028	CG86-053B	CG86-746A	MN86-224	RM12-005	CG86-344
SiO2	68.75	64.05	64.65	66.60	58.95	65.75
TiO2	0.574	0.85	0.87	0.69	0.663	0.81
Al2O3	13.89	16.65	15.36	15.65	18.17	15.37
FeO	3.36	2.98	3.07	2.34	3.28	3.86
Fe2O3	1.25	2.30	2.24	2.08	1.96	1.58
FeOt	4.98	5.61	5.65	4.68	5.61	5.87
MnO	0.101	0.15	0.11	0.09	0.101	0.09
MgO	0.34	1.75	1.53	1.61	1.76	1.84
CaO	1.89	3.07	3.43	2.13	4.40	2.99
Na2O	3.09	3.52	3.29	3.30	5.99	2.58
K2O	4.96	3.87	4.17	4.41	3.81	3.62
P2O5	0.121	0.21	0.28	0.15	0.281	0.21
LOI	0.21	0.53	0.43	1.02	0.68	0.80
Total	98.91	99.93	99.43	100.07	100.41	99.50
Cr	-1	17.00	18.00	16.00	10	30.00
Ni	4	12.00	12.00	11.00	247	9.00
Rb	111	83.00	86.00	111.00	112	129.00
Ba	976	1786.00	1825.00	1164.00	867	801.00
Th	10.9	8.00	-1.00	7.00	11.29	-1.00
U	1.1	0.70	0.90	1.30	1.31	1.00
Ce	295.6	96.00	73.00	87.00	71.7	83.00
Cu	13	40.00	34.00	24.00		13.00
Ga	38	11.00	11.00	21.00	16	25.00
La	132.7	48.00	34.00	46.00	35.2	40.00
Li	8.8	7.10	6.60	14.30		16.20
Mo	2	3.00	4.00	2.00	-1	3.00
Nb	57	12.00	11.00	13.00	11.0	15.00
Pb	25	14.00	19.00	21.00	18	12.00
Sr	132	389.00	282.00	291.00	243	241.00
V	9	88.00	83.00	77.00		92.00
Y	107	20.00	25.00	29.00	27	25.00
Zn	122	88.00	88.00	70.00		76.00
Zr	808	405.00	337.00	283.00		342.00

Sample #	CG87-312	RH 030	RH 037	RH 035A	RH 036	RM12-002
SiO2	69.15	62.12	68.24	62.35	62.05	63.13
TiO2	0.69	0.774	0.399	0.546	0.622	0.793
Al2O3	13.57	16.93	15.31	16.58	16.54	14.28
FeO	3.10	4.07	2.43	3.06	3.79	4.34
Fe2O3	1.14	2.20	0.82	1.42	1.41	1.82
FeOt	4.59	6.72	3.52	4.82	5.62	6.64
MnO	0.08	0.105	0.065	0.117	0.101	0.137
MgO	0.66	2.38	1.22	2.27	2.26	2.79
CaO	1.87	4.98	3.27	3.90	4.35	4.05
Na2O	2.94	3.29	3.23	4.31	3.72	4.03
K2O	5.73	2.43	3.13	2.63	2.75	2.53
P2O5	0.22	0.164	0.126	0.199	0.179	0.182
LOI	0.63	0.95	0.61	1.40	0.81	0.73
Total	99.78	100.86	99.13	99.13	99.00	99.30
Cr	9.00	6	9	27	15	2
Ni	-1.00	9	7	12	13	253
Rb	133.00	91	96	82	95	155
Ba	1106.00	664	816	1346	823	817
Th	22.00	5.3	8.8	10.8	9.1	15.82
U	2.70	3.3	1.2	2.2	1.9	4.48
Ce	215.00	56.2	78.1	85.9	73.2	137.5
Cu	8.00	39	10	3	45	
Ga	13.00	23	19	22	22	24
La	112.00	27.7	39.1	42.7	36.6	57.1
Li	20.60	32.2	24.8	22.7	23.9	
Mo	4.00	-2	-2	-2	2	1
Nb	26.00	13	12	13	16	29.2
Pb	24.00	30	28	30	27	19
Sr	160.00	478	412	556	496	150
V	28.00	143	52	86	107	
Y	45.00	22	16	28	20	45
Zn	81.00	79	57	60	74	71.00
Zr	504.00	149	157	243	152	203.00

Sample #	RM12-003	RM12-004	RM12-006	RM12-007	RM12-009	CG87-262
SiO2	65.82	66.64	62.67	62.39	63.05	62.45
TiO2	0.434	0.470	1.016	0.786	0.895	0.55
Al2O3	16.49	16.81	13.47	15.11	16.62	17.79
FeO	1.89	1.28	4.88	2.69	3.17	2.02
Fe2O3	1.62	1.08	2.30	4.14	2.93	1.77
FeOt	3.72	2.50	7.72	7.13	6.45	4.02
MnO	0.077	0.063	0.076	0.183	0.090	0.11
MgO	1.16	0.74	2.96	2.08	2.04	1.17
CaO	2.45	1.98	3.42	2.63	3.43	2.87
Na2O	4.51	4.59	3.97	2.89	3.39	4.77
K2O	4.19	6.48	3.43	4.28	3.82	4.65
P2O5	0.153	0.120	0.170	0.145	0.081	0.23
LOI	0.73	0.42	0.90	0.41	0.38	0.51
Total	99.30	100.80	99.82	98.03	100.25	99.11
Cr	1	10	3	2	7	2.00
Ni	197	527	267	231	236	7.00
Rb	78	105	149	77	140	111.00
Ba	254	893	399	956	1091	2270.00
Th	15.14	14.04	8.98	3.84	8.17	2.00
U	1.45	1.31	0.92	0.39	0.62	0.30
Ce	280.3	115.1	75.7	132.4	118.2	71.00
Cu						13.00
Ga	28	23	17	22	22	23.00
La	137.4	35.6	46.6	50.5	50.6	35.00
Li						10.10
Mo	1	1	-1	-1	1	3.00
Nb	15.3	22.7	15.7	18.7	19.3	11.00
Pb	16	14	20	19	21	5.00
Sr	40	220	104	135	222	677.00
V						51.00
Y	26	44	16	56	38	26.00
Zn	73.00	52	71	96	39	110
Zr	280.00	238	434	347	93	769

Sample #	CG87-265	RH 031	RH 038	RH 084	RH 039	RH 080
SiO2	66.90	71.85	68.62	62.58	67.27	60.51
TiO2	0.40	0.307	0.717	0.682	0.224	1.041
Al2O3	15.60	14.43	14.06	16.76	17.10	17.16
FeO	1.62	1.32	2.00	2.84	1.13	3.84
Fe2O3	1.53	0.53	2.14	2.25	0.54	1.90
FeOt	3.33	1.99	4.36	5.40	1.80	6.17
MnO	0.12	0.092	0.072	0.148	0.052	0.196
MgO	1.05	0.46	0.67	1.79	0.98	1.17
CaO	2.28	1.21	2.12	4.05	2.36	2.92
Na2O	4.38	4.38	3.25	4.85	5.45	4.50
K2O	4.72	4.38	4.46	2.62	3.16	4.54
P2O5	0.18	0.087	0.242	0.209	0.116	0.459
LOI	0.61	0.30	0.33	0.46	0.63	0.32
Total	99.39	99.48	98.91	99.55	99.14	98.99
Cr	8.00	1	2	5	14	1
Ni	3.00	1	4	8	11	6
Rb	125.00	138	118	82	61	71
Ba	1356.00	794	1292	794	2796	2525
Th	4.00	14.9	13.9	14.3	3.2	2.5
U	0.70	2.4	3.7	3.3	1.9	1.0
Ce	84.00	118.2	133.4	114.6	34.6	141.1
Cu	5.00	5	8	6	3	26
Ga	9.00	21	25	26	19	26
La	46.00	60.1	65.3	51.8	17.8	66.8
Li	8.40	12.8	13.4	10.8	17.8	10.5
Mo	4.00	-2	2	3	2	2
Nb	14.00	19	33	29	7	25
Pb	1.00	32	37	20	21	33
Sr	446.00	229	208	430	1456	380
V	54.00	19	28	94	27	34
Y	34.00	39	45	45	10	53
Zn	31	29.00	71.00	41.00	99.00	68.00
Zr	88	89.00	297.00	255.00	503.00	403.00

Sample #	RH 040	CG87-461	CG87-445A	CG87-445B	CG87-426A	VN93-662
SiO2	69.08	68.08	65.45	72.65	64.30	67.56
TiO2	0.174	0.18	0.70	0.32	0.87	0.64
Al2O3	17.54	17.14	16.28	13.60	15.77	14.99
FeO	0.87	1.02	1.50	1.06	2.52	2.19
Fe2O3	0.49	0.29	3.02	0.39	1.68	0.74
FeOt	1.45	1.43	4.69	1.57	4.48	3.18
MnO	0.036	0.02	0.10	0.04	0.15	0.08
MgO	0.48	0.34	0.88	0.61	1.08	0.85
CaO	2.47	2.16	1.88	1.00	2.20	1.56
Na2O	5.81	5.17	4.94	3.36	4.38	3.86
K2O	2.65	3.69	4.22	5.57	5.64	5.46
P2O5	0.063	0.06	0.25	0.05	0.31	0.23
LOI	0.31	0.41	0.86	0.71	0.68	0.43
Total	100.06	98.69	100.08	99.36	99.58	98.84
Cr	5	-1.00	10.00	-1.00	9.00	5.00
Ni	2	2.00	4.00	2.00	4.00	-1.00
Rb	48	63.00	105.00	89.00	119.00	110.00
Ba	1994	2096.00	1390.00	1126.00	2489.00	1708.00
Th	1.3	-1.00	2.00	17.00	4.00	
U	0.5	0.40	1.50	0.90	1.00	1.80
Ce	17.9	24.00	48.00	111.00	122.00	173.00
Cu	12	23.00	17.00	10.00	15.00	13.00
Ga	17	19.00	11.00	14.00	11.00	17.00
La	9.5	13.00	21.00	53.00	64.00	80.00
Li	8.7	12.30	12.90	11.10	11.90	10.90
Mo	-2	3.00	3.00	2.00	4.00	4.00
Nb	3	3.00	18.00	13.00	20.00	18.00
Pb	15	-1.00	23.00	19.00	18.00	29.00
Sr	1162	1077.00	249.00	260.00	255.00	308.00
V	17	14.00	42.00	16.00	29.00	44.00
Y	5	8.00	40.00	18.00	50.00	57.00
Zn	62	74	72	56	53	48
Zr	305	316	140	279	283	282

Sample #	RH 043	RH 088	RH 044	RH 091	RH 045	RH 093
SiO2	67.17	60.47	56.21	65.16	66.85	67.37
TiO2	0.497	0.752	0.764	0.810	0.470	0.455
Al2O3	15.06	17.44	18.98	16.69	16.13	15.64
FeO	1.86	3.05	3.97	1.57	1.59	1.46
Fe2O3	1.39	1.51	2.71	1.23	1.48	1.34
FeOt	3.45	4.89	7.12	2.97	3.24	2.97
MnO	0.102	0.118	0.123	0.089	0.081	0.074
MgO	0.90	1.62	2.06	0.69	0.83	0.78
CaO	2.25	3.85	6.64	1.67	2.25	1.93
Na2O	3.91	4.73	4.90	3.98	4.13	3.92
K2O	4.21	3.76	1.97	5.84	4.56	4.46
P2O5	0.138	0.270	0.532	0.168	0.214	0.190
LOI	0.33	0.36	0.70	0.24	0.35	0.36
Total	98.02	98.27	99.99	98.31	99.11	98.15
Cr	2	6	5	-1	4	3
Ni	3	7	9	2	4	4
Rb	141	71	62	95	102	91
Ba	928	2187	1225	2148	1781	1774
Th	11.4	6.3	5.6	7.4	7.5	8.0
U	3.9	1.8	3.0	1.8	1.4	1.7
Ce	115.9	91.6	74.2	95.9	111.4	113.2
Cu	14	28	73	16	16	7
Ga	22	22	21	19	22	21
La	52.0	45.7	35.4	48.3	55.7	59.4
Li	14.3	21.9	28.4	7.1	11.5	11.4
Mo	-2	-2	-2	-2	2	-2
Nb	22	12	9	13	19	13
Pb	22	29	17	28	24	26
Sr	335	611	978	191	397	335
V	46	80	144	27	42	33
Y	45	26	23	27	26	24
Zn	81	38	37	79	58	69.00
Zr	124	268	272	327	340	421.00

Sample #	RH 046	RH 096	RH 101	RH 104	RH 098	CG93-698
SiO2	57.98	69.42	63.01	57.03	59.80	69.67
TiO2	0.599	0.464	0.291	0.714	0.713	0.79
Al2O3	17.14	15.26	19.48	18.62	20.07	14.19
FeO	4.35	1.07	1.09	4.03	2.27	1.68
Fe2O3	2.48	1.47	0.56	2.06	1.90	1.87
FeOt	7.31	2.66	1.77	6.54	4.42	3.73
MnO	0.168	0.063	0.076	0.125	0.122	0.06
MgO	3.32	0.77	0.74	2.46	1.13	0.84
CaO	6.05	1.78	2.13	4.48	3.48	1.98
Na2O	4.44	3.95	5.55	5.37	4.97	3.54
K2O	2.45	4.31	4.63	2.46	5.01	5.09
P2O5	0.320	0.106	0.045	0.398	0.315	0.30
LOI	0.50	0.46	0.50	0.51	0.42	0.44
Total	100.29	99.24	98.22	98.70	100.45	100.64
Cr	27	4	2	3	-1	7.00
Ni	19	3	2	9	4	-1.00
Rb	50	109	163	61	81	89.00
Ba	1223	1129	676	1474	4098	1701.00
Th	4.2	16.1	28.9	5.3	2.8	
U	0.7	3.3	5.1	1.0	1.2	0.80
Ce	71.1	107.8	112.2	113.3	60.2	170.00
Cu	67	6	8	26	13	5.00
Ga	21	19	23	23	19	26.00
La	33.9	50.4	53.5	54.8	32.3	82.00
Li	13.5	16.2	12.5	15.4	12.5	9.20
Mo	-2	-2	4	-2	-2	4.00
Nb	11	18	35	8	8	17.00
Pb	16	34	43	35	17	36.00
Sr	793	305	181	709	721	425.00
V	163	41	51	114	34	42.00
Y	29	28	51	22	15	29.00
Zn	138	106	73	77	49.00	155
Zr	221	412	218	180	338.00	256

Sample #	RH 108	RH 111	RH 112	RH 113	CG93-027A	RH 110
SiO2	58.32	54.32	65.47	62.67	68.03	58.13
TiO2	0.910	1.136	0.534	0.725	0.57	0.673
Al2O3	17.64	18.83	16.37	15.48	15.93	17.95
FeO	4.05	3.89	2.24	3.09	0.74	3.70
Fe2O3	2.81	3.75	1.89	2.06	1.71	2.36
FeOt	7.31	8.07	4.38	5.49	2.53	6.47
MnO	0.199	0.156	0.140	0.132	0.08	0.175
MgO	2.14	2.50	1.51	2.04	0.58	2.30
CaO	3.77	4.78	2.94	3.94	1.69	4.41
Na2O	4.11	4.36	4.32	4.31	4.21	5.91
K2O	2.94	3.47	3.68	3.05	5.77	2.05
P2O5	0.491	0.624	0.234	0.446	0.12	0.386
LOI	0.52	0.46	0.35	0.41	0.35	0.42
Total	98.34	98.70	99.94	98.70	99.86	98.87
Cr	-1	-1	-1	15	2.00	-1
Ni	7	8	4	15	-1.00	7
Rb	90	66	59	57	137.00	47
Ba	3188	4615	1351	1517	1628.00	830
Th	2.8	1.4	7.4	5.3		1.8
U	1.6	0.4	0.3	0.4	0.40	0.3
Ce	95.2	113.5	99.8	138.8	126.00	89.8
Cu	16	11	10	49	3.00	66
Ga	24	25	20	23	17.00	26
La	45.0	54.9	49.1	61.8	60.00	41.7
Li	22.1	18.0	25.9	12.7	9.50	13.7
Mo	-2	-2	-2	-2	3.00	-2
Nb	9	8	13	18	15.00	20
Pb	18	19	41	41	31.00	27
Sr	574	1091	538	833	281.00	640
V	88	109	70	96	36.00	105
Y	33	28	30	60	30.00	43
Zn	46.00	72.00	100.00	119.00	28.00	65.00
Zr	127.00	122.00	288.00	145.00	90.00	206.00

Sample #	CG86-005	RH 019	RH 032	RH 033	RM12-009
SiO2	65.95	74.54	55.47	68.46	63.05
TiO2	0.92	0.414	1.497	0.425	0.895
Al2O3	12.64	12.65	17.99	14.99	16.62
FeO	4.28	1.48	5.61	1.64	3.17
Fe2O3	1.72	2.15	1.63	1.43	2.93
FeOt	6.48	3.80	7.86	3.25	6.45
MnO	0.20	0.028	0.112	0.047	0.090
MgO	2.88	0.20	2.06	0.66	2.04
CaO	5.15	1.26	4.46	1.99	3.43
Na2O	1.89	2.66	4.54	3.51	3.39
K2O	2.47	4.71	3.70	4.15	3.82
P2O5	0.18	0.054	0.647	0.128	0.081
LOI	0.97	0.13	0.81	0.75	0.38
Total	99.25	100.44	99.14	98.36	100.25
Cr	40.00	3	9	4	7
Ni	19.00	96	67	121	236
Rb	118.00	1334	3173	1281	140
Ba	630.00	18.4	6.7	46.0	1091
Th	5.00	0.8	2.8	1.8	8.17
U	3.30	166.3	222.1	262.4	0.62
Ce	73.00	2	26	13	118.2
Cu	12.00				
Ga	24.00	90.3	95.2	135.5	22
La	34.00	10.6	15.9	15.2	50.6
Li	26.00	-2	3	3	
Mo	3.00	9	39	31	1
Nb	16.00	19	45	34	19.3
Pb	6.00	386	945	333	21
Sr	209.00	6	87	23	222
V	107.00	23	53	37	
Y	34.00	51	147	71	38
Zn					
Zr					

Sample #	CG93-268A	CG81-215A	CG85-280	CG85-492A	CG85-532A	CG85-654A
SiO2	73.99	64.5	63.5	57.55	76.3	66.30
TiO2	0.22	0.46	0.89	0.82	0.13	0.62
Al2O3	13.27	16.85	16.34	18.10	12.25	15.20
FeO	0.24	2.57	3.46	4.50	0.65	3.07
Fe2O3	1.27	1.57	2.25	2.08	0.20	1.60
FeOt	1.54	4.43	6.10	7.08	0.92	5.01
MnO	0.06	0.10	0.13	0.17	0.02	0.10
MgO	0.60	1.85	1.85	2.49	0.12	1.99
CaO	0.93	3.68	3.11	6.34	0.59	3.60
Na2O	3.71	4.04	3.07	3.94	2.43	3.25
K2O	4.71	2.30	4.21	1.78	6.66	3.50
P2O5	0.06	0.21	0.27	0.33	0.02	0.19
LOI	0.64	1.64	1.07	0.84	0.46	0.50
Total	99.73	99.77	100.15	98.94	99.83	99.92
Cr	11.00	13.00	27.00	12.00	2.00	21.00
Ni	3.00	7.00	14.00	5.00	-1.00	9.00
Rb	116.00	53.00	125.00	50.00	136.00	128.00
Ba	886.00	984.00	1550.00	894.00	423.00	1310.00
Th		10.00	16.00	4.00	7.00	9.00
U	0.80	1.20	0.90	1.30	0.60	2.60
Ce	68.00	43.00	109.00	89.00	42.00	97.00
Cu	4.00	4.00	54.00	34.00	5.00	6.00
Ga	14.00	23.00	23.00	25.00	13.00	20.00
La	34.00	21.00	53.00	46.00	18.00	39.00
Li	11.00	20.70	16.40	14.30	5.50	25.00
Mo	3.00	5.00	2.00	3.00	2.00	3.00
Nb	8.00	6.00	12.00	7.00	2.00	14.00
Pb	42.00	6.00	15.00	6.00	25.00	22.00
Sr	176.00	1082.00	343.00	902.00	173.00	480.00
V	21.00	71.00	90.00	124.00	5.00	91.00
Y	11.00	8.00	25.00	22.00	5.00	22.00
Zn	138.00	517	868	358		
Zr	256.00					

Values of -1 are below detection limits

Appendix C

Table C.1. Nd-Isotope data for the Grenville Province in southwest Labrador

Map #	Sample #	UTM N NAD 27	UTM E NAD 27	Rock type	Suture (km)	Nd ppm	Sm ppm	147 Sm / 144 Nd	143 Nd / 144 Nd	E Nd (T)	TDM Ga	Q	P
	Pinware	**North**											
1*	VN92-197A	5771550	445850	QMZ	11	38.1	6.32	0.1003	0.511659	1.2	1.85	65	-102
2	CG99-002	5767289	429932	QMZ	6	45.9	8.50	0.1115	0.511825	2.1	1.81	46	-123
3	CG99-050A	5774107	422605	SY	13	42.7	6.83	0.0966	0.511663	2.0	1.80	4	-30
4	CG99-191	5765740	386298	GR	5	27.7	4.80	0.1044	0.511708	1.3	1.86	188	-13
5^	CG99-195A*	5762342	377348	GR	1	26.6	6.00	0.1359	0.511950	-0.6	2.15	164	-18
6	CG99-259A	5783976	372580	GD	23	46.8	7.85	0.1014	0.511747	2.7	1.76	234	-112
7	CG99-259B	5783976	372580	GR	23	21.2	3.57	0.1017	0.511729	2.3	1.79	199	-20
8^	CG99-254	5784611	373843	QMD	24	31.7	5.55	0.1058	0.511753	1.9	1.82	93	-142
9	CG00-169	5779217	338753	MG	18	38.5	7.08	0.1111	0.511833	2.3	1.80	108	-95
10	CG00-115	5782990	329047	QMZ	22	52.8	9.90	0.1135	0.511836	1.9	1.83	91	-93
11	CG99-141	5799535	393219	GR	39	65.1	10.50	0.0979	0.511654	1.6	1.83	109	-19
12^	CG00-319A	5812334	343243	MG	51	52.9	10.37	0.1186	0.511847	1.0	1.91	133	-79
13	CG08-048C	5831999	390353	MG	71	34.8	6.15	0.1068	0.511789	2.4	1.79	163	-52
14^	CG97-220	5830857	400988	QMD	70	41.2	8.14	0.1196	0.511863	1.1	1.91	61	-127
15^	CG97-161A	5836945	404410	GR	76	35.5	5.63	0.0960	0.511638	1.7	1.81	207	11
16	CG07-027B	5844263	403892	GR	83	45.9	7.17	0.0945	0.511573	0.7	1.88	140	-44
	Lake	**Melville**											
17	CG03-354F	5865203	484471	SED	104	20.3	3.60	0.1071	0.511443	-4.5	2.30	53	-28
18	CG03-354G	5865203	484471	MG	104	59.7	11.03	0.1117	0.511762	0.8	1.91	137	-53
	Mealy	**Mountains**											
19*	CG91-072A	5827650	453625	GR	67	62.8	10.56	0.1016	0.511643	0.6	1.90	155	-1
20*	VN91-233A	5837217	462216	QSY	76	71.3	13.25	0.1123	0.511785	1.1	1.89	99	-48
21	RH 7b	5880166	456286	GD	119	39.7	7.37	0.1123	0.511753	0.5	1.93	116	-161
22	RH 15	5880232	456183	GR	119	77.7	15.34	0.1193	0.511913	2.1	1.82	188	-7
23	RH8c	5879978	455758	GR	119	47.9	9.26	0.1167	0.511860	1.6	1.85	131	-47
24	RH 9	5878693	450034	QD	118	48.0	9.33	0.1174	0.511841	1.1	1.90	92	-186
25	RH 12	5871849	433759	MZ	111	36.0	7.27	0.1220	0.511936	2.0	1.84	38	-124
26	CG07-012B	5872575	435295	MZ	112	83.2	15.74	0.1143	0.511874	2.4	1.79	44	-105
27^	CG95-341A	5875024	416650	GR	114	30.9	5.70	0.1120	0.511603	-2.4	2.15	152	-25
28	RH 14A	5866870	419825	GR	106	44.4	6.92	0.0941	0.511627	1.9	1.80	199	52
29^	CG97-061	5858075	422025	GR	97	30.3	5.59	0.1114	0.511757	0.8	1.91	229	89
30	CG07-023C	5852516	408614	QMZ	92	33.9	5.82	0.1037	0.511740	2.0	1.80	47	-111
31^	CG97-028	5851921	369905	SY	91	83.3	15.21	0.1104	0.511803	1.9	1.82	5	-71
32^	CG98-218B	5852094	344843	DI	91	10.5	2.23	0.1286	0.511974	1.4	1.91	3	-265
33^	CG98-128A	5836488	344444	GR	75	48.4	8.76	0.1096	0.511726	0.5	1.92	189	74
34	CG98-243	5846050	311983	GR	85	52.5	9.71	0.1118	0.511831	2.1	1.81	110	-51
35	CG10-004B	5849327	306672	SY	88	49.9	8.39	0.1016	0.511704	1.8	1.82	15	-45
36	CG09-047B	5851421	300754	MD	90	25.8	4.85	0.1134	0.511815	1.5	1.87	18	-216
37^	VN95-060	5904951	411624	GR	144	34.8	6.17	0.1072	0.511669	-0.1	1.96	136	-19
38^	CG95-096A	5911514	405328	TN	151	21.3	4.76	0.1351	0.511910	-1.3	2.19	129	-191
39	CG95-128	5921794	388071	MG	161	47.2	9.38	0.1201	0.511813	0.0	2.00	160	-49
40^	CG83-181	6006382	345362	MZ	245	55.8	9.54	0.1034	0.511691	1.2	1.86	7	-164
41	RH 52	5877394	674536	MD	116	31.0	5.65	0.1103	0.511788	1.6	1.85	38	-172
42	CG11-003A	5903768	667178	GR	143	101.9	18.62	0.1104	0.511758	1.0	1.90	153	-42
43	RH 57	5902225	648077	ND	141	43.3	7.13	0.0995	0.511704	2.2	1.78	ND	ND
44	RM12-003	5897496	636073	QMZ	136	28.7	5.01	0.1053	0.511785	2.6	1.76	102	-100

	Mealy	**Mountains**	**Cont'd**										
45	RM12-004	5880014	617498	QSY	119	24.8	3.44	0.0838	0.511488	1.3	1.83	61	-45
46	RH 63	5877548	607483	TN	117	18.9	3.19	0.1021	0.511722	-0.1	1.80	115	-183
	Wilson	**Lake**	**Terrane**										
47	RH 65	5879531	596668	GR	119	31.7	6.44	0.1230	0.511838	-0.1	2.02	181	-6
48	RM12-009	5881042	577142	MG	120	76	12.5	0.0994	0.511567	-0.4	1.97	119	-89
49	RH 73	5885167	569989	GR	124	44.8	7.09	0.0957	0.511535	-0.3	1.95	140	-4
50	RH 72	5890469	557926	MG	129	31.6	5.27	0.1007	0.511582	-0.4	1.97	138	-86
	Trans	**Labrador**	**Batholith**										
51	RM12-021	5928150	449680	MG	167	38.4	7.20	0.1126	0.511679	-1.0	2.06	145	-89
52	RM12-022	5935390	438829	QMZ	174	33.1	5.90	0.1084	0.511591	-1.9	2.10	106	-105
53	RM12-023	5944158	413587	SY	183	41.6	7.30	0.1055	0.511524	-2.6	2.14	7.9	-97
54	RM12-027	5941635	390184	MD	181	37.4	6.20	0.0996	0.511347	-4.8	2.27	38	-153
55	RM12-025	5926734	392322	MG	166	32.3	5.40	0.1014	0.511537	-1.4	2.04	122	-78
56	RM12-026	5923126	382832	QMD	162	36.6	6.20	0.1027	0.511509	-2.3	2.11	82	-131
	Young	**Mantle**											
57	CG09-009b	5828456	350930	SY	67	67.7	11.73	0.1048	0.511874	4.4	1.64	15	-61
58	CG97-173	5835103	398951	QSY	74	126.6	21.29	0.1017	0.511865	4.9	1.60	69	-66
59	CG84-317	5876075	435845	QMZ	115	72.9	10.90	0.0902	0.511703	4.2	1.65	65	-79
60	RH13	5870785	430601	MG	110	49.7	7.03	0.0855	0.511625	3.6	1.68	207	-46
61	CG97-300	5845171	389799	GR	84	77.8	14.51	0.1127	0.511948	4.2	1.65	151	11
62	RM12-002	5901434	640794	GD	140	43.9	9.06	0.1249	0.512026	3.2	1.74	119	-148
63	RM12-006	5878121	602941	QMD	117	33	5.83	0.1069	0.511914	4.8	1.61	106	-116
64	RM12-014	5904625	527150	GR	144	51.8	5.97	0.0696	0.511529	5.1	1.60	136	-23

Denotes samples analyzed by Daly. ^Denotes samples analyzed by Creaser.
The reproducibility of $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ is estimated at 0.1% and 0.002% (1 sigma). Average within-run precision on the samples was ± 0.000014 (2 sigma). Value of T= 1.65 Ga. Q= [Si/3-(K+Na+2Ca/30)], P=[K-(Na+Ca)], expressed as grams-atoms x10^3 of each element in 100g of rock. 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

Table C.2. Major and trace element data

Sample #	VN92-197	CG99-002A	CG99-050A	CG99-191	CG99-195A	CG99-259A
SiO2	62.23	62.12	60.07	74.03	73.02	75.90
TiO2	0.76	0.72	0.62	0.31	0.25	0.50
Al2O3	17.20	16.92	19.77	13.37	14.02	10.90
FeO	1.91	2.12	0.85	1.80	0.94	2.28
Fe2O3	2.19	2.10	2.19	0.36	1.02	0.75
FeOt	4.31	4.46	3.13	2.36	2.06	3.28
Fe2O3t						
MnO	0.13	0.14	0.05	0.05	0.04	0.03
MgO	1.13	1.35	0.98	0.32	0.25	2.15
CaO	2.83	2.94	2.69	1.02	1.24	0.38
Na2O	4.63	5.18	4.33	3.19	3.45	4.47
K2O	4.59	4.53	7.40	5.09	5.43	1.83
P2O5	0.29	0.37	0.15	0.07	0.06	0.09
LOI	0.61	0.48	0.51	0.50	0.55	0.67
Total	98.70	99.21	99.72	100.29	100.37	100.21
Cr	2.00	2.51	5.47	2.32	1.27	1.96
Ni	6.00	-1.00	2.15	-1.00	-1.00	1.33
Rb	88.00	102.00	46.00	149.00	149.00	40.00
Ba	2409.00	1676.71	1984.25	1148.36	1196.57	197.02
Th	-1.00	3.70	3.90	15.00	5.50	11.00
U	0.20	0.90	-1.00	0.40	0.80	1.80
Ce	107.00	102.36	92.28	98.68	49.70	89.68
Cu	22.00	4.58	16.25	1.72	2.23	1.93
F						
Ga	20.00					
La	56.00	57.37	50.50	47.20	27.87	38.22
Li	10.40	16.42	6.28	9.27	11.05	18.95
Mo	4.00	1.43	-1.00	-1.00	-1.00	-1.00
Nb	9.00	23.86	12.11	15.34	10.57	10.65
Pb	11.00	14.10	12.10	20.93	15.63	5.59
Sr	511.00	434.74	613.44	120.25	146.28	72.77
V	65.00	70.23	55.76	4.85	3.53	40.38
Y	31.00	44.41	22.26	28.99	33.85	16.82
Zn	79.00	79.86	47.60	65.28	40.31	37.91
Zr	429.00	245.94	536.48	311.17	232.59	275.06

Sample #	CG99-259B	CG99-254	CG00-169	CG00-115	CG99-141	CG00-319A
SiO2	77.04	62.20	69.34	69.59	67.67	66.25
TiO2	0.08	0.63	0.56	0.33	0.37	0.86
Al2O3	13.07	17.64	13.55	13.78	15.35	14.68
FeO	0.21	2.83	1.71	1.45	2.37	2.87
Fe2O3	0.59	1.94	1.42	1.10	0.63	2.62
FeOt	0.83	5.09	3.32	2.71	3.27	5.81
Fe2O3t						
MnO	0.01	0.10	0.06	0.07	0.09	0.13
MgO	0.16	1.84	0.57	0.48	0.24	1.10
CaO	0.65	4.23	1.70	1.62	1.47	2.38
Na2O	3.55	4.17	4.99	5.28	3.75	3.77
K2O	5.01	3.20	4.53	4.99	6.01	3.99
P2O5	0.02	0.20	0.18	0.14	0.08	0.33
LOI	0.52	0.64	0.29	0.40	0.35	0.45
Total	100.95	99.94	99.07	99.38	98.65	99.73
Cr	-1.00	6.33	6.95	2.20	1.41	3.73
Ni	-1.00	2.09	5.52	3.20	-1.00	5.41
Rb	140.00	66.00	142.91	158.90	126.00	113.39
Ba	257.11	1019.28	1663.21	1021.88	1909.91	1643.44
Th	14.00	2.30	7.90	11.00	13.00	8.30
U	0.50	-1.00	1.50	1.90	1.30	0.20
Ce	54.50	62.55	77.25	122.42	184.01	100.15
Cu	3.21	3.95	-1.00	24.03	4.04	25.62
F						
Ga						
La	30.96	35.65	48.77	82.79	89.97	55.98
Li	6.47	17.64	13.33	12.57	13.16	29.41
Mo	-1.00	-1.00	-1.00	1.15	1.24	-1.00
Nb	2.74	9.31	14.03	18.35	17.95	17.84
Pb	18.32	9.32	20.88	15.44	22.17	10.73
Sr	72.72	579.91	204.44	141.66	149.33	312.16
V	1.26	85.32	31.75	9.90	1.58	39.77
Y	12.06	22.15	31.17	48.64	40.53	51.01
Zn	20.62	80.83	72.25	60.24	90.18	103.05
Zr	90.00	177.40	303.89	322.53	426.25	365.40

Sample #	CG07-027B	CG08-048C	CG97-220	CG97-161A	CG03-354F	CG03-354G
SiO2	71.05	58.66	76.35	71.14	52.89	63.28
TiO2	0.25	0.57	0.09	0.19	0.79	1.05
Al2O3	14.55	16.74	12.14	15.37	24.43	15.50
FeO		3.53	0.47	1.09	4.91	5.06
Fe2O3		2.45	0.87	1.32	3.18	1.43
FeOt	2.26	6.37	1.39	2.53	8.63	7.06
Fe2O3t						
MnO	0.05	0.14	0.01	0.09	0.10	0.11
MgO	0.53	2.37	0.09	0.35	2.65	1.82
CaO	1.80	4.23	0.44	1.34	1.17	3.15
Na2O	3.57	4.12	2.99	4.02	3.63	2.69
K2O	4.49	3.82	5.43	5.13	5.15	4.22
P2O5	0.08	0.40	0.01	0.04	0.04	0.30
LOI	0.69	0.66	0.50	0.46	1.02	0.89
Total	99.33	98.07	99.45	100.67	100.51	100.08
Cr	-1.00	11.00	-1.00	1.04	173.00	39.00
Ni	-1.00	6.00	1.19	2.22	43.00	12.00
Rb	106.00	102.00	179.00	129.00	107.00	92.00
Ba	1422.00	1553.00	674.09	1187.87	1211.00	1168.00
Th	14.30	5.38	13.00	11.00	7.41	16.73
U	1.09	0.78	1.40	2.50	1.44	2.55
Ce	123.00	75.00	118.20	92.12	44.00	136.00
Cu	10.00	47.00	1.69	2.02	18.00	12.00
F						
Ga	18.00	19.00	18.31	16.23	31.00	25.00
La	69.00	37.00	52.26	53.26	30.00	71.00
Li	13.90	26.70	9.31	12.43	19.00	11.80
Mo	-1.00	-1.00	-1.00	-1.00	1.00	1.00
Nb	7.40	11.60	7.18	8.88	33.60	20.20
Pb	20.00	20.00	24.70	23.58	28.00	15.00
Sr	253.00	923.00	52.65	221.89	208.00	301.00
V	18.00	103.00	4.76	12.11	124.00	86.00
Y	13.00	20.00	14.82	20.42	19.00	47.00
Zn	49.00	91.00	31.07	44.62	71.00	100.00
Zr	228.00	149.00	167.83	199.82	159.00	432.00

Sample #	CG91-072A	VN91-233	RH 007	RH 015	RH 008	RH 009
SiO2	70.00	63.75	58.37	70.77	66.20	62.32
TiO2	0.51	0.99	1.017	0.509	0.878	0.616
Al2O3	13.89	14.94	16.42	13.08	15.18	18.20
FeO	1.49	2.63	6.83	2.23	2.77	2.56
Fe2O3	1.85	2.63	1.26	1.95	1.68	1.24
FeOt	3.50	5.55	8.84	4.42	4.76	4.08
Fe2O3t						
MnO	0.04	0.10	0.135	0.065	0.121	0.094
MgO	0.43	1.19	2.80	0.31	1.12	1.19
CaO	2.02	2.95	4.76	1.40	2.55	4.57
Na2O	2.70	3.34	3.53	2.65	3.22	4.71
K2O	5.76	5.30	1.79	4.85	4.81	2.23
P2O5	0.12	0.41	0.301	0.083	0.328	0.186
LOI	0.72	0.49	0.36	0.45	0.37	0.17
Total	99.53	98.72	98.33	98.59	99.55	98.37
Cr	5.00	3.00	54	3	6	6
Ni	-1.00	-1.00	22	4	6	6
Rb	194.00	84.00	77	128	121	63
Ba	810.97	1823.37	900	753	2138	884
Th	-1.00	-1.00	7.3	20.9	5.2	7.5
U	0.40	0.20	0.9	2.5	1.1	4.7
Ce	153.48	128.62	100.3	174.6	141.0	102.7
Cu	8.93	5.17	24	7	9	34
F						
Ga	22.00	22.00	26	30	27	26
La	75.89	56.45	49.0	83.9	62.6	39.2
Li	4.57	4.14	19.7	4.4	10.2	10.5
Mo	1.19	-1.00	-2	2	-2	-2
Nb	11.64	18.40	21	37	25	29
Pb	20.38	16.28	23	29	27	24
Sr	169.23	426.24	351	101	362	508
V	13.39	32.53	119	8	38	53
Y	28.77	43.56	33	74	53	49
Zn	48.52	80.98	116	89	98	62
Zr	378.00	472.00	445	569	383	233

Sample #	RH 012	CG07-012B	CG95-341A	RH 014A	CG97-061	CG07-023C
SiO2	59.30	58.65	68.38	72.82	74.73	61.13
TiO2	0.836	1.68	0.40	0.341	0.53	0.53
Al2O3	16.55	13.98	14.94	14.01	10.45	17.86
FeO	5.68	8.02	2.91	1.91	1.55	2.33
Fe2O3	1.19	1.46	1.05	0.45	1.50	2.37
FeOt	7.50	10.38	4.28	2.57	3.23	4.96
Fe2O3t						
MnO	0.236	0.30	0.08	0.042	0.03	0.11
MgO	0.58	1.50	1.56	0.57	0.56	0.83
CaO	2.99	3.54	1.17	0.82	0.23	2.51
Na2O	5.05	4.37	3.37	2.00	1.40	5.09
K2O	4.34	4.65	4.93	6.17	6.50	4.61
P2O5	0.379	0.97	0.07	0.110	0.08	0.15
LOI	0.24	0.03	1.16	0.23	0.56	0.34
Total	98.01	100.04	100.34	99.69	98.29	98.11
Cr	-1	-1.00	43.46	3	7.22	1.00
Ni	5	-1.00	16.51	2	4.50	1.00
Rb	37	59.00	105.00	124	155.00	80.00
Ba	1955	2218.00	1001.78	1300	951.56	3104.00
Th	0.5	1.06	15.00	14.6	10.00	4.40
U	0.2	0.33	2.40	0.7	0.70	0.81
Ce	63.1	180.00	84.64	129.2	87.80	81.00
Cu	5	-1.00	10.98	4	9.65	2.00
F						
Ga	25	24.00	16.86	21	13.01	18.00
La	28.9	83.00	46.67	64.2	38.14	49.00
Li	6.5	9.30	11.65	7.8	7.39	10.60
Mo	-2	1.00	1.14	3	-1.00	-1.00
Nb	4	14.80	9.98	10	13.51	8.30
Pb	20	17.00	25.82	24	17.37	14.00
Sr	199	223.00	262.37	249	87.90	372.00
V	-5	24.00	58.72	43	26.99	23.00
Y	29	70.00	10.25	15	16.37	24.00
Zn	123	190.00	72.00	39	30.84	74.00
Zr	161	397.00	223.31	250	277.35	573.00

Sample #	CG97-028	CG98-218B	CG98-128B	CG98-243	CG10-004B	CG09-047B
SiO2	61.18	48.95	75.22	68.73	61.95	52.36
TiO2	1.00	1.85	0.17	0.53	0.98	0.77
Al2O3	17.77	21.63	13.02	14.55	17.59	19.00
FeO	2.08	5.22	0.72	1.53	1.81	4.69
Fe2O3	2.70	4.04	0.63	1.37	1.58	3.67
FeOt	5.01	9.84	1.44	3.08	3.60	8.89
Fe2O3t						
MnO	0.22	0.10	0.00	0.08	0.19	0.18
MgO	0.90	1.51	0.17	0.65	0.55	4.07
CaO	2.11	8.59	0.62	1.01	1.17	7.41
Na2O	5.32	4.30	2.11	4.54	5.26	4.16
K2O	6.51	1.31	7.20	5.33	6.82	2.39
P2O5	0.26	0.29	0.02	0.15	0.22	0.33
LOI	0.33	0.60	0.39	0.67	0.93	0.32
Total	100.63	98.97	100.35	99.33	99.25	99.88
Cr	-1.00	20.09	2.45	2.38	1.00	8.00
Ni	2.94	8.23	-1.00	-1.00	-1.00	8.00
Rb	82.00	7.00	107.00	86.00	46.00	39.00
Ba	2019.71	1065.05	1372.03	1100.79	343.00	1467.00
Th	2.00	-1.00	10.00	0.50	0.21	0.13
U	-1.00	-1.00	1.00	0.70	0.13	0.13
Ce	164.45	18.36	71.22	107.00	62.00	49.00
Cu	13.66	14.34	6.40	8.53	-1.00	80.00
F						
Ga	20.34				20.00	19.00
La	85.01	9.70	49.00	63.76	30.00	25.00
Li	4.90	4.42	10.55	4.11	1.70	6.60
Mo	1.14	1.91	-1.00	1.31	-1.00	-1.00
Nb	23.63	5.77	1.86	16.19	10.70	2.90
Pb	16.14	-1.00	10.82	15.37	8.00	10.00
Sr	224.99	915.72	417.50	259.45	75.00	1027.00
V	16.14	155.94	7.89	22.27	19.00	182.00
Y	55.67	11.41	6.59	47.66	15.00	16.00
Zn	150.13	100.76	15.23	77.84	64.00	92.00
Zr	618.26	29.14	201.36	451.17	8.00	108.00

Sample #	VN95-060	CG95-096A	CG95-128	CG83-181	RH 052	CG11-003A
SiO2	66.38	58.21	70.75	58.10	57.46	72.49
TiO2	0.60	0.86	0.31	1.10	0.546	0.22
Al2O3	15.28	18.00	13.36	18.40	18.50	13.27
FeO	1.60	3.37	1.91	3.07	3.50	1.45
Fe2O3	3.11	3.64	2.68	2.60	2.89	1.45
FeOt	4.89	7.38	4.79	6.01	6.77	3.06
Fe2O3t						
MnO	0.04	0.11	0.10	0.21	0.169	0.07
MgO	1.83	3.37	0.44	1.28	2.78	0.07
CaO	1.47	6.47	2.06	3.90	5.35	1.02
Na2O	3.22	2.98	3.42	5.64	4.55	4.06
K2O	5.24	0.98	4.63	4.10	3.32	5.03
P2O5	0.07	0.12	0.07	0.42	0.326	0.03
LOI	0.65	0.74	0.34	0.35	0.30	0.29
Total	99.67	99.21	100.27	99.17	100.07	99.60
Cr	23.69	139.23	8.57	2.00	22	2.00
Ni	8.81	47.02	4.02	-1.00	11	4.00
Rb	110.00	39.00	66.00	30.00	36	110.00
Ba	1356.45	516.36	747.99	4951.00	1655	353.00
Th	16.00	7.80	3.30	-1.00	0.7	6.01
U	1.60	1.40	-1.00	0.20	0.2	1.71
Ce	106.77	50.24	89.58	107.00	73.7	266.00
Cu	11.19	40.95	5.65	8.00	61	1.00
F						
Ga	18.81	17.86	17.99	26.00	20	42.00
La	56.67	26.16	54.41	54.00	37.3	126.00
Li	19.15	12.24	5.35	10.00	7.2	1.70
Mo	-1.00	-1.00	1.77	4.00	-2	2.00
Nb	9.59	9.21	10.88	15.00	4	40.70
Pb	27.75	6.38	14.40	9.00	19	20.00
Sr	298.84	383.02	126.90	899.00	827	57.00
V	59.57	120.11	23.02	28.00	139	2.00
Y	16.42	17.71	39.71	31.00	23	110.00
Zn	92.14	81.76	123.78	170.00	77	181.00
Zr	340.42	139.13	309.04	184.00	167	480.00

Sample #	RM12-003	RM12-004	RH 063	RH 065	RM12-009	RH 073
SiO2	65.82	66.64	65.61	72.47	63.05	56.89
TiO2	0.434	0.470	0.347	0.228	0.895	0.880
Al2O3	16.49	16.81	17.31	14.30	16.62	21.92
FeO	1.89	1.28	1.70	1.20	3.17	2.43
Fe2O3	1.62	1.08	1.27	0.50	2.93	5.64
FeOt	3.72	2.50	3.15	1.83	6.45	8.34
Fe2O3t						
MnO	0.077	0.063	0.063	0.088	0.090	0.126
MgO	1.16	0.74	0.85	0.69	2.04	2.74
CaO	2.45	1.98	3.20	0.96	3.43	1.35
Na2O	4.51	4.59	5.23	3.08	3.39	2.17
K2O	4.19	6.48	2.01	5.22	3.82	4.24
P2O5	0.153	0.120	0.163	0.131	0.081	0.071
LOI		0.42	0.44	0.27	0.38	0.66
Total		100.80	98.37	99.27	100.25	99.38
Cr	1	10	3	12	7	58
Ni	197	527	4	8	236	30
Rb	78	105	28	170	140	64
Ba	254	893	1749	597	1091	1558
Th	15.14	14.04	2.7	20.5	8.17	14.3
U	1.45	1.31	0.5	2.4	0.62	1.1
Ce	280.3	115.1	54.8	90.5	118.2	163.1
Cu			14	3		3
F						
Ga	28	23	21	19	22	39
La	137.4	35.6	29.2	40.4	50.6	81.8
Li			14.2	6.9		11.8
Mo	1	1	-2	-2	1	4
Nb	15.3	22.7	7	7	19.3	25
Pb	16	14	20	27	21	28
Sr	40	220	950	162	222	401
V			35	29		108
Y	26	44	11	43	38	18
Zn			54	37		91
Zr			155	140		269

Sample #	RH 072	RM12-021	RM12-022	RM12-023	RM12-025	RM12-026
SiO2	64.21	65.80	63.09	58.70	59.92	67.43
TiO2	0.581	0.441	0.708	1.150	0.733	0.513
Al2O3	16.06	16.00	16.08	18.17	18.51	14.29
FeO	2.22	4.75	5.40	5.11	4.34	3.58
Fe2O3	3.05	1.49	1.39	2.10	1.34	1.27
FeOt	5.52	2.93	3.61	2.71	2.70	2.08
Fe2O3t						
MnO	0.094	0.098	0.086	0.106	0.082	0.081
MgO	1.76	1.96	1.78	1.53	1.47	1.60
CaO	2.34	3.27	4.12	3.33	4.57	1.93
Na2O	3.65	3.29	3.52	4.90	4.83	4.24
K2O	3.44	3.53	3.86	5.67	3.96	4.35
P2O5	0.102	0.157	0.260	0.426	0.246	0.212
LOI	0.41		0.50	0.67	0.58	0.56
Total	98.17		99.40	99.76	99.23	98.78
Cr	68	-100	-100	-100	-100	-100
Ni	25	18	9	5	7	7
Rb	68	96	81	111	72	112
Ba	1381	1094	1785	6374	2442	782
Th	10.8	11.22	5.61	1.73	7.33	14.59
U	0.6	1.78	1.78	0.38	1.55	1.81
Ce	93.9	89.9	81.9	93.1	97.0	108.9
Cu	3	16	34	4	13	-1
F						
Ga	22	17	19	17	19	18
La	48.6	44.2	38.3	45.2	46.8	55.5
Li	12.6	25.3	22.3	20.3	17.6	31.8
Mo	2	-1	-1	1	-1	-1
Nb	15	11.9	10.6	11.0	12.4	11.3
Pb	22	14	-1	5	9	8
Sr	564	422	496	495	659	226
V	68	60	78	48	54	46
Y	16	27	23	25	25	18
Zn	79	74	52	76	64	52
Zr	242	239	243	178	418	178

Sample #	RM12-027	CG09-009B	CG84-319	CG97-173	RH 013	CG97-300
SiO2	62.08	59.51	65.60	62.93	74.91	72.62
TiO2	0.617	1.49	0.57	1.03	0.176	0.33
Al2O3	15.64	17.40	16.84	15.66	12.47	14.02
FeO	5.28	2.96	2.04	2.83	1.23	0.49
Fe2O3	2.03	2.30	1.06	2.84	1.00	1.41
FeOt	2.93	5.59	3.33	5.98	2.37	1.96
Fe2O3t						
MnO	0.090	0.18	0.11	0.11	0.068	0.05
MgO	2.22	1.54	0.82	1.46	0.06	0.28
CaO	4.40	2.64	1.95	2.80	0.67	0.69
Na2O	4.07	4.63	4.97	4.07	3.66	3.42
K2O	3.70	6.35	5.47	5.43	3.92	6.29
P2O5	0.220	0.54	0.15	0.60	0.015	0.05
LOI	0.65	0.45	0.51	0.70	0.45	0.58
Total	98.96	100.32	100.09	100.77	98.76	100.28
Cr	-100	-1.00	-1.00	4.05	-1	1.65
Ni	12	-1.00	2.00	4.37	-1	1.93
Rb	97	119.00	79.00	132.00	50	220.00
Ba	1180	3407.00	2583.00	2096.86	76	1249.64
Th	8.05	1.36	-1.00	14.00	5.9	6.80
U	1.40	0.96	0.60	-1.00	1.7	2.40
Ce	75.4	143.00	103.00	294.77	127.7	163.04
Cu	20	6.00	5.00	15.33	4	3.33
F						
Ga	20	22.00	20.00	26.27	20	25.33
La	35.7	68.00	50.00	158.11	67.0	84.17
Li	26.2	23.50	7.70	19.63	1.5	22.92
Mo	2	-1.00	3.00	2.01	2	1.33
Nb	11.3	17.50	12.00	37.72	6	51.06
Pb	8	20.00	11.00	31.61	20	38.74
Sr	557	375.00	353.00	507.69	11	183.43
V	90	45.00	20.00	46.91	5	10.31
Y	16	37.00	27.00	62.52	16	53.67
Zn	66	111.00	75.00	152.48	63	66.54
Zr	191	562.00	358.00	760.98	344	333.12

Sample #	RM12-002	RM12-014	RM12-006
SiO2	63.13	68.49	62.67
TiO2	0.793	0.485	1.016
Al2O3	14.28	14.59	13.47
FeO	4.34	2.66	4.88
Fe2O3	1.82	1.02	2.30
FeOt	6.64	1.47	7.72
Fe2O3t			
MnO	0.137	0.050	0.076
MgO	2.79	1.01	2.96
CaO	4.05	1.41	3.42
Na2O	4.03	3.50	3.97
K2O	2.53	5.39	3.43
P2O5	0.182	0.242	0.170
LOI	0.73	0.89	0.90
Total	99.30	98.71	99.82
Cr	2	-100	3
Ni	253	14	267
Rb	155	100	149
Ba	817	1570	399
Th	15.82	34.96	8.98
U	4.48	2.13	0.92
Ce	137.5	176.9	75.7
Cu		3	
F			
Ga	24	22	17
La	57.1	99.4	46.6
Li		20.2	
Mo	1	3	-1
Nb	29.2	8.7	15.7
Pb	19	44	20
Sr	150	710	104
V		36	
Y	45	10	16
Zn		52	
Zr		347	

Values of -1 are below detection limits