ND ISOTOPE DELINEATION OF CRUSTAL TERRANES IN THE BANCROFT AREA OF ONTARIO AND THE SAGUENAY AND BAIE COMEAU REGIONS OF CENTRAL QUEBEC: ENSIALIC RIFTING AND ARC FORMATION

By

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A Thesis

Submitted to the School of Graduate Studies

In Partial Fulfillment of the Requirements

for the Degree

Master of Science

McMaster University

Master of Science (April, 2010) McMaster University

(Geography and Earth Sciences) Hamilton, Ontario

Title: Nd isotope delineation of crustal terranes in the Bancroft area of Ontario and the Saguenay and Baie Comeau regions of central Quebec: Ensialic rifting and arc formation

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Number of Pages: x, 102

Abstract

The Grenville Province is a highly metamorphosed region of the Canadian shield which contains numerous lithotectonic domains of various ages and characteristics all affected by the c.a. 1.0 Ga Grenville Orogeny. The present study investigates, through reconnaissance neodymium isotope mapping, three under-mapped areas of the Province: the Weslemkoon study area of Ontario and the Saguenay and Baie Comeau study areas of central Quebec. These locations represent areas where previous studies have identified the presence of older crustal blocks which predate the Grenville Orogeny. But further detailed mapping is required to test and formulate interpretations regarding their evolutionary history.

The Weslemkoon Study area is found within the Central Metasedimentary Belt (CMB) of Ontario. The CMB has been interpreted as a composite arc belt (on the basis of structural studies of shear zones) or alternatively, as a failed ensialic rift zone (on the basis of isotope evidence and geometrical relationships). The Grimsthorpe Domain found within the CMB is of major importance in investigating both of these interpretations. In the situation where the CMB is viewed as a composite arc belt, the Grimsthorpe Domain has been interpreted as an allochthon on the basis of its bounding shear zones. However, in current research which views the CMB as a juvenile rift zone, the Grimsthorpe Domain has been interpreted as a horst structure composed of remnant old crust that formed in situ. The latter situation considers evidence from isotope signatures as well as the en echelon geometry of marble domains which are predominant on either side of, but completely absent from the Grimsthorpe Domain. This raises the possibility that the Grimsthorpe Domain did indeed form *in situ.* The Weslemkoon Batholith largely lies within the Grimsthorpe Domain but extends past the eastern shear zone of the Grimsthorpe Domain. Thus it provides an ideal location to test whether the Grimsthorpe Domain is an allochthon or a horst.

The present study finds that there are consistent Nd isotope signatures spanning the boundary of the Grimsthorpe Domain indicating that the shear zones are reflective of metamorphism, but not transportation of this block of crust. As well, the extent and geometry of old crust is defined and found to have isotope signatures relating this structure to the flanks of the rift zone and thus strengthening the argument that the Grimsthorpe Domain represents a horst structure. Further, the juvenile and old blocks have a ringed geometry in which inter-fingered lobes are identified.

The Saguenay and Baie Comeau study areas of central Quebec are located within the Central Gneiss Terrain and Baie Comeau Segment found within the Allochthonous Polycyclic Belt. While anorthosite-mangerite-charnockite-granite suites have received much attention in the literature, the basement rocks have only recently been studied in any detail with identification of Quebecia. Quebecia, a broad juvenile 1.5 Ga arc terrane has been defined on

the basis of relatively homogenous Nd isotope signatures indicating a common basement. Previous studies identified a few isolated areas of crust with signatures predating the Quebecia terrane and these are investigated in detail in this study.

Through more detailed isotope analysis and mapping of the Saguenay and Baie Comeau regions, the extent and geometry of these old blocks of crust have been defined. These old crustal blocks are completely encompassed by the Quebecia arc terrane which the present study interprets as indicating that Quebecia represents a composite arc where fragments of old crust were incorporated into an area dominated by juvenile subduction-related magmatism. These fragments are possibly connected to form a 'panel' of old crust running through the younger Quebecia arc terrane. Hence their identification provides a critical piece of evidence in understanding the geological evolution of the central Grenville Province.

Acknowledgements

Without the guidance, knowledge and, support of my supervisor, Dr. Alan P. Dickin, this paper could not have been written. I would like to thank him for his endless patience with me, his good humour in the field and, for showing me the back routes (read: washed out forestry access roads) of this gorgeous province of ours. Being accepted as a student of his is truly like being welcomed into his family, making the experience of working on an M.Sc. both enjoyable and worthwhile.

I would also like to whole heartedly thank my lab family. To my lab mom: Kathy Moretton, you taught me the ropes in the geochronology lab and have always been a solid voice of perspective and reason. To my lab brother: Mark Zelek, without your pep talks, moral support and our insightful geology debates, I could never have dreamed of finishing this thesis. My lab sisters: Esther Moore, Stephanie Thomson and Rebecca Moumblow Hewitson, you have helped endlessly in the field with sample collection, in the lab with keeping the process moving along, and as friends you have all provided many smiles. All of you have provided laughs and joy in an otherwise sensory deprived clean lab environment.

A special thank you to my mom and dad, Susanne and David Hynes for tolerating a daughter who has been forever in school and my dear departed brother Davey Hynes whose rock and mineral collection inspired me early in the wonders of geology.

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Chapter 1: Grenville Background Geology

1.1 – Grenville Background

The Grenville Province of Ontario and Quebec is the youngest province in the Laurentian Shield and represents a highly metamorphosed and deformed part of the craton with lithologic components ranging from Archean to Mesoproterozoic in age (Moore, 1986).

Spatially, the Canadian expression of the Grenville Province is an extensive longitudinal belt that covers an area 2000 km long and 500 km wide reaching from Labrador in the east to Georgian Bay in the west. This area represents the southeastern margin of the Laurentia craton and is bounded to the north by the Superior, Rae, Nain and Makkovik Provinces which were unaffected by the 1.0 Ga metamorphism which defines the Grenville Province. These provinces are shown in their North American context in figure 1.1. This figure depicts the major Proterozoic orogenic belts (shown in figure 1.1 with no pattern) and reports the timing of these orogenies and their distinction as either collisonal (c) or accretionary (a, as given by the inset). Major orogenic fronts are also illustrated in figure 1.1 by thrust symbols which distinguish the thrust sense of the fronts. To establish context for the work contained within this paper the lithologic divisions and corresponding tectonic divisions for the Grenville Province will be outlined in conjunction with the insights provided from advancing field of isotopic research.

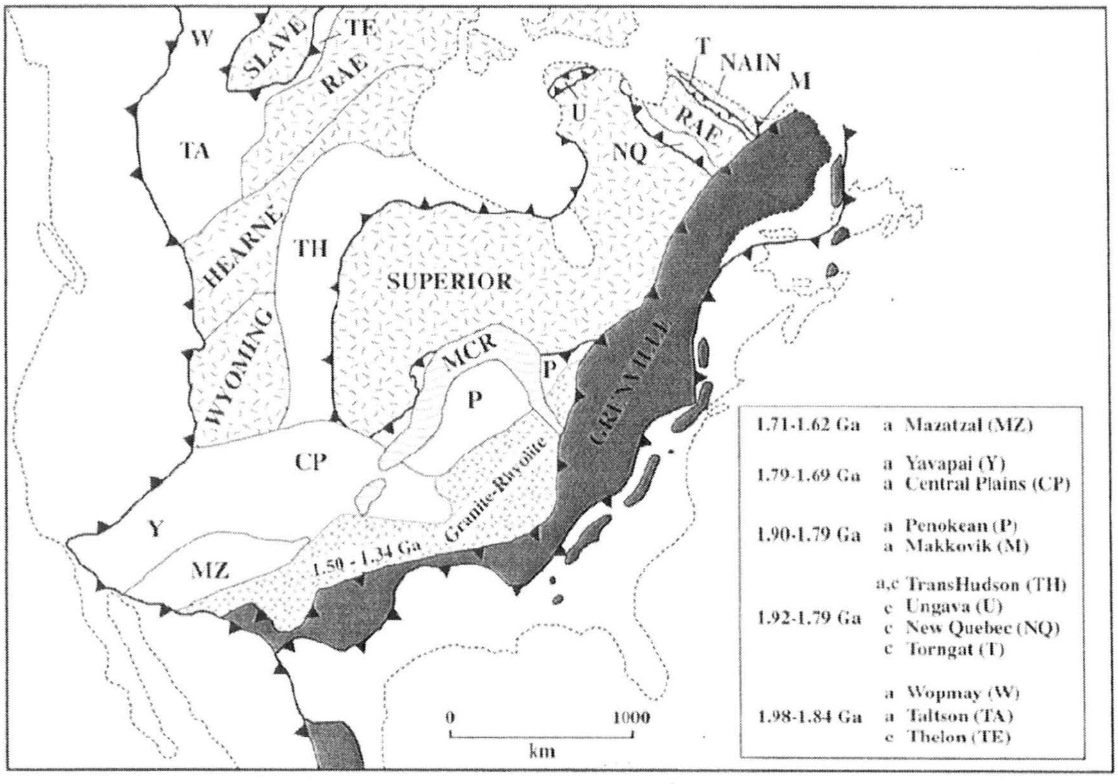

Figure 1.1: Sketch map of the Precambrian Provinces of Laurentia in the context of present day North America to show the location of the Grenville Province. Grenville Province – shaded, Archean provinces – random dash marks, Mid-continental rift system (1.1 - 1.09 Ga) = MCR (from Rivers, 1997).

The Grenville Province forms the eastern margin of Laurentia, which was tectonically active between ca. 1.9 Ga – 1.0 Ga. The Grenville Province has been affected by several collisional events leading up to the terminal Grenville Orogeny. This terminal orogeny affected the entire province from 1.09 Ga – 980 Ma through two distinct phases, the Ottawan orogenic phase and the Rigolet orogenic phase (Rivers, 2008). These phases of metamorphism affected the Grenville in pulses of heat and temperature regimes with a general intensifying trend from northeast to southwest along the Grenville Front and Allochthon Boundary Thrust (Rivers, 2008). The timing of the orogeny has been defined by

K-Ar ages obtained from hornblende and biotite as well as U-Pb ages obtained from zircon, monazite and titanite (Easton, 2008 and references contained therein).

1.2 – Geological Subdivisions

Broad lithologic divisions for the Grenville Province were put forth by Wynne-Edwards (1972). These include the Grenville Front Tectonic Zone (GFTZ), Central Gneiss Belt (CGB), Central Metasedimentary Belt (CMB), Adirondack Highlands (AH), Central Granulite Terrane (CGT), Baie Comeau Segment (BCS), and Eastern Grenville Province (EGP) which can be identified in Figure 1.2. These lithologic units are further recognized to be made-up of accreted arcs, magmatic plutons and intrusions, and volcanic as well as supracrustal rocks (Rivers, 1997 and references contained therein). Distinguishing the boundaries has been complicated by the large-scale deformation and metamorphism imparted by the Grenville Orogeny as well as previous collisional events. Much work has been conducted to identify the boundaries and provenance of each of these lithologic units; the effect of which is the modification of the map of Wynne-Edwards. However, the divisions of Wynne-Edwards (1972) still apply as a general framework for the lithology of the Grenville and represent a convenient label for major geographical areas within the geological Province.

Following is a description of the Grenville Front Tectonic Zone which is an important unit described by Wynne-Edwards (1972) as it stretches the entire length of the Grenville Province. The Central Metasedimentary Belt, Central Granulite Terrain and the Baie Comeau Segment will also be discussed as they encompass the three study areas that are investigated in the present study.

The Grenville Front Tectonic Zone: The Grenville Front Tectonic Zone (GFTZ) (figure 1.2) was identified by Wynne-Edwards (1972) by highly metamorphosed terranes within the Grenville Province that appeared to be the continuation of Archean lithologies from the Provinces to the northwest. As reported by Moore (1986), as early as the mid-1950's the truncation of units to the northwest of the Grenville's entire length, high grade of metamorphism, reverse faulting and mylonitization distinguished the GFTZ from the lower grade metamorphic rocks of the older provinces. As isotopic dating advanced in precision the northwest boundary of the GFTZ was recognized as the extent of Grenvillian metamorphism termed the Grenville Front. The Grenville front (GF) marks the extent of Grenvillian orogenic metamorphism and deformation and defines the Grenville Province from the Archean Provinces shown in figure 1.3. This boundary is a crustal scale discontinuity where the northwestern limit of Grenvillian metamorphism has been recorded by K-Ar isotope system resetting asserted by Rivers et al. (1989) to represent geologically long periods of heat and pressure. The GF was established during the Rigolet orogenic phase between 1100 Ma and 980 Ma (Rivers, 2008). The GF dips at 30° to the southeast and is distinguished by major thrust uplift and change in metamorphic grade and is marked by mylonitization and faulting (Rivers et al., 1989). Vertical uplift and a sinistral strike-slip displacement are more exaggerated in the eastern Grenville (Rivers et al., 1989).

The Central Metasedimentary Belt: The Central Metasedimentary Belt (CMB) can be identified in figure 1.2. This belt is distinguished by the volume of metamorphic carbonates, calc-sillicates, quartzites, paragneiss, amphibolite and metavolcanics which are the dominate lithologies of this belt (Wynne-Edwards, 1972). The CMB is also characterized by major granitoid plutons, one of which, the Weslemkoon Batholith is a focus of investigation in the present study. Wynne-Edwards (1972) identified the northern boundary of the CMB on the basis of prominent lineaments "associated with steeply southeast-plunging structures" and a broad area of migmatites dividing quartzofeldspathic gneissic rocks to the northwest from metacarbonate rocks to the southeast. Wynne-Edwards (1972) identified the southern boundary of the CMB on the basis of another prominent lineament of mylonites which marks a change from amphibolite facies within the CMB to granulite facies to the southeast of the CMB in the Central Granulite Terrain.

The Central Granulite Terrain: The Central Granulite Terrain (CGT) lies to the east of the CMB and can be identified in figure 1.2. This terrain is characterized by granulite facies assemblages and numerous anorthosite massifs (Wynne-Edwards, 1972). The Saguenay study area falls largely within this area.

The eastern boundary of the CGT is identified by Wynne-Edwards (1972) as being roughly coincident with the position of the granulite facies isograd between this terrain and the Baie Comeau Segment.

Baie Comeau Segment: The Baie Comeau Segment (BCS) lies east of the CGT and can be identified in figure 1.2. While the BCS has numerous anorthosite massifs, they are on a smaller scale than those seen in the CGT and this area is distinguished by amphibolite grade metamorphism rather than granulite facies as seen in the CGT (Wynne-Edwards, 1972). The BCS spans the area from the St. Lawrence River in the south to the GFTZ in the north and Wynne-Edwards (1972) marked the eastern boundary of this segment as the limit of homogeneous metamorphism of grey gneisses. As its name indicates, the Baie Comeau study area of the present study falls within this segment.

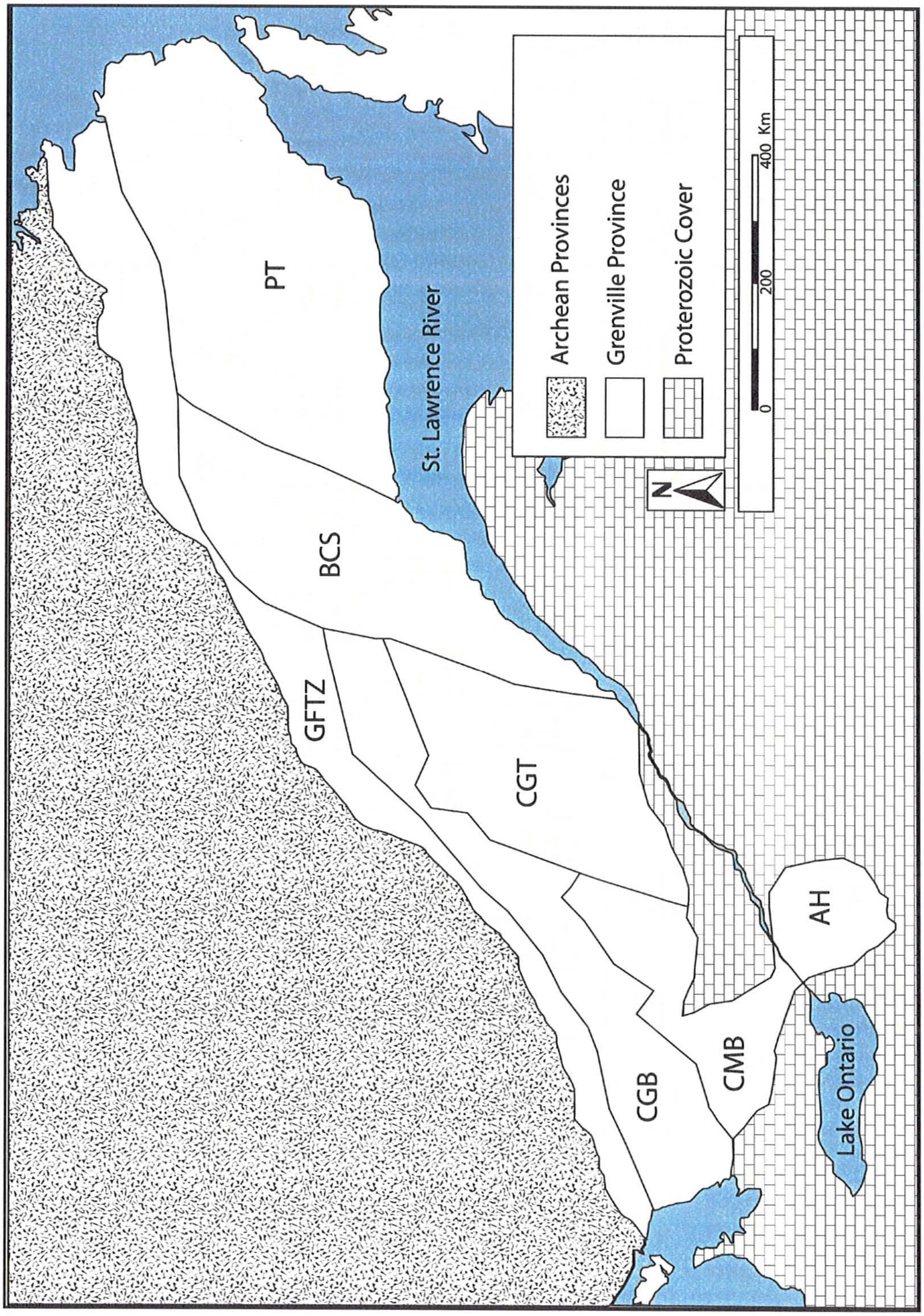

Figure 1.2: Subdivisions of the Grenville Province as outlined by Wynne-Edwards (1972). GFTZ =Grenville Front Tectonic Zone, CGB = Central Gneiss Belt, CMB = Central Metasedimentary Belt, CGT = Central Granulite Terrane, AH = Adirondack Highlands, BCS = Baie Comeau Segment, EGP = Eastern Grenville Province.

The divisions of Wynne-Edwards (1972) have been superseded to some extent by a tectonic division of the province into three structural belts as first developed by Rivers et. al., (1989). These belts are the Parautochthon, Allochthonous Polycyclic Belt and the Allochthonous Monocyclic Belt (figure 1.3). The first two of these belts extend the entire length of the Grenville Province and have been identified on the basis metamorphic grade and magnetic signatures (Rivers et al., 1989; Rivers, 1997; Rivers et al., 2002). The Parautochthonous Belt (a largely *in situ* terrane) and Allochthonous Belt (which partially tectonically overlays the Parautochthon) are defined in terms of their lateral displacement in relation to the foreland of Laurentia (Rivers et al., 1989).

From previous research it is clear that the Grenville Province can be interpreted as a mosaic of terranes formed in a variety of tectonic, magmatic and sedimentary environments that became metamorphosed and juxtaposed through the action of multiple orogenic cycles. As such, it is important to recognize the components of the three structural belts of Rivers et al. (1989), their context as defined in terms of Grenvillian orogenic cycle transposition and overprinting, as well as the first order tectonic boundaries which demarcate them. These components can be identified in Figure 1.3.

Following is a description of the major structural belts, and the bounding first order tectonic boundaries and the geologic tools used to discern them:

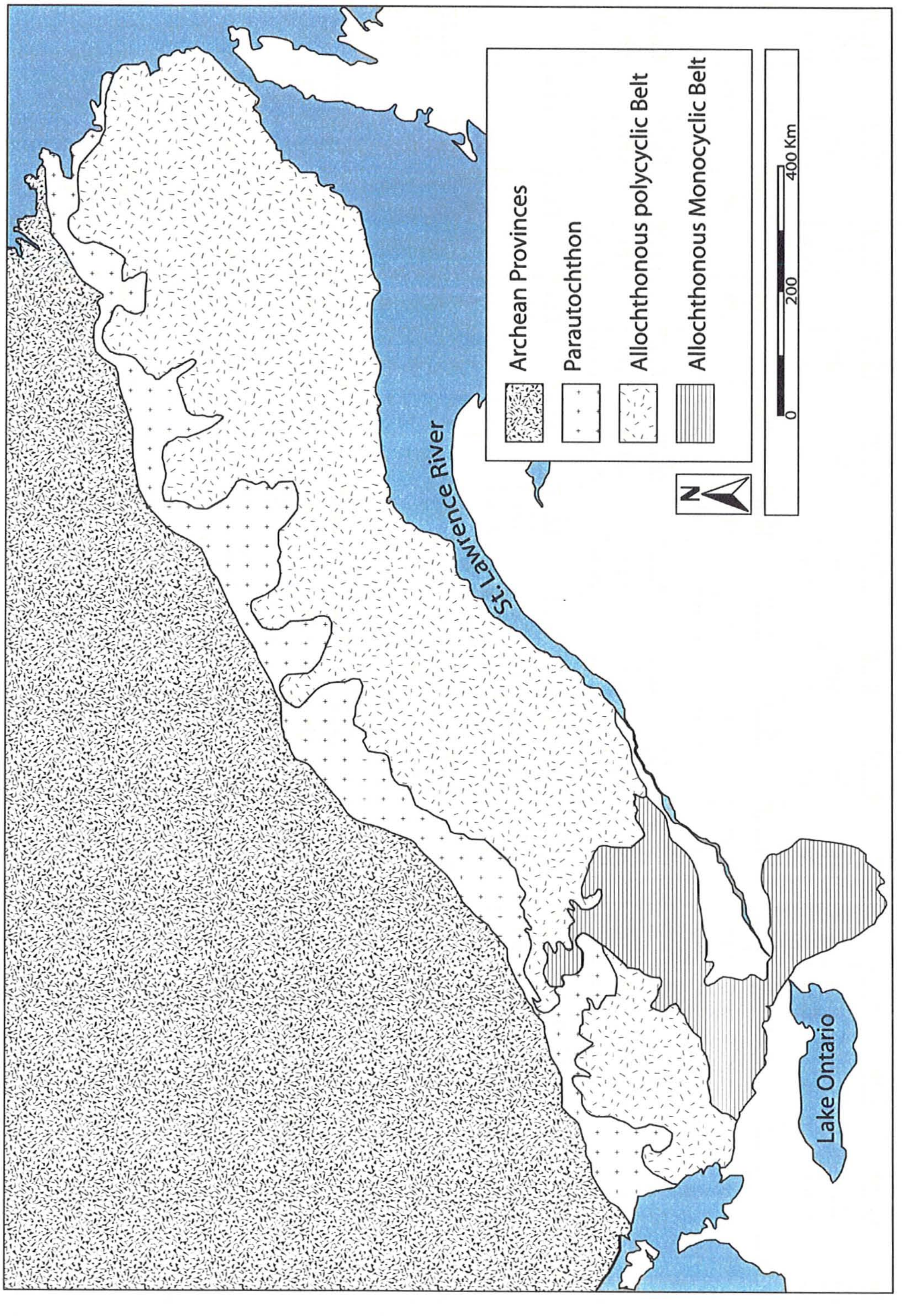

Figure 1.3: The Grenville Province overview showing the three major structural belts: the Parautochthonous Belt, Allochthonous Polycyclic Belt and less spatially extensive Allochthonous Monocyclic Belt. (after Rivers, 2008).

The Parautochthonous Belt: The largely *in situ* Parautochthonous Belt (PB) contains lithologic units which despite their metamorphic imprinting from the Grenville Orogeny can be traced to their Archean protoliths across the GF (Rivers, 1997 and references contained therein). The metamorphic grade of the PB reaches amphibolite to granulite facies with slightly increasing metamorphic grades to the south (Woussen et al., 1986; Wardle et al., 1986). The extent of the PB and its situation within the Grenville is depicted in figure 1.3.

The Allochthon Boundary Thrust: The Allochthon Boundary Thrust (ABT) has in recent years been studied in great detail. Despite masking of the boundary by Mesoproterozoic plutonism in much of Quebec and Labrador, recent success in mapping the boundary have arisen from utilizing magnetic data which show the Archean PB as magnetically quiescent, while to the south, Proterozoic rocks have a noisy magnetic signature (Rivers et al., 1989). The ABT has further been distinguished by Nd model ages, since the hanging wall (PB) has ages > 1.8 Ga while the footwall (corresponding with the Allochthonous Belt) exhibits Nd model ages < 1.8 Ga (Dickin and Guo, 2001; Herrell et al., 2006). The magnetic boundary is largely geographically coincident with the distinct Nd isotope boundary between the PB and Allochthonous Polycyclic Belt (Dickin and Guo, 2001).The ABT was established during the Ottawan orogenic phase (Rivers, 2008). The ABT can be seen to trace the northern extent of a series of lobate thrust sheets of the Allochthonous Belt as outlined in figure 1.3.

The Allochthonous Belt: The AB has been described as a vast and complicated collage of para- and ortho-gneisses contained therein (Davidson, 1986; Rivers, 2008). The Allochthonous Belt is further subdivided into the Allochthonous Polycyclic Belt (APB) and the Allochthonous Monocyclic Belt (AMB) (Rivers et al., 1989). These belts differ as the AMB has undergone only one orogenic cycle where the APB has undergone more than one.

The **APB** lies to the south of the ABT and is composed of lobate, tectonically transported nappes that partially overly the PB (Rivers et al., 1989; Wardle et al., 1986). Supracrustals and some of the plutonic rocks of the APB show polydeformed fabrics (Rivers et al., 1989). Metamorphic grade in the APB is typically of the upper amphibolite and granulite facies although localized areas of greenschist facies are found (Rivers, 2008) and it is thought that thickening in this belt is a result of crustal stacking (Rivers et al., 1989). The APB extends the entire length of the Grenville Province.

The **Monocyclic Belt Boundary Zone** (MBBZ) is a décollement zone which separates the APB and the AMB. In Ontario this boundary is termed the Central Metasedimentary Belt Boundary Zone (CMBBZ). This zone is an area of ductile thrusting of the AMB over the APB (Nadeau and van Breeman, 1998). Kinematic indicators imply a northwest displacement and folding of the AMB over the APB, causing considerable shortening and crustal thickening (Rivers et al., 1989).

The **AMB** is less spatially extensive and represents an area of the relatively youngest rocks in the Grenville which are metamorphosed from greenschist to granulite facies, are cut by syn- to late-tectonic plutons and show evidence of late extensional mylonites (Rivers et al., 1989). Rivers et al. (1989) defined the AMB as including the Central Metasedimentary Belt and Adirondack Highlands of Wynne-Edwards (1972). The AMB has been viewed to partially structurally overlie the APB which was compressed by the Shawinigan Orogeny (ca. 1190 Ma – 1149 Ma) (Rivers, 2008). Conversely, Dickin and McNutt (2007) proposed that the area of monocyclic crust was much smaller than that proposed by Rivers et al. (1989) and represents a rift zone behind an Andean-type arc.

With the growing body of Nd isotope data within the Grenville it is now possible to dissect the broad lithologic and tectonic divisions into several distinct pre-Grenvillian environments of coeval accretion and magmatism. Dickin (2000) investigates crustal formation throughout the Grenville Province using Nd isotope signatures to delineate crustal terranes whose boundaries are otherwise obliterated by the Grenville Orogeny. Areas which display consistent Nd isotope signatures are indicative of distinct episodes of crustal formation and can be viewed as distinct arc terranes, formed and subsequently accreted to Laurentia (Dickin, 2000). Hence the Nd isotope system has proven a very useful tool in mapping crustal formation and is discussed in chapter 2.

1.3 – Introduction to Study Areas

The present study specifically utilizes isotope evidence in reconnaissance efforts to investigate interesting geologic structures in three portions of the Grenville Province in Ontario and Quebec. The aim is to constrain terrane boundaries and to explore the geologic environment encompassing the Tweed - Bancroft area (Weslemkoon Batholith) of Ontario, and the Saguenay and Baie Comeau regions of Quebec through spatial, temporal and tectonic relationships. The Grenville Orogeny (1.20 - 1.00 Ga) metamorphosed this area, obscuring boundaries between lithotectonic domains of pre-Grenvillian crust. Neodymium (Nd) isotope data has been successfully utilized in mapping many terrane boundaries in the Grenville Province, and will be applied to these three areas which are yet to be defined in detail. In each of these regions reconnaissance work has revealed portions of crust with older isotope signatures surrounded by more juvenile terranes. The following chapters will provide detailed discussions of pre-Grenvillian tectonic models which pertain to the specific study areas.

Chapter 3 describes the investigation of the Weslemkoon Batholith of the Elzevir Terrane which lies within the Central Metasedimentary Belt (CMB). This area was formerly considered to be a composite arc belt but current evidence suggests that it represents a failed back-arc rift zone. The Weslemkoon batholith is emplaced into what appears to be a remnant block of older crust within the rift, with Nd model ages that are progressively more juvenile to the east. This scenario is consistent with the distinction of the Grimsthorpe Domain as a horst structure preserving a buried block of crust that formed *in situ,* where magmatism sampled basement crust with varying formation ages prior to back arc extension. The objective of this study is to test this model by more detailed sampling across the Weslemkoon Batholith.

Chapter 4 contains the investigation of the Saguenay and Baie Comeau regions of the Pinwarian-aged Quebecia Terrane, where two older blocks of crust have recently been identified. These blocks are possible evidence that the Quebecia Terrane represents a composite arc belt similar to the model previously proposed for the CMB. Such circumstance would infer that these older blocks represent continent building through arc accretion along the eastern margin of Laurentia.

Chapter 2: Nd Model Ages

2.1 – Nd Model Ages in the Grenville

The REE signature of solid rocks provides a means of tracing the geologic provenance of samples back to their now all but obliterated original petrogenetic conditions and mantle precursors. The orogenic event that metamorphosed the Grenville Province was responsible for resetting many of the isotope systems which could provide formation ages or clues to the provenance of its terranes. However, several characteristics of the Nd isotope system make it a useful tool in determining the evolution of continents. These characteristics include the very similar chemical properties of Sm and Nd (DePaolo and Wasserburg, 1976a) as well as relative immobility during metamorphic events (DePaolo, 1981) or igneous intrusion into country rocks (Dickin, 2005). Further, the isotope ^{147}Sm has a half life of 106 billion years equivalent to a decay constant of $6.54 \times 10^{-12} yr^{-1}$ resulting in sufficient variation in abundance of the daughter isotope ^{143}Nd over the course of billions of years.

McCulloch and Wasserburg (1978), through analysis of an extensive sample set which included igneous, sedimentary and metamorphic rocks from both continental and oceanic origins, demonstrated that the Sm-Nd isotope system remains closed during erosion, diagenesis and metamorphism of each of the rock types. Since the Sm-Nd isotope system remains closed, it is effective for dating the Grenvillian gneisses and their igneous precursors. Effectively, the Sm-Nd isotope system 'sees through' intense deformation so it is possible to delineate individual pre-Grenvillian crustal terranes and their arrangement prior to orogeny.

2.2 – Nd Model Ages

At the time of condensation of the earth the abundance of $\frac{^{143}Nd}{^{144}\mathrm{Nd}}$ was equal to the abundance of that in the solar nebula (DePaolo and Wasserburg, 1976a) from which it and all other chondritic material in our solar system condensed. Using data from early Archean plutons and chondritic meteorites, DePaolo and Wasserburg (1979a) noted that the plutons had initial ratios that clustered tightly around an isotopic growth line defined by chondritic meteorites. They were thus able to establish the mantle Sm/Nd composition which is taken to be equal to the Sm/Nd composition of the chondritic earth. This reservoir is termed the Chondritic Uniform Reservoir (CHUR). From this initial value it is possible to construct a growth curve of the bulk earth. These findings led to the first method for model age dating using the Sm-Nd isotope system which calculated T_{CHUR} model ages found through the following equation from DePaolo and Wasserburg (1976b):

$$\mathrm{T}_{CHUR} = \frac{1}{\lambda}\ln\left[1 + \frac{\left(\frac{^{143}\mathrm{Nd}}{^{144}\mathrm{Nd}}\right)_{meas} - \left(\frac{^{143}\mathrm{Nd}}{^{144}\mathrm{Nd}}\right)_{CHUR}}{\left(\frac{^{147}\mathrm{Sm}}{^{144}\mathrm{Nd}}\right)_{meas} - \left(\frac{^{147}\mathrm{Sm}}{^{144}\mathrm{Nd}}\right)_{CHUR}}\right]$$

The T_{CHUR} model ages as proposed by DePaolo and Wasserburg (1976b) rely on the assumption that at the time of extraction from the chondritic reservoir there was sufficient Nd/Sm fractionation to cause the crustal evolution line to diverge from the mantle evolution line (figure 2.1). This fractionation would lead to an Nd-depleted residual mantle ($f_{Sm/Nd} > 0$) and an enriched crust ($f_{Sm/Nd} < 0$). The evolution of the Bulk Earth ($f_{Sm/Nd} = 0$) represents an average vector between the depleted residual mantle and the enriched crust.

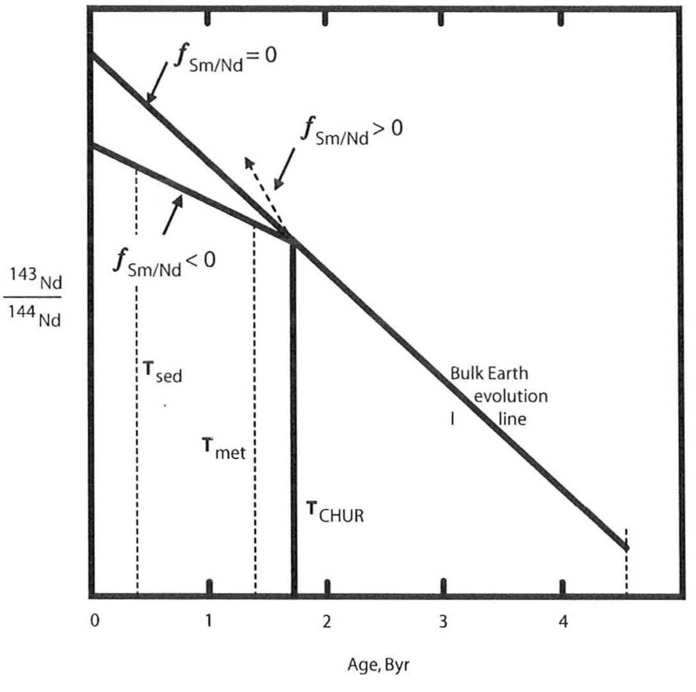

Figure 2.1: The evolution of $^{143}Nd/^{144}Nd$ for the earth through time as represented schematically by McCulloch and Wasserburg (1978) since the time of condensation from the solar nebula.

As a result of these processes, through time it is seen that the mantle becomes enriched in ^{143}Nd relative to the CHUR. While this departure from CHUR is small, as this system undergoes only slight fractionation during crystal – liquid processes, there are measurable and meaningful time dependant deviations. DePaolo and Wasserburg (1976a) introduced epsilon notation (εNd) which represents parts per 10^4 deviations from CHUR. This term allows for easy comparison of initial ratios for many samples and in granitic rocks its value reflects its age (DePaolo, 1988). The equation used to calculate εNd for a rock sample is as follows:

$$\varepsilon Nd(T) = 10^4 \left[\frac{\left(\frac{^{143}Nd}{^{144}Nd}\right)_{rock}(T)}{\left(\frac{^{143}Nd}{^{144}Nd}\right)_{CHUR}(T)} - 1 \right]$$

Where: $\varepsilon Nd(T) =$ deviation from the CHUR at time (T) which is measured backwards from present (age), $\left(\frac{143Nd}{144Nd}\right)_{CHUR}(T) = 0.51264 - 0.1967\ (e^{\lambda T} - 1)$ and $\lambda =$ the decay constant $(6.54 \times 10^{-6} Myr^{-1})$ as established by DePaolo (1981). The evolution of the Bulk Earth occurs along the vector where $\varepsilon Nd = 0$ or $f_{Sm/Nd} = 0$ as seen in figure 2.1.

DePaolo and Wasserburg (1976a/b) noted the good fit of Archean plutons to the CHUR evolution line ($\varepsilon Nd = 0$) but also identified that MORB samples fell +7 to +12 ε units above this line. They proposed that these findings indicated the possibility of the existence of a residual depleted-mantle (i.e. $\varepsilon Nd > 0$) evolution line where there is a progressive increase in Sm/Nd and $\frac{^{143}Nd}{^{144}Nd}$ ratios.

Subsequently, DePaolo (1981) conducted research on the Proterozoic basement rocks of the Colorado Front Range aiming to test the T_{CHUR} model and investigate the possibility of a depleted mantle evolution vector. The Colorado Front Range had been previously well characterized and fell within an intermediate age span between the Archean plutons and young MORB samples between 1.0 and 1.8 Ga and thus was a suitable location to carry out such work.

DePaolo found that samples that were spatially and genetically distinct from one another defined an isochron that represents a true magmatic age of 1.8 Ga. Such findings require a magma source that is homogeneous over distances of several hundred kilometres. Each of these samples returned initial εNd (i.e. εNd (0)) values elevated in Sm/Nd from the Sm/Nd of the CHUR which indicate a source region that was depleted in crustal components, a characteristic that has also been identified in island arcs and contemporary crust (DePaolo, 1981). Figure 2.2 presents the findings of DePaolo's study plotted as εNd against time. The line labelled "depleted mantle" represents a quadratic curve that diverges from the CHUR evolution line in the early Archean and is fitted to the average εNd values from the samples at 1.8 Ga and the average εNd value from contemporary island arcs. This curve represents the evolution of a mantle reservoir that through time has become increasingly depleted in crustal components.

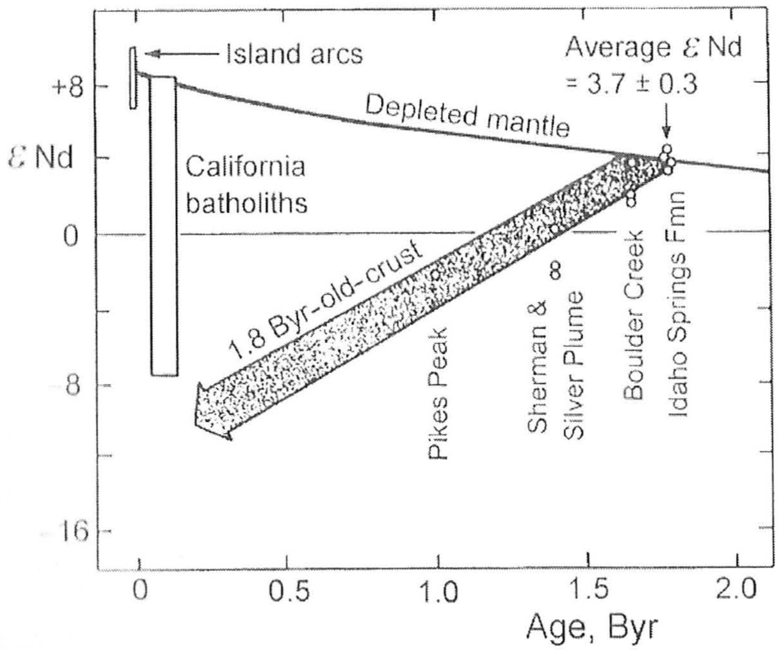

Figure 2.2: Plot of εNd against time, showing Colorado data relative to a model depleted-mantle evolution curve (From: Dickin, 2005 as modified from DePaolo, 1981).

The divergence of the Depleted Mantle curve from the CHUR at a time (T) can be calculated from the following equation:

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

Using this relationship it was found that samples from previous studies that returned seemingly young T_{CHUR} model ages, when calculated relative to the Depleted Mantle were reconciled with known crystallization ages (DePaolo, 1981). DePaolo found that calculated ages relative to the Depleted Mantle gave much more reliable ages than those calculated relative to CHUR, leading to a revised model: Depleted Mantle model ages (T_{DM}).

Thus, the current accepted Neodymium model age dating technique compares the ratios of $\frac{^{143}Nd}{^{144}\mathrm{Nd}}$ and $\frac{^{147}Sm}{^{144}\mathrm{Nd}}$ to the depleted mantle model of DePaolo (1981). Ages are calculated relative to DePaolo's mantle evolution curve.

2.3 – Crustal Formation Age Mapping

Early work in the Sm-Nd isotope system focused on characterizing the evolution of this system through time, developing a reliable dating method from these isotopes and establishing how the characteristics of Sm-Nd data could be used to make inferences about the mantle source, crustal formation and generation as well as mixing processes. While it is known that the mantle is heterogeneous, DePaolo (1981) identified a mantle source that was homogeneous over 100s of km from his observations of the 1.8 Ga age found in the Colorado Front Range and in other subduction related environments. This has the implication that such magma sources can be uniform, and the addition of new crust from these sources can be compiled into crustal formation maps which characterize and define crustal blocks (or terranes) on the basis of similar isotopic characteristics and model ages.

Since the development of the Depleted Mantle Model many studies have utilized the Sm-Nd isotope system in unravelling the geologic history of highly complex areas where other methods have proven less effective. For example: Dickin and McNutt (1989) were able to successfully map a suture between Archean and Proterozoic crust in the southwest Grenville Province of Ontario which other methods failed to recognize because of the complicating stitching plutons which occurred in several generations of magmatism.

Twenty plus years of work by Alan Dickin and colleagues have led to much of the Grenville province being mapped using the Sm-Nd isotope system. This has lead to the compilation of a crustal formation map for the Grenville Province (figure 2.3).

The map shown in figure 2.3 was created using a very large body of Nd isotope data which effectively showed spatial trends and allowed identification of distinctive terranes. These pre-Grenvillian terranes are distinguished on the basis of isotopic homogeneity and coherent T_{DM} age results and isotope ratios (Dickin et al., 2010).

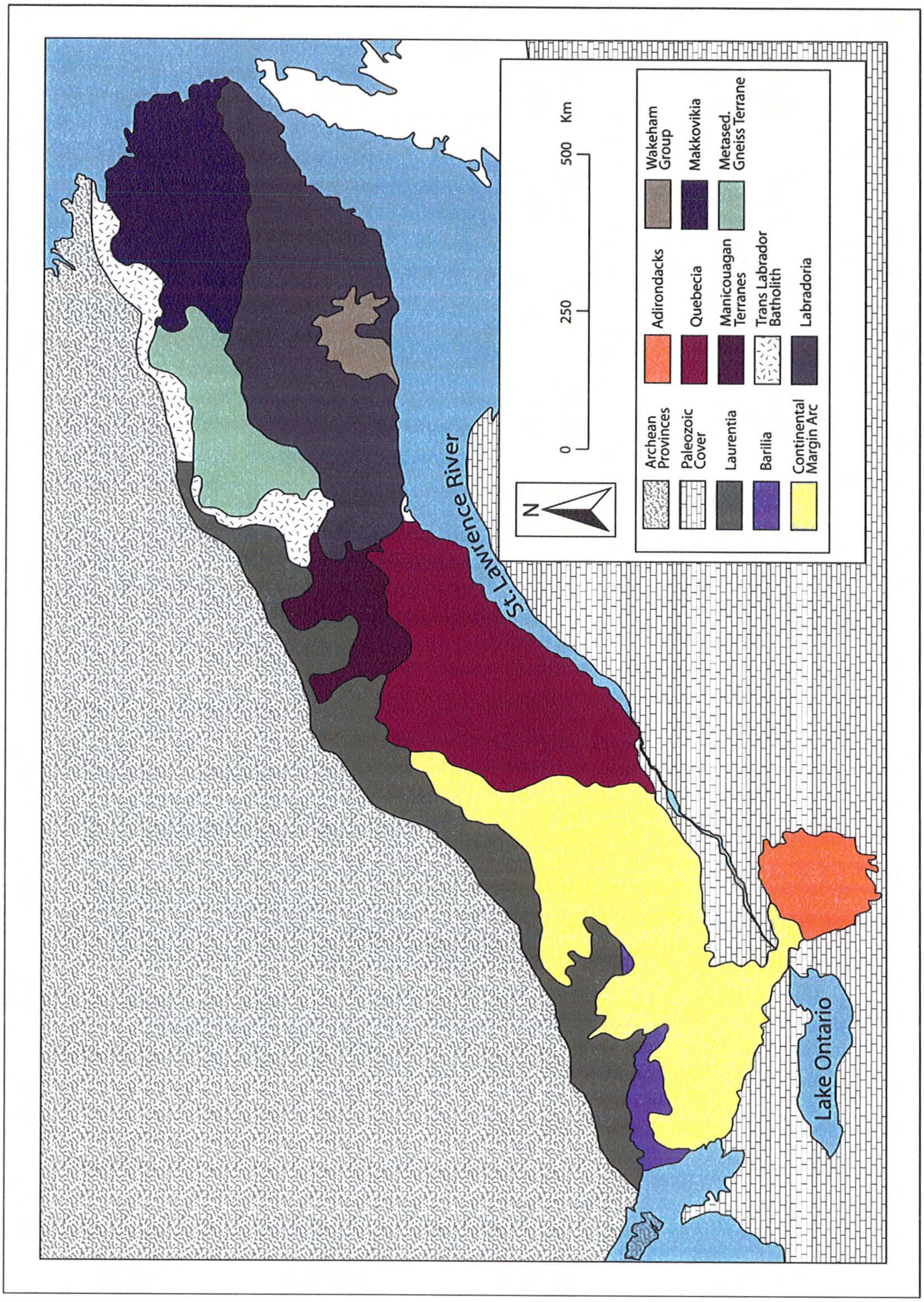

Figure 2.3: Crustal formation map of the Grenville Province as established by Nd isotope dating method after Dickin et al. (2010).

Chapter 3: Weslemkoon Study Area, Ontario

3.1 – Grenvillian Geologic Context

The CMB in Ontario is part of the Allochthonous Monocyclic Belt and is composed of immediately pre-Grenvillian rocks that include the clastic and carbonate metasediments and bimodal metavolcanics of the Flinton Group and Grenville Supergroup as well as a series of plutonic rocks with ranging compositions from felsic to ultramafic (Easton, 1992).

In a Grenvillian tectonic context the CMB is further divided into northeast trending structural domains, each separated by a series of like-trending ductile strain zones (Carr et al., 2000). These domains are identified in figure 3.1 along with the boundary between the CMB and the CGB (the CMBBZ). The southern extent of these terranes is obscured by Proterozoic cover.

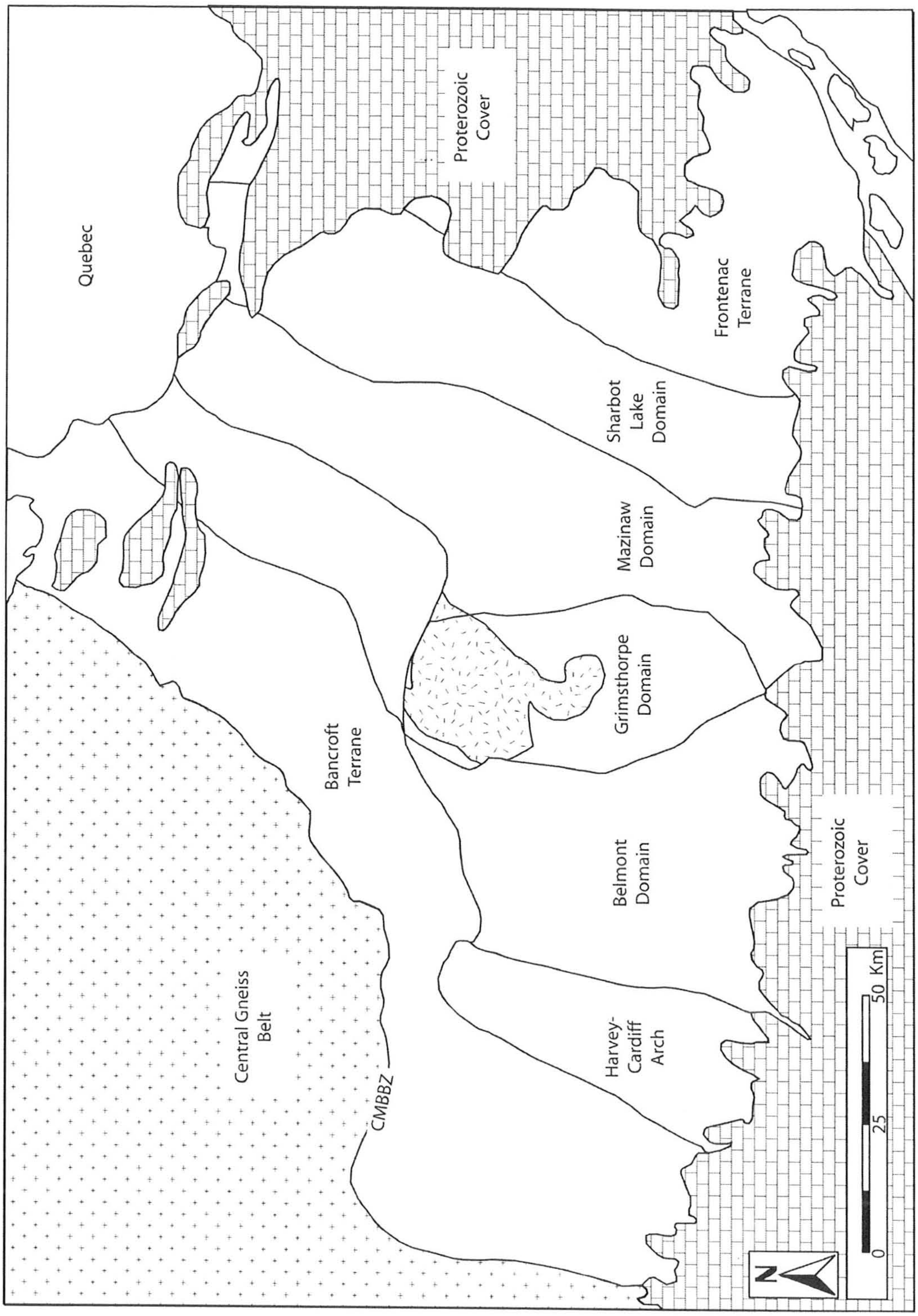

Figure 3.1: Lithotectonic domains of the Composite Arc Belt of the Grenville Province after Easton (1992).

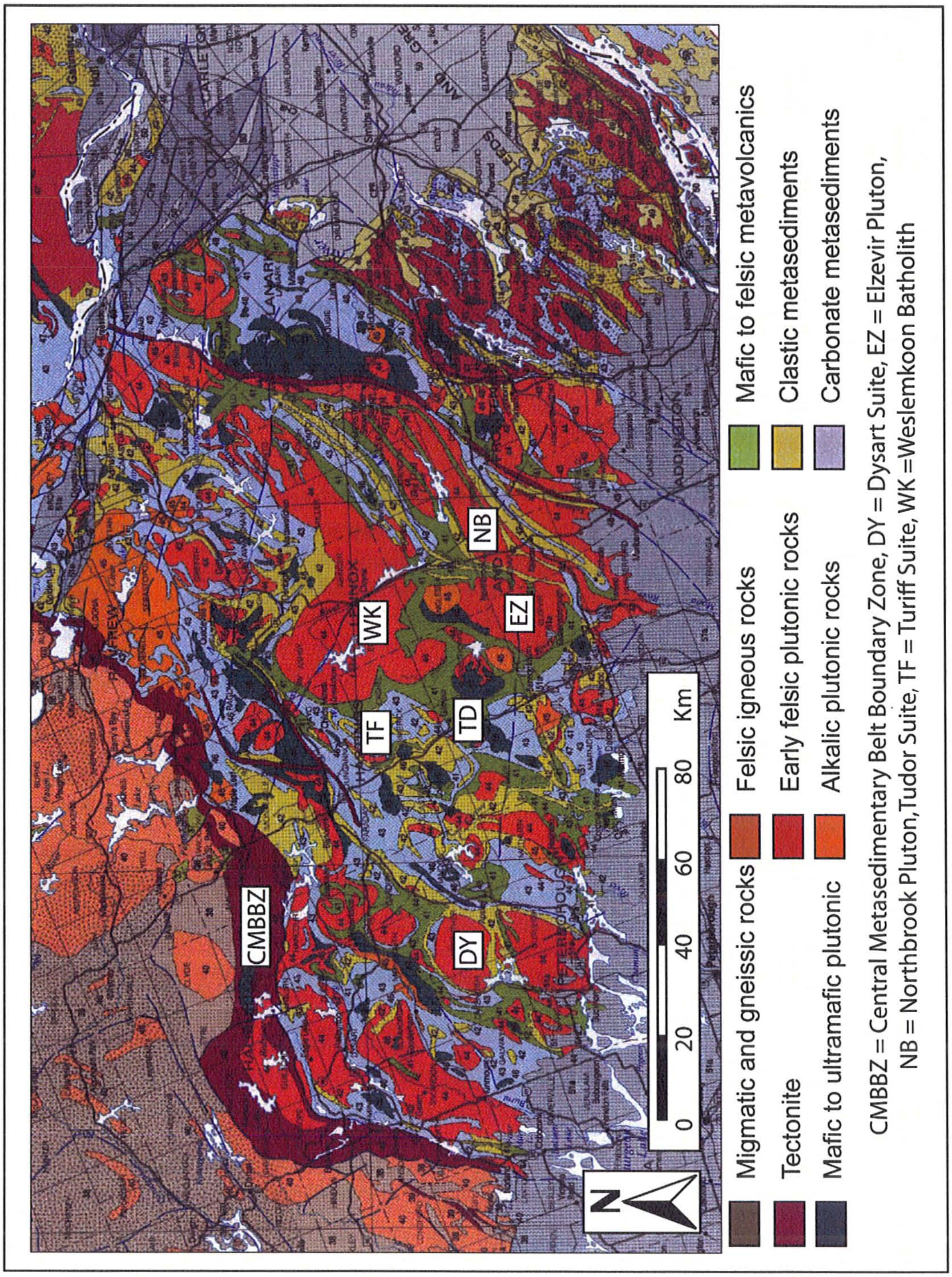

Figure 3.2: Geology of the CMB modified from Davidson (1998). Abbreviations refer to specific features of the CMB discussed following this figure.

3.1.1 - Tectonic Models

The Central Metasedimentary Belt (CMB) of Southern Ontario and its extension into western Quebec make up a large portion of the AMB as defined by Rivers et al. (1989). Various genetic and tectonic models have been applied to the AMB. A model of Composite Arc Belt (CAB) genesis has been applied to the CMB (Carr et al., 2000). The terranes within the CAB were defined by Easton (1990) and are flanked by the Frontenac Terrane to the southeast and the Central Gneiss Belt (of the APB) to the northwest (Figure 3.1). This model considers the terranes of the AMB to be allochthonous fragments on the basis of the shear zones which demarcate them.

Brown et al. (1975) in a very early study, used stratigraphic relationships and chemical analysis of mafic rocks to classify the tectonic framework of the Grenville Province in southeastern Ontario; an area which included the southern portions of the Weslemkoon Batholith and the northern portions of the Elzevir Batholith and Northbrook Pluton. The latter two bodies are separated by metavolcanics and the metasediments of the Flinton Group (see figure 3.2).

The model of Brown et al. (1975) is one of subduction at a convergent margin where pillow lava formed in an arc environment. They proposed that partial melting of the subducting slab and the resulting diapiric intrusion of granodioritic material (Elzevir and Weslemkoon Batholiths and the Northbrook Pluton) caused deformation and uplift. The deposition of the Flinton Group of shallow marine clastic-carbonates occurred during a hiatus between deformation episodes. Their model concludes with a terminal continental collision which closed the arc environment around 1050 ma. They identified lavas which are in contact with mafic and ultramafic rocks, implying the extrusion of the lava onto oceanic crust – their "relict oceanic lithosphere" (Brown et al., 1975).

An alternative model for these rocks was proposed by Baer (1976). He Pointed out that marble of the Grenville Supergroup (metasediments in figure 3.2), originally deposited in a restricted basin directly on basement gneiss, has a thickness of 15km near Bancroft to just a few km near the Morin massif in Quebec (Baer, 1976). Similarly, the metavolcanics, which include pillow lavas, rhyolite and andesite have a total thickness of 8 km. They were dated at c.a.1310 Ma (a date obtained during the infancy of radiometric lead dating by Silver and Lumbers, 1965) and are found southeast of Bancroft, but have not been recognized in Quebec (Baer, 1976).

Baer (1976) argued that the associations discussed between the metasedimentary, metavolcanic and intrusive suites is evidence of the opening and closure of a 'proto-Atlantic' basin (or aulacogen) that was well developed and had thus experienced greater subsidence in southwestern Ontario and terminated in northeastern Quebec. Further, clastic and carbonate metasediments which include occurrences of gypsum and anhydrite from the Adirondacks are found in association with metavolcanics indicative of a shallow restricted sea (Woussen et al., 1986) representing the possible extension of this aulacogen into the northern New York State. Baer (1976) concludes with his interpretation of the aulacogen as a failed arm off a triple junction which would be somewhere south of Lake Ontario.

Holm et al. (1986) sought to characterize the geochemistry of metavolcanics and dykes in the CMB which lie to the southwest of the Weslemkoon batholith. The Tudor and Turiff metavolcanics are found to be bimodal, the Tudor suite comprising theoleiitic basalt and dacite/rhyolite and the Turiff suite comprising theoleiitic basalt and calc-alkalic andesite/(minor rhyolite) while the dyke suite was found to be entirely theoleiitic basalt (Holm et al., 1986).

Niobium, Yttrium, and Zirconium concentrations were used to classify the basalts from each of these suites. Three alternative models were examined to account for the Nb, Y and Zr compositions: partial batch melting of an enriched mantle; partial melting of chondritic mantle followed by fractional crystallization of olivine, or partial melting followed by contamination of the melt by the crust (Holm et al., 1986). All three suites were found to have compositions originating from melts that were not in equilibrium with the mantle, due to inconsistent nickel concentrations, thus eliminating the proposed enriched mantle source and indicating instead, crustal contamination or fractional crystallization (Holm et al., 1986).

Bimodal volcanism is said to occur contemporaneously with crustal extension in a continental rift environment, and the study by Holm et al. (1986) proposes that they were erupted on sialic crust in a restricted marine basin. Since the bimodal metavolcanics are found spatially associated with a carbonate-clastic succession (which is what one would expect in a restricted sea contained within a continental rift environment) it was concluded that the elemental signatures measured in these three suites originated from partial melting in conjunction with back-arc continental rifting (Holm et al., 1986). Widespread mafic dyke intrusion is noted by Woussen et al. (1986) to accompany crustal extension and subarial volcanism, and occurs once there is an evolved active rifting process. These are associations clearly identified in the study by Holm et al. (1986).

Rivers and Corrigan (2000) reviewed the advances in understanding of the pre-Grenvillian history of the Grenville Province in the context of back-arc environments. An account of back-arc extension and basin formation is given by Rivers and Corrigan (2000) and is outlined below:

- Descent of the subducting slap results in convective heating in the back-arc
- Rise of aesthenospheric mantle results in decompression of mantle, doming and, extension parallel to the arc
- Upward transfer of mafic magma creates mafic dyke swarms (which are accommodated by extensional faults), crustal melt (due to heat transfer), bimodal suites of volcanic (rhyolitic and basaltic) rocks onto continental rocks, and eventually subarial flood basalts
- Crustal collapse of the heated, stretched continental crust facilitates marine incursion and thus submarine volcanism and sedimentation

Each of these stages in back-arc extension and rifting is expressed in the geology of the CMB. The rifting process produced theoleiitic metavolcanics in the Elzevir and Sharbot Lake terranes, while in the Mazinaw terrane there was coeval eruption of rhyolite (Holm et al., 1986 and; Rivers and Corrigan, 2000). These volcanic units are closely associated with pillow basalts, with carbonate and clastic sediments as well as preserved stromatolites in the Elzevir and Sharbot Lake terranes which imply the opening of a restricted marine basin which was compared to the Sea of Japan (Rivers and Corrigan, 2000).

Hanmer et al. (2000) worked to characterize the Andean-type margin active on the southeastern margin of Laurentia between 1400 – 1200 Ma and argue for the case of back-arc extension instead of arc-accretion for the CMB, which was inboard from the established Laurentian margin to the southeast.

The model of arc-accretion for the terranes of the CMB would consider the volcanic rocks of the Elzevir terrane as a fragment of an island arc, but as the studies discussed above have shown, there is much consistent evidence that these volcanics formed in a back-arc basin on thinned continental crust (Hanmer et al., 2000; Rivers and Corrigan, 2000; lumbers et al., 1990; Holm et al., 1986; Windley, 1986; Woussen et al., 1986; Baer, 1976 and; Brown, 1975).

Hanmer et al. (2000) also cite several orogen-wide events prior to the proposed dates of the suturing events between 1.2 Ga and 1.03 Ga (in the case of the CAB terranes being allochthonous). These events in the CMB can be traced across terrane boundaries, requiring that the terranes had been assembled prior to the onset of major compressional tectonics. They include:

- Pre-Grenville Supergroup potential basement with Nd model ages of 1.50 Ga and the remnants of a 1.35 Ga - 1.30 Ga continental arc
- Shallow water carbonates deposited on the basement between 1.30 Ga and 1.25 Ga
- the closure of a marginal basin at 1.20 Ga

These observations cannot be reconciled with a model of arc-accretion where the characteristics of each accreted terrain would be isolated within their structural domains.

The rift zone model of Dickin and McNutt (2007) proposes that the CMB is the expression of a juvenile ensimatic rift where *en echelon* juvenile crust and marble domains form two rift segments on either side of the Grimsthorpe Domain (GD) as depicted in figure 3.3. The extent of the rift can be traced beneath the Paleozoic cover in southern Ontario, Lake Ontario and into the United States as identified by seismic reflection profiling of the CMBBZ (western limit) and Maberly Shear Zone (eastern limit) which becomes the Clarendon-Lindon Fault System in the vicinity of Lake Ontario (Forsyth et al., 1994) and is identified in figure 3.3. The ensimatic nature of the rift zone is distinguished by Dickin and McNutt (2007) by the strongly juvenile Nd isotope signatures for orthogneisses indicating a crust which completely ruptured by extension. The northern extent of this rift (near Maniwaki, Quebec in figure 3.3) is marked by the limit of marble zones and a change from ensimatic petrology to ensialic petrology "where crust was thinned but not completely ruptured" (Dickin and McNutt, 2007; p.104).

Nd Isotope signatures indicating old crust in the Ontario composite arc belt are limited to the GD (Dickin and McNutt, 2007). Easton (1992) and Hildebrand and Easton (1995) had used the presence of Grenvillian shear zones bounding the GD to suggest that this domain is part of an allochthonous thrust sheet. However, isotopic study of the GD has revealed that there are juvenile isotopic signatures in the north eastern area, suggesting that the block is not allochthonous, since plutonism spans across the boundary between old and young Nd model age signatures (Dickin and McNutt, 2007). Further, marble outcrops (dark shading in figure 3.3) are found throughout the area of the proposed rift, but are distinctly absent from the GD. This would instead imply that the Elzevir Block represents a buried block of old crust that formed *in situ* prior to back arc extension and thus represents a horst structure (Dickin and McNutt, 2007).

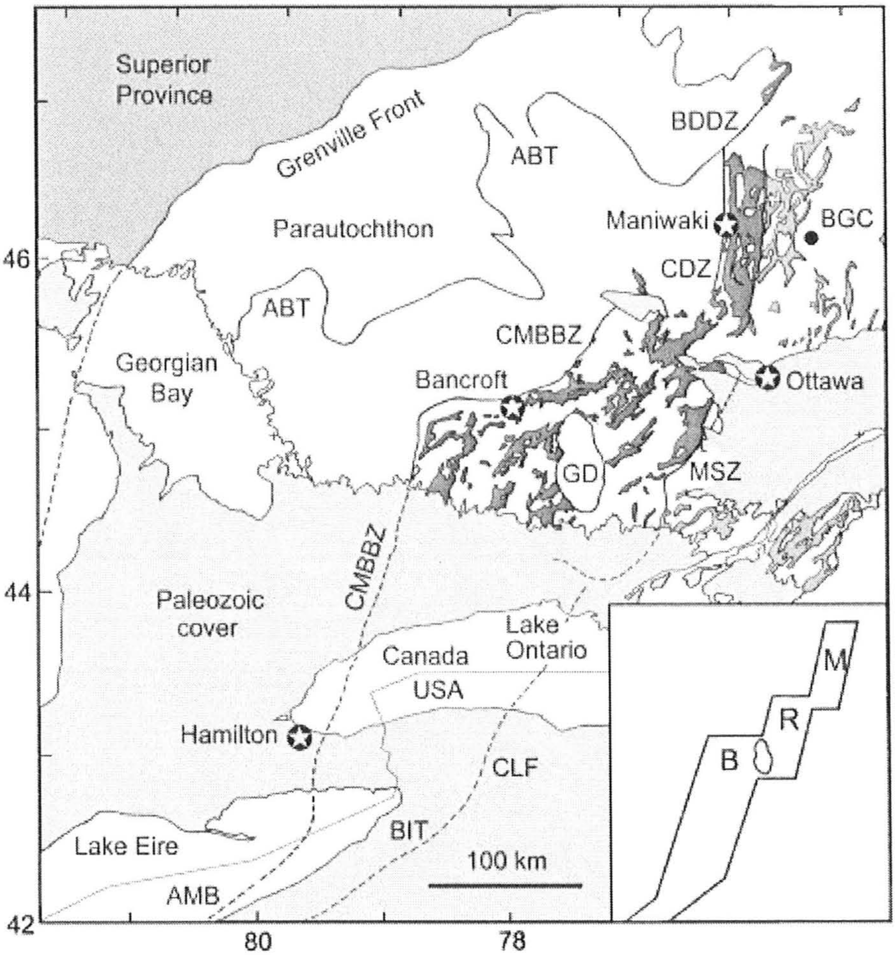

Figure 3.3: Map showing the extent of the rift zone as proposed by Dickin and McNutt (2007) and the proposed continuation of the CMB into the subsurface of the eastern US. Dark and medium shading = outcrops of Grenville marble (Davidson, 1998), which we interpret as within the rift zone or on its flanks, respectively. ABT = Allochthon Boundary Thrust; BDDZ = Baskatong-Desert Deformation Zone; CMBBZ = Central Metasedimentary Belt Boundary Zone; CDZ = Cayament Deformation Zone; MSZ = Maberly Shear Zone; GD = Grimsthorpe Domain; BGC = Bondy Gneiss Complex. Inset shows a tectonic interpretation in terms of *en echelon* rift segments (B = Bancroft; R = Renfrew; M = Maniwaki) separated by wrench zones. Subsurface lineaments are as follows: AMB = Akron Magnetic Boundary; BIT = Bass Island Trend; CLF = Clarendon-Linden Fault. Figure and figure caption are after Dickin and McNutt (2007).

3.1.2 – Study Focus of the Weslemkoon Area

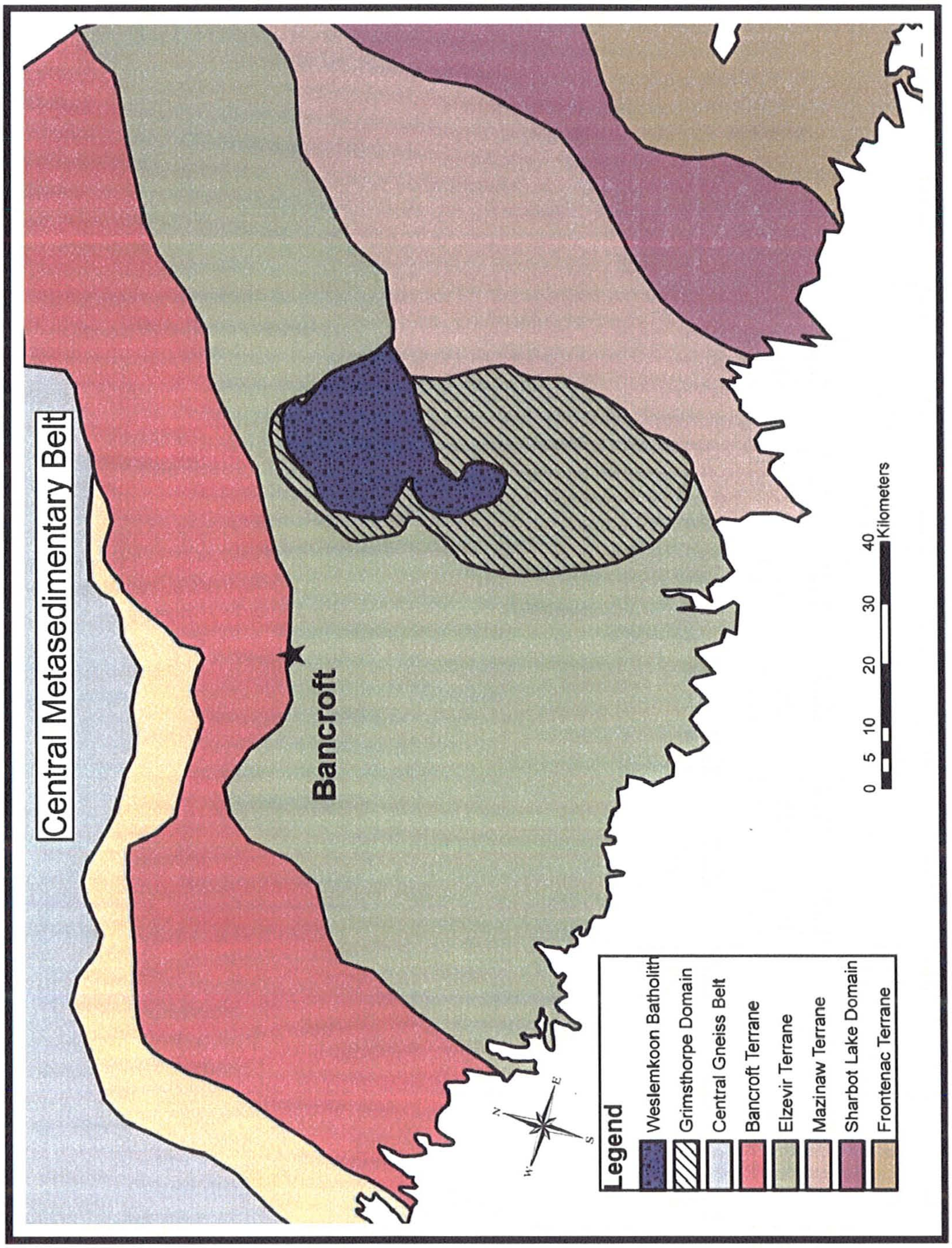

Figure 3.4: Map of the Weslemkoon study area showing the situation of the Weslemkoon Batholith within the Grimsthorpe Domain of the Central Metasedimentary Belt. The western limit of the rift zone (as proposed by Dickin and McNutt (2007) coincides with the boundary between the Bancroft and Elzevir Terranes, while the Maberly Shear Zone coincides with the boundary between the Sharbot Lake Domain and Frontenac Terrane.

This portion of the present study aims to map more precisely the extent of the old block in the Weslemkoon Batholith (WKB) of the GD to test the rift model proposed by Dickin and McNutt (2007). The location of the WKB as well as the GD can be identified in Figure 3.4 along with the proximal terranes.

The Weslemkoon Batholith is identified by Lumbers et al. (1990) as part of a suite of rocks considered to be late trondhjemite, which "makes up the largest volume of plutonic rocks within the CMB... which intrude all of the supracrustal rocks except those of the Flinton Group" (Lumbers et al., 1990 p. 259). While igneous crystallization ages given by U-Pb geochronology are not cited specifically for the Weslemkoon batholith, it is stated that the late trondhjemite suite plutons (which includes the Weslemkoon Batholith) all fall within the range of 1280 Ma - 1270 Ma (Lumbers et al., 1990).

A suite of alaskite is closely associated with this batholith to the east (which is mapped as an elongated 'early felsic pluton' that stretches away from the Weslemkoon Batholith in figure 3.2) and metavolcanics to the east and southeast (light green unit which surrounds the lower reaches of the Weslemkoon Batholith in figure 3.2) . They interpret this magmatic assemblage to have developed in a mantle activated rift from either necking of the lithosphere or lithospheric thinning due to a mantle plume (Lumbers et al., 1990). Major element analysis of the late trondhjemite and closely spatially associated alaskite suite show Sr, Al_2O_3/(CaO Na_2O K_2O) and Na/K ratios that define them as derived by either "sinking and partial melting of theoleiitic basalt in a mantle activated rift" or as generated in an island-arc complex (Lumbers et al., 1990). Theoleiitic metavolcanics in the Elzevir have been dated between 1290 -1289 Ma while less mafic trondhjemite, diorite and, granodiorite plutonic rocks were emplaced between 1280 Ma - 1230 Ma (Rivers and Corrigan, 2000).

3.2 – Results

Thirty one new Nd model age results are presented here for the Weslemkoon Batholith. These samples are supplemented by the dataset of Dickin and McNutt (2007), who first identified the presence of old crustal signatures within the Grimsthorpe Domain. The results of the analysis of the samples from the present study are presented in Table 3.1 and 3.2. Dickin and McNutt (2007) noted from a frequency plot of epsilon Nd, a correlation between their juvenile peak TDM average 1.25 Ga and the average U-Pb dates from Davis and Bartlett (1988) and Lumbers et al. (1990) for meta-igneous rocks within the CMB. They thus equate ages < 1.35 Ga to crust separated from the mantle immediately before the Grenville orogenic cycle. Therefore table 3.1 presents the Nd isotope analysis results for crust found to be juvenile (< 1.35 Ga) and table 3.2 presents such data for old crust (> 1.35). The reference age of 1.35 Ga is thought to be the oldest crystallization age found within the CMB as defined by U-Pb dating by Lumbers et al. (1990), and 'juvenile crust' is taken to be that crust which is a immediately predates the Grenville orogenic cycle and 'old crust' refers to crust which carries a significant pre-Grenvillian signature.

Table 3.1

Juvenile (<1.35 Ga)

MAP #	SAMPLE	EASTING	NORTHING	Nd (ppm)	Sm (ppm)	147Sm/144Nd	143Nd/144Nd	E(t) at 1.35	Tdm (Ga)
This Study: Juvenile									
1	WK35	18289760	4985076	11.91	2.50	0.1269	0.512336	6.18	1.24
2	WK24	18308548	4988631	13.56	1.80	0.0801	0.511945	6.65	1.25
3	WK11	18311053	4994818	7.78	1.56	0.1212	0.512282	6.12	1.25
4	WK8	18318093	4993204	10.73	1.80	0.1012	0.512112	6.28	1.26
5	WK5	18318277	4983466	13.52	2.12	0.0949	0.512060	6.33	1.26
6	WK33	18306680	4987411	9.26	1.84	0.1204	0.512268	5.98	1.27
7	WK12	18309575	4996302	9.39	1.72	0.1108	0.512171	5.76	1.29
8	WK32	18311091	4986325	9.70	1.80	0.1119	0.512162	5.41	1.32
9	WK7	18315029	4986351	7.62	1.54	0.1224	0.512247	5.24	1.33
10	WK9	18315994	4992436	10.69	1.93	0.1094	0.512128	5.16	1.34
11	WK18	18303934	4992265	7.82	1.21	0.0936	0.511982	5.07	1.34
12	WK29	18309993	4989884	14.08	1.84	0.0792	0.511861	5.20	1.34
Dickin and McNutt (2007): Juvenile									1.29
13	EZ13			27.50	7.20	0.1583	0.512632	6.50	1.13
14	CR4			34.70	7.93	0.1381	0.512455	6.53	1.19
15	EZBA37			23.40	3.38	0.0874	0.512061	7.58	1.19
16	CR5			60.50	8.94	0.0893	0.512063	7.29	1.20
17	MCM			72.40	15.00	0.1254	0.512342	6.51	1.21
18	ELP			15.80	2.81	0.1073	0.512197	6.80	1.21
19	EZ7			75.90	17.70	0.1410	0.512462	6.16	1.22
20	EZ3			8.60	1.63	0.1149	0.512247	6.47	1.23
21	EZ6			45.00	11.55	0.1550	0.512570	5.86	1.23
22	EZ29			87.00	21.27	0.1478	0.512509	5.91	1.23
23	EZ10			5.20	1.10	0.1289	0.512353	6.10	1.24
24	SLP			38.60	6.02	0.0942	0.512072	6.62	1.24
25	EZ1			13.20	2.20	0.1003	0.512120	6.50	1.24
26	EZ16			6.60	1.38	0.1252	0.512325	6.21	1.24
27	BTB			13.40	2.02	0.0914	0.512041	6.49	1.25
28	EZ30			9.60	1.97	0.1236	0.512256	5.10	1.33
29	EZ27			15.90	3.14	0.1193	0.512235	5.47	1.30
30	NBB			18.30	2.72	0.0899	0.511977	5.50	1.31
31	EZ33			13.50	2.34	0.1044	0.512106	5.50	1.31
32	EZ2			20.10	3.26	0.0985	0.512044	5.33	1.32
33	EZ4			18.10	2.90	0.0970	0.512028	5.27	1.33
34	EZBA36			36.70	8.58	0.1412	0.512408	5.07	1.33

Table 3.2

Old (>1.35 Ga)

MAP #	SAMPLE	EASTING	NORTHING	Nd (ppm)	Sm (ppm)	147Sm/144Nd	143Nd/144Nd	E(t) at 1.35	Tdm (Ga)
This Study: Old									
35	WK1a	18308770	4930900	9.39	1.09	0.0703	0.511761	4.75	1.36
36	WK13	18309115	4999242	9.28	1.80	0.1170	0.512182	4.89	1.36
37	WK31	18310377	4987857	12.30	2.21	0.1083	0.512103	4.85	1.36
38	WK30	18309560	4988789	10.84	1.87	0.1045	0.512058	4.63	1.37
	WK30*			14.53	2.52	0.1049	0.512060	4.79	1.36
39	WK17	18308106	4993917	10.18	2.13	0.1266	0.512253	4.62	1.38
40	WK10	18313698	4993201	6.18	1.27	0.1239	0.512227	4.58	1.38
41	WK40	18309080	4999326	9.66	1.73	0.1083	0.512085	4.69	1.39
42	WK6	18317077	4985280	8.77	1.69	0.1163	0.512153	4.46	1.40
43	WK28	18312365	4992914	5.05	1.02	0.1227	0.512208	4.42	1.40
44	WK41	18309860	4996482	6.31	1.27	0.1218	0.512192	4.26	1.41
45	WK22b	18301928	4985458	15.63	2.87	0.1108	0.512090	4.16	1.41
46	WK1	18308770	4983100	23.29	4.46	0.1158	0.512130	4.08	1.42
	WK1**						0.512140		
47	WK22a	18301928	4985458	14.79	2.21	0.0903	0.511890	3.81	1.42
48	WK20	18304371	4988261	11.71	2.35	0.1215	0.512162	3.72	1.45
49	WK26	18309108	4991021	5.34	1.14	0.1287	0.512222	3.65	1.47
50	WK0	18302538	4995785	15.25	2.76	0.1095	0.512033	3.28	1.47
51	WK2	18306160	4981850	12.61	2.17	0.1040	0.511978	3.18	1.48
52	WK23	18306586	4968122	19.03	3.27	0.1038	0.511942	2.51	1.52
53	WK39	18309900	5000731	21.86	4.08	0.1128	0.512012	2.49	1.56
From Dickin and McNutt: Old									
54	WKM	18302800	4994600	13.50	2.40	0.1077	0.51202	3.27	1.47
55	EZ21	19324400	4951600	13.30	2.33	0.106	0.511991	2.99	1.49
56	EZ28	19239000	4965500	12.90	2.25	0.1058	0.511975	2.71	1.51
57	EZ17	19317000	4938300	15.80	2.88	0.1098	0.512015	2.81	1.51
58	EZ14	19311400	4941800	24.60	4.71	0.1155	0.512057	2.64	1.53
59	EZ23	18303000	4968000	19.00	3.27	0.1038	0.511933	2.24	1.54

The results for the ratios $\frac{^{143}Nd}{^{144}Nd}$ and $\frac{^{147}Sm}{^{144}Nd}$ which are presented in tables 3.1 and 3.2 have been plotted on an Sm-Nd isochron diagram in figure 3.5. This figure shows a reference line representing the age of 1.25 Ga as found from the results of all the previously published data for Ontario juvenile crust (open green circles in figure 3.5). Samples from the present study with juvenile signature (model ages < 1.35 Ga expressed as closed blue circles in figure 3.5) fit closely with this array. Dickin et al. (2010) note that this clustering is consistent with the 'rift-filling mafic crust' reported to be 1.25 Ga – 1.29 Ga by Davis and Bartlett (1988) which host the juvenile crust. Samples with old crustal signatures (model ages > 1.35 Ga, expressed as squares in figure 3.5) plot as a distinct array below the juvenile data and display a greater degree of scatter.

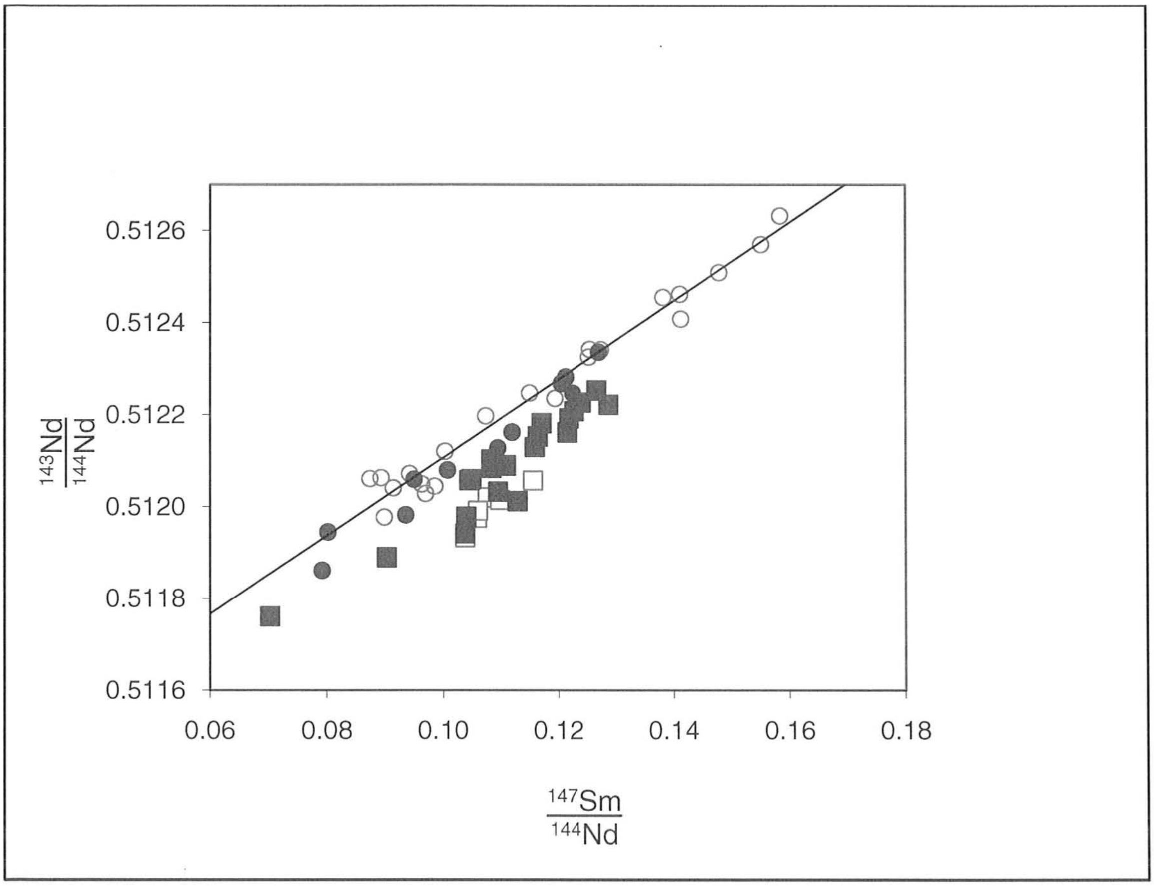

Figure 3.5: Isochron diagram for the Elzevir Terrane. Closed, blue symbols represent samples from the Weslemkoon Batholith analyzed in the present study, while open green symbols represent samples from the entire Elzevir Terrane following Dickin and McNutt (2007).

For further comparison, frequency plots for εNd values calculated at 1.35 Ga (the oldest known crystallization ages found in the CMB by Lumbers et al., 1990) have been constructed for the Weslemkoon Batholith (present study) and samples for the juvenile zone and the Elzevir Block (from Dickin and McNutt, 2007). The samples from the Dickin and McNutt (2007) suite form two distinct peaks, the left peak representing old crust (> 1.35 Ga) and the right representing juvenile crust (< 1.35 Ga), while the Weslemkoon Batholith forms a near normal distribution of samples around a peak representative of model ages of 1.37 Ga. The Weslemkoon sample suite defines a peak between the two peaks defined for the rest of the Composite Arc Belt. This indicates that the Weslemkoon Batholith spans across the boundary between the old crust component and the juvenile crust identified in the eastern part of the Grimsthorpe Domain by Dickin and McNutt (2007) (dark green within the right peak on the bottom section of the frequency plot).

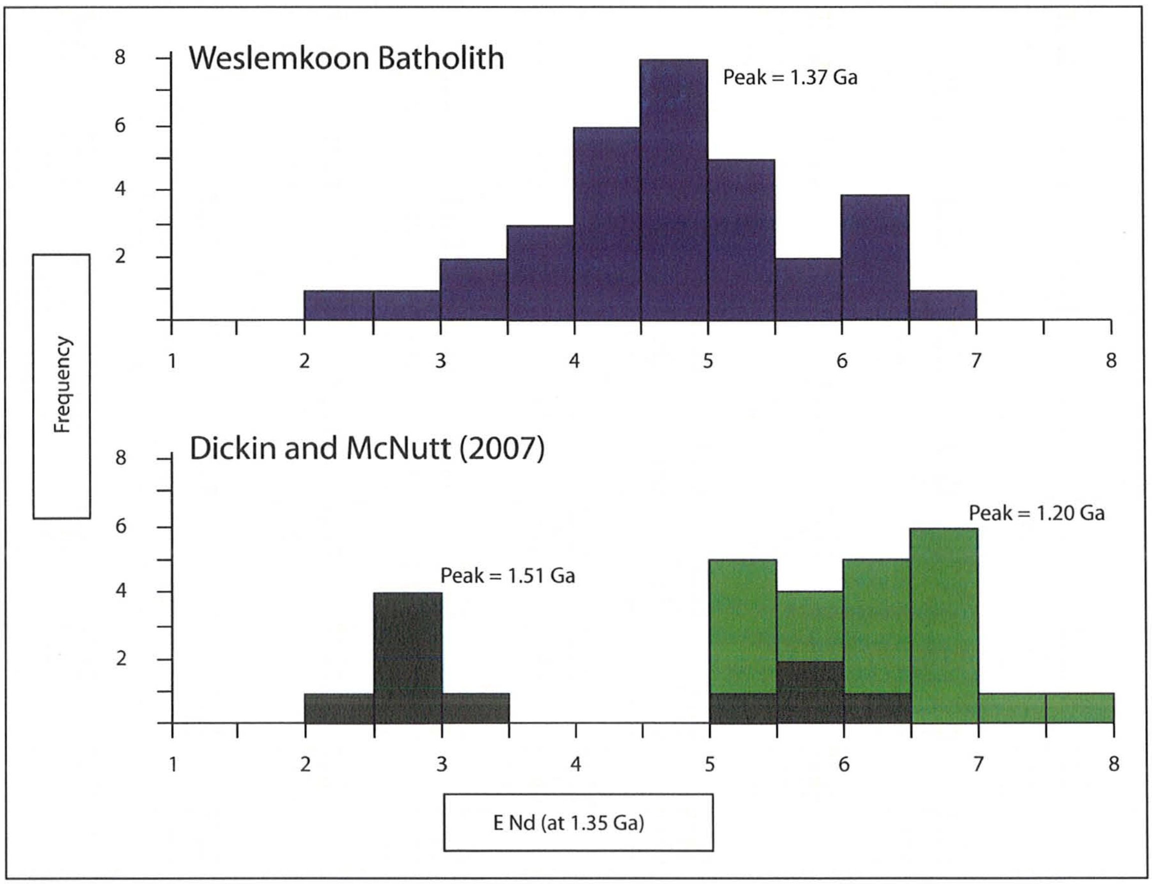

Figure 3.6: Frequency plots for εNd values calculated at 1.35 Ga. samples analysed by Dickin and McNutt (2007) represent juvenile samples from the rift zone (light green) and samples from within the Grimsthorpe Domain (dark green).

Results from the present study as well as the study by Dickin and McNutt (2007) for the Elzevir Terrane have also been plotted in a graph of εNd values (which reflect isotope enrichment or depletion relative to crust formed at 1.35 Ga) against Nd concentration (in ppm) in figure 3.7. As indicated above, the reference age of 1.35 Ga was utilized to calculate εNd values as it represents the oldest known crystallization age of rocks from the CMB. Previously published juvenile samples have distinct εNd ranges (between +5 and +8) but a large variation in Nd concentration (from 6.5 ppm to 87 ppm). This finding is consistent with the observation that samples from the juvenile sample suite of Dickin and McNutt (2007) have compositions ranging from plagioclase-rich granite to plagioclase-poor tonalite (as seen in figure 3.8). This contrasts with the samples from the current study which are defined by limited variation in Nd concentration (between 5 ppm and 23 ppm) but a large variation in εNd values (between +2.5 and +6.5). Such a limited variation in Nd concentration (as seen in the samples from the current study) is consistent with the samples being predominantly tonalite with a small occurrence of granodiorite (as seen in figure 3.8).

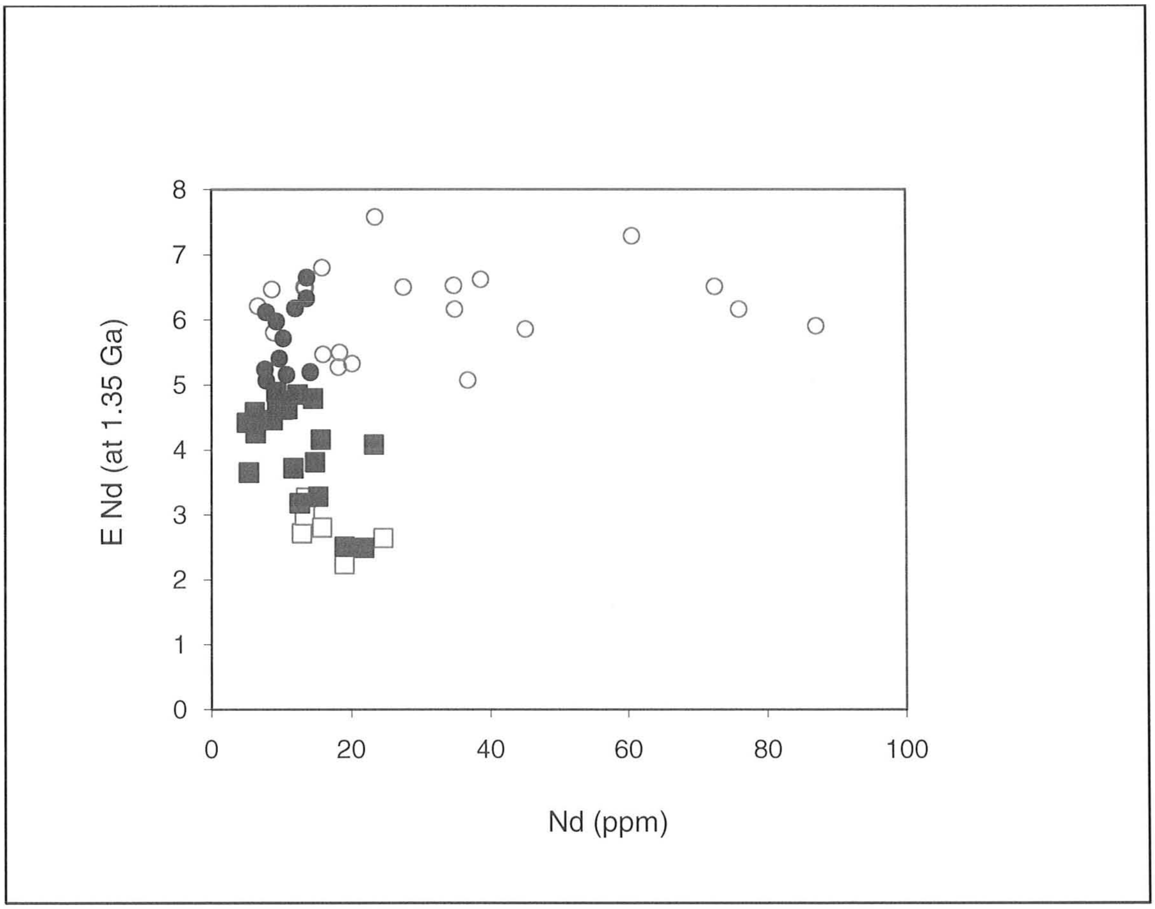

Figure 3.7: εNd (at 1.35 Ga) against the concentration of Nd (in ppm) from samples from the Weslemkoon study area (blue symbols) and the Elzevir Block of Dickin and McNutt (2007) (green symbols) that are distinguished as juvenile (< 1.35) which are represented as circles, or old (> 1.35) which are represented by squares.

Major element analysis was performed for select samples from the Weslemkoon sample suite and the sample suite of Dickin and McNutt (2007). The results of these analyses are presented in table 3.3. These results are plotted on a Q (quartz) and P (plagioclase) petrochemical grid (figure 3.8).

Juvenile (< 1.35 Ga) samples from the Weslemkoon Batholith (within the Grimsthorpe Domain) plot predominately within the tonalite field, with the exception of one sample which plots within the granodiorite field. Samples from the Weslemkoon Batholith with model ages > 1.35 Ga (indicating old crust) plot within the tonalite and granodiorite fields. The 'old' granodiorite samples are all found in the northern part of the batholith along with the sole juvenile granodiorite sample from the present study. As expected, samples taken from within the Weslemkoon Batholith form a relatively tight array reflecting their common magmatic history and less evolved composition. Of the samples of Dickin and McNutt (2007), which largely occur outside of the Grimsthorpe Domain, much greater scatter is observed. Juvenile (< 1.35 Ga) samples from the Dickin and McNutt (2007) sample suite plot throughout the quartz-rich fields of tonalite, granodiorite, monzogranite, while their samples with old crustal signatures (all of which are from the Grimsthorpe Domain) plot between the boundary of the tonalite and granodiorite fields into the monzogranite field.

Table 3.3

Analyte Symbol	SiO2	Al2O3	Fe2O3(T)	MnO	MgO	CaO	Na2O	K2O	TiO2	P2O5	LOI	Total	Ba	Sr	Y	Sc	Zr	Be	V	Si	K	Na	Ca	Q	P
Unit Symbol	%	%	%	%	%	%	%	%	%	%	%	%	ppm	ppm	ppm	ppm	ppm	ppm	ppm						
Juvenile Samples (< 1.35 Ga): This study																									
WK 5	68.47	16.09	2.67	0.035	1.20	3.57	4.78	1.50	0.390	0.12	0.74	99.57	323	481	4	4	122	1	38	1141.17	31.91	154.19	63.75	151.78	-186.03
WK 7	68.74	16.22	2.37	0.035	1.03	3.51	4.83	1.43	0.346	0.09	0.71	99.31	236	402	4	4	95	1	24	1145.67	30.43	155.81	62.68	153.87	-188.06
WK 9	70.47	15.60	2.42	0.043	0.73	2.77	4.97	1.88	0.299	0.09	0.65	99.92	242	434	6	5	109	2	28	1174.50	40.00	160.32	49.46	158.20	-169.79
WK 11	72.26	14.59	1.35	0.032	0.39	1.85	4.42	2.97	0.163	0.04	0.56	98.61	434	312	5	3	75	1	12	1204.33	63.19	142.58	33.04	173.65	-112.42
WK 18	68.23	16.11	2.42	0.031	1.02	3.24	4.99	1.38	0.306	0.08	0.90	98.69	219	339	2	5	105	1	23	1137.17	29.36	160.97	57.86	150.15	-189.46
WK 24	71.53	15.34	1.87	0.032	0.53	2.54	4.76	1.79	0.200	0.07	0.84	99.48	270	409	3	2	82	1	11	1192.17	38.09	153.55	45.36	175.52	-160.82
WK 27	71.69	14.47	2.14	0.040	0.66	2.32	4.54	1.73	0.267	0.08	0.72	98.64	228	358	4	3	112	2	18	1194.83	36.81	146.45	41.43	187.40	-151.07
WK 29	71.61	14.49	1.76	0.026	0.59	2.63	4.85	1.32	0.224	0.08	1.01	98.60	258	456	3	2	92	1	18	1193.50	28.09	156.45	46.96	181.99	-175.33
WK 32	68.46	16.65	2.39	0.033	1.13	3.73	4.94	1.28	0.331	0.10	0.91	99.95	216	394	4	5	106	1	28	1141.00	27.23	159.35	66.61	149.34	-198.73
WK 33	70.71	15.75	2.06	0.036	0.68	2.68	4.78	2.03	0.256	0.08	0.86	99.92	333	430	5	3	88	1	18	1178.50	43.19	154.19	47.86	163.54	-158.86
Juvenile Samples (<1.35 Ga): Dickin and McNutt (2007)																									
NBB	70.61	13.94	2.22	0.035	1.02	1.94	4.13	2.74	0.256	0.09	1.84	98.84	631	274	6					1176.83	58.30	133.23	34.64	177.66	-109.57
BTB	72.90	15.10	1.25	0.018	0.46	2.67	4.94	2.01	0.178	0.07	0.43	100.03	950	787	2					1215.00	42.77	159.35	47.68	171.09	-164.27
BUR	68.90	13.90	3.96	0.089	1.17	2.84	4.48	2.38	0.541	0.13	0.40	98.78	443	210	43					1148.33	50.64	144.52	50.71	153.81	-144.59
MCM	69.79	13.34	3.75	0.062	0.56	1.54	3.81	5.00	0.576	0.10	0.40	98.92	1210	273	61					1163.17	106.38	122.90	27.50	140.10	-44.02
ELP	70.89	13.91	3.68	0.047	0.79	2.67	4.38	1.66	0.305	0.13	0.66	99.12	322	220	14					1181.50	35.32	141.29	47.68	185.44	-153.65
SLP	68.32	14.98	3.14	0.039	0.88	1.96	4.43	4.52	0.373	0.17	0.70	99.52	1167	561	23					1138.67	96.17	142.90	35.00	117.15	-81.73
CR4	70.19	13.19	2.07	0.104	1.03	2.42	5.34	3.32	0.542	0.09	1.11	99.41	759	98	45					1169.83	70.64	172.26	43.21	118.24	-144.83
CR5	68.87	14.25	2.22	0.035	0.78	2.06	3.80	5.74	0.392	0.14	1.32	99.60	1701	1115	42					1147.83	122.13	122.58	36.79	113.38	-37.24
MU10	71.16	15.02	2.48	0.029	0.88	3.40	4.62	1.33	0.190	0.07	0.63	99.81	351	309	4					1186.00	28.30	149.03	60.71	177.53	-181.45
EZ1	73.16	13.57	2.03	0.044	0.82	1.50	5.04	2.07	0.284	0.07	1.24	99.82	337	120	9					1219.33	44.04	162.58	26.79	181.96	-145.32
EZ2	72.40	14.40	2.13	0.033	0.58	2.57	3.84	2.85	0.176	0.05	0.75	99.77	788	245	14					1206.67	60.64	123.87	45.89	187.12	-109.13
EZ3	69.54	15.45	2.44	0.022	1.38	2.57	5.11	1.61	0.306	0.08	0.98	99.49	254	312	4					1159.00	34.26	164.84	45.89	156.64	-176.48
EZ4	68.22	16.03	2.70	0.035	1.25	3.55	5.05	1.35	0.333	0.10	0.91	99.52	163	306	6					1137.00	28.72	162.90	63.39	145.11	-197.57
EZ6*	78.22	11.70	1.23	0.006	0.16	0.38	5.25	1.91	0.074	0.02	0.44	99.40	81	53	96					1303.67	40.64	169.35	6.79	220.04	-135.50
EZ7	73.96	12.01	2.81	0.040	0.40	0.73	4.01	3.94	0.202	0.02	1.13	99.25	511	33	123					1232.67	83.83	129.35	13.04	189.01	-58.56
EZ13	72.28	13.07	2.97	0.060	0.65	2.00	3.91	3.26	0.307	0.12	1.03	99.66	381	96	56					1204.67	69.36	126.13	35.71	182.26	-92.48
EZ16	72.51	14.69	0.83	0.007	0.44	1.62	7.10	0.75	0.178	0.08	1.56	99.76	62	102	5					1208.50	15.96	229.03	28.93	138.56	-242.00
EZ27	62.53	15.82	5.01	0.065	3.03	4.82	4.46	2.05	0.598	0.17	1.09	99.63	328	436	15					1042.17	43.62	143.87	86.07	102.52	-186.33
EZBA36	58.85	17.62	8.21	0.164	3.93	2.91	2.92	1.87	0.987	0.28	2.26	99.98	438	189	47					980.83	39.79	94.19	51.96	158.32	-106.37
EZBA37	70.13	15.98	1.79	0.027	0.78	3.24	5.25	1.38	0.249	0.09	0.86	99.76	398	921	3					1168.83	29.36	169.35	57.86	152.32	-197.85
EZ29	73.95	11.50	2.69	0.025	0.20	0.86	4.10	4.27	0.172	0.02	1.15	98.92	340	22	174					1232.50	90.85	132.26	15.36	177.49	-56.76
Old Samples (>1.35 Ga): This study																									
WK 1	72.80	14.53	1.97	0.035	0.60	1.89	3.86	3.48	0.217	0.07	0.49	99.95	340	196	3	3	113	1	10	1213.33	74.04	124.52	33.75	183.39	-84.22
WK 1A	73.12	14.64	1.72	0.022	0.64	2.75	4.36	1.65	0.257	0.07	0.74	99.96	207	278	2	1	93	2	13	1218.67	35.11	140.65	49.11	197.73	-154.65
WK 2	69.64	14.64	2.66	0.045	1.03	2.84	3.72	3.24	0.370	0.12	0.92	99.22	472	288	6	5	144	2	25	1160.67	68.94	120.00	50.71	164.14	-101.78
WK 6	69.36	16.15	1.99	0.029	0.85	3.35	5.04	1.28	0.285	0.09	0.54	98.95	252	372	4	5	102	1	27	1156.00	27.23	162.58	59.82	155.64	-195.17
WK 13	67.50	16.47	2.47	0.032	1.11	3.43	4.44	1.73	0.327	0.10	0.91	98.51	308	369	5	4	104	1	21	1125.00	36.81	143.23	61.25	154.13	-167.67
WK 17	65.91	17.15	3.45	0.054	1.56	3.91	4.80	1.67	0.471	0.10	0.86	99.94	224	365	7	7	130	2	37	1098.50	35.53	154.84	69.82	129.25	-189.13
WK 20	63.95	17.74	3.41	0.058	1.66	4.70	4.56	1.42	0.473	0.12	0.76	98.86	267	414	6	7	117	1	37	1065.83	30.21	147.10	83.93	122.02	-200.81
WK 22A	69.23	15.12	2.74	0.035	1.08	3.33	4.08	1.82	0.378	0.11	0.93	98.85	218	323	5	4	141	2	23	1153.83	38.72	131.61	59.46	174.63	-152.35
WK 22B	65.29	16.13	3.66	0.051	1.66	3.77	4.06	2.32	0.484	0.15	1.23	98.81	355	291	9	7	173	2	38	1088.17	49.36	130.97	67.32	137.51	-148.93
WK 26	71.83	14.94	1.35	0.031	0.37	2.08	4.53	2.98	0.158	0.05	0.79	99.12	361	328	3	3	69	2	13	1197.17	63.40	146.13	37.14	164.76	-119.87
WK 28	71.92	14.94	1.33	0.029	0.39	2.10	4.51	2.83	0.165	0.05	0.66	98.93	503	371	4	3	76	2	13	1198.67	60.21	145.48	37.50	168.86	-122.77
WK 30	71.13	15.12	1.65	0.034	0.53	2.62	4.62	2.17	0.183	0.07	0.91	99.05	389	367	4	3	76	1	13	1185.50	46.17	149.03	46.79	168.77	-149.65
WK 31	67.37	16.37	2.76	0.035	1.22	3.70	4.54	1.62	0.378	0.10	1.08	99.17	252	356	3	5	112	1	34	1122.83	34.47	146.45	66.07	149.31	-178.05
Old Samples (>1.35 Ga): Dickin and McNutt (2007)																									
EZG	66.95	15.61	3.39	0.047	1.51	3.6	4.57	1.82	0.518	0.16	0.82	98.98	301	403	9					1232.50	90.85	132.26	15.36	177.49	-56.76
WKM	73.9	13.2	1.41	0.022	0.38	1.38	3.33	4.70	0.163	0.05	0.33	98.85	451	146	7					1042.17	43.62	143.87	86.07	102.52	-186.33
EZ 5	66.66	16.34	3.15	0.046	1.61	3.73	4.98	2.03	0.391	0.13	0.68	99.75	391	487	10					1111.00	43.19	160.65	66.61	122.09	-184.06
EZ 28	70.24	14.84	2.24	0.036	1.02	2.28	4.16	3.51	0.296	0.09	1.24	99.95	362	276	7					1170.67	74.68	134.19	40.71	154.20	-100.23
EZ 21	69.53	15.14	2.63	0.039	1.11	2.69	4.83	2.31	0.404	0.12	0.93	99.74	368	399	6					1158.83	49.15	155.81	48.04	149.30	-154.69
EZ 17	72.13	13.3	1.91	0.028	0.67	1.63	3.82	3.85	0.261	0.06	1.62	99.27	311	133	11					1202.17	81.91	123.23	29.11	176.18	-70.42
EZ 14	66.32	15.71	3.87	0.050	1.74	3.69	4.26	2.12	0.635	0.17	1.37	99.93	281	293	15					1105.33	45.11	137.42	65.89	141.99	-158.21

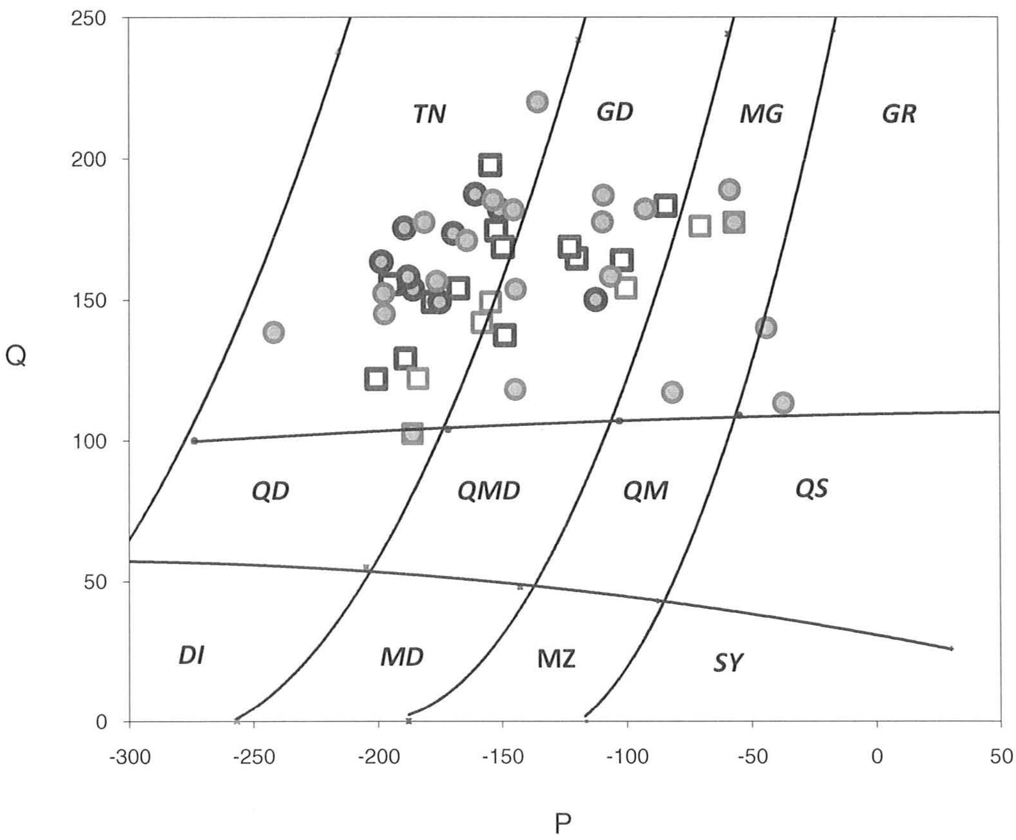

Figure 3.8: Q (quartz) – P (plagioclase) petrochemical classification grid after Debon and LeFort (1983) for samples from the Weslemkoon Batholith sample suite (blue symbols) and samples from the Elzevir Terrane as analysed by Dickin and McNutt (2007) (green symbols). TN=tonalite; GD=granodiorite; MG=monzogranite; GR=granite; QD=quartz diorite; QMD=quartz monzodiorite; QSY=quartz syenite; DI=diorite; MD=monzodiorite; SY=syenite.

3.3 – Discussion

The current study aimed to investigate the extent of old (> 1.35 Ga) crust which was first identified within the Grimsthorpe Domain of the CMB by Dickin and McNutt (2007) and the distribution of juvenile model age signatures within the vicinity of this domain to test the validity of the rift model which they applied to the CMB. Previously models by Easton (1992) and Hildebrand and Easton (1995) viewed the CMB as a composite arc belt made up of accreted and transported terranes which could account for the Grimsthorpe Domain as an allochthonous sheet thrust onto the Elzevir Terrane. If the Grimsthorpe Domain was indeed an allochthonous thrust sheet, then the isotope signatures from samples taken within this domain should be isolated within its boundaries. For the Grimsthorpe Domain to be classified as a horst structure surrounded by the two juvenile rift segments proposed by Dickin and McNutt (2007), the isotope signatures found within the Grimsthorpe Domain must be shown to have formed *in situ* and have common model age signatures with terranes outside the CMB. Since the Weslemkoon Batholith extends outside the boundaries of the Grimsthorpe Domain, this is an ideal location to test this model.

Justification for the existence of a distinct block of old crust as well as the coherency of the juvenile data set from within the Weslemkoon Batholith (from the present study) and from the juvenile rift zone of the Elzevir Terrane (from Dickin and McNutt, 2007) is provided by the isochron diagram (figure 3.5), plot of frequency vs. εNd (figure 3.6), plot of εNd vs. concentration of Nd (figure 3.7) and the petrochemical classification plot (figure 3.8). In each of these diagrams, one can identify that the samples with juvenile model ages from the present study form arrays that are collinear with the juvenile samples of Dickin and McNutt (2007), while the old crust forms distinct arrays differing from that of the juvenile crust.

Figure 3.9 is a map of the study area showing sample locations, model ages and the extent of old crust and juvenile crust within the Weslemkoon Batholith and Grimsthorpe Domain. Figure 3.10 is an enlarged map of the Weslemkoon Batholith where map numbers reference the data back to tables 3.1 and 3.2. The boundary between granite samples bearing the isotopic signature of old and juvenile crust can be seen to form a ringed and inter-fingered expression of two pulses of magma into the Grimsthorpe Domain. Figure 3.11 is a cross section representing the evolution of the Weslemkoon Batholith.

Juvenile samples are isolated to the northeastern portion of the batholith as depicted in figure 3.10. This juvenile block stretches past the shear zone which marks the boundary of the Grimsthorpe Domain, requiring that this is an *in situ* block of crust. The old model ages (> 1.35 Ga) correspond with both the Laurentian margin (Laurentia in figure 2.3) and the Frontenac - Adirondack Belt (figure 3.1) which flank the proposed rift segment. The spatial relationship of these units is outlined with their ages in figure 3.11. Dickin et al. (2010) reports model ages for the Muskoka domain of the Laurentian margin as well as the Frontenac - Adirondack Belt whose average model ages are 1.51 Ga and 1.44

Ga respectively and whose average εNd values are +2.9 and +3.8 respectively. The average model age for old crust samples from the present study is 1.48 Ga while the average εNd value is 3.8. The similarities between the results from the Laurentian margin and the Frontenac - Adirondack Belt, which would form the flanks of the proposed rift and the old block from this study which is found within the Grimsthorpe domain is further compelling evidence that this block is indeed a horst structure and not an allochthon.

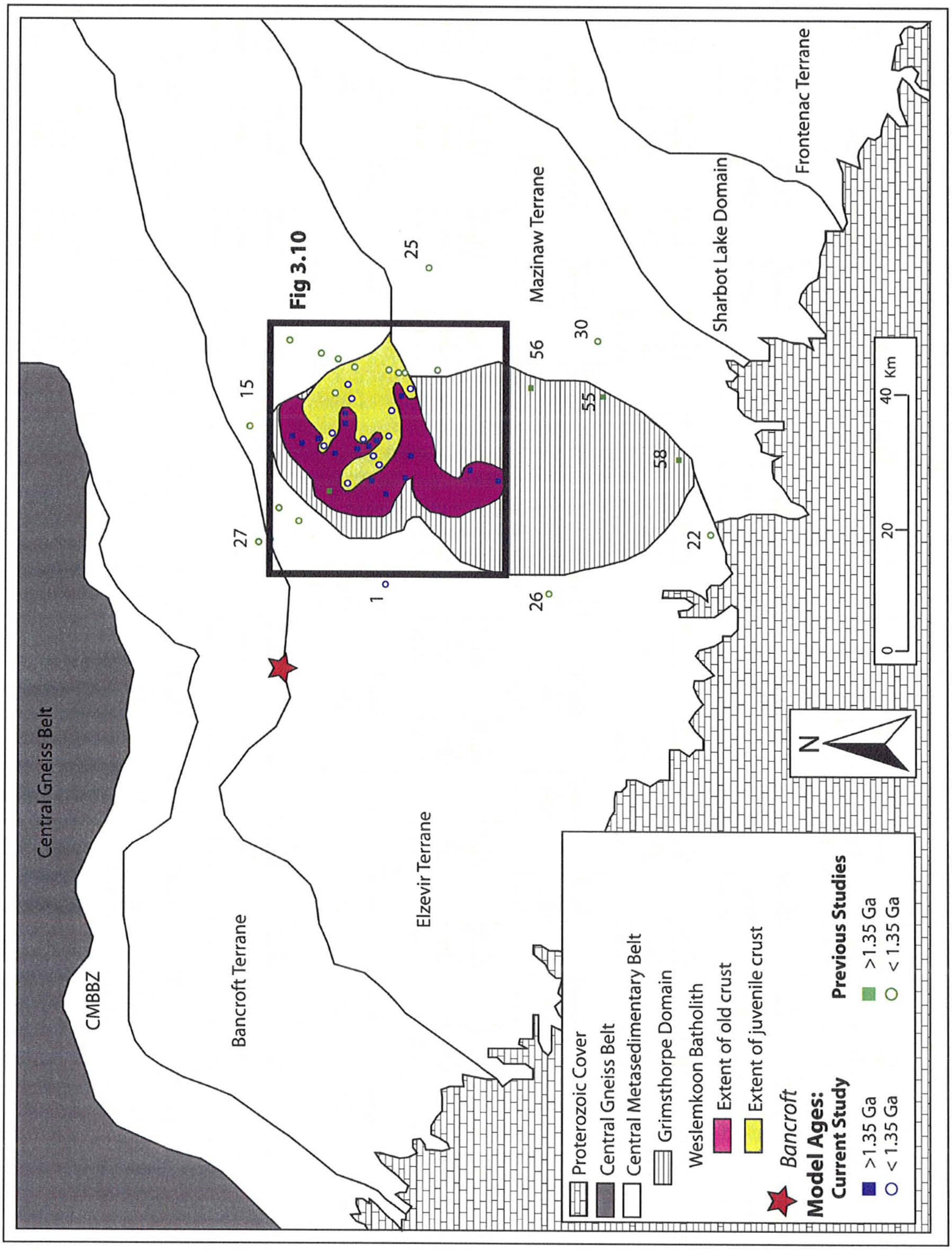

Figure 3.9: Map of the Central Metasedimentary Belt showing the location of the Grimsthorpe Domain, sample distribution and the extent of old and juvenile crust within the Weslemkoon Batholith. Samples plotted are from the current study and Dickin and McNutt (2007). Map numbers refer to data in tables 3.1 and 3.2.

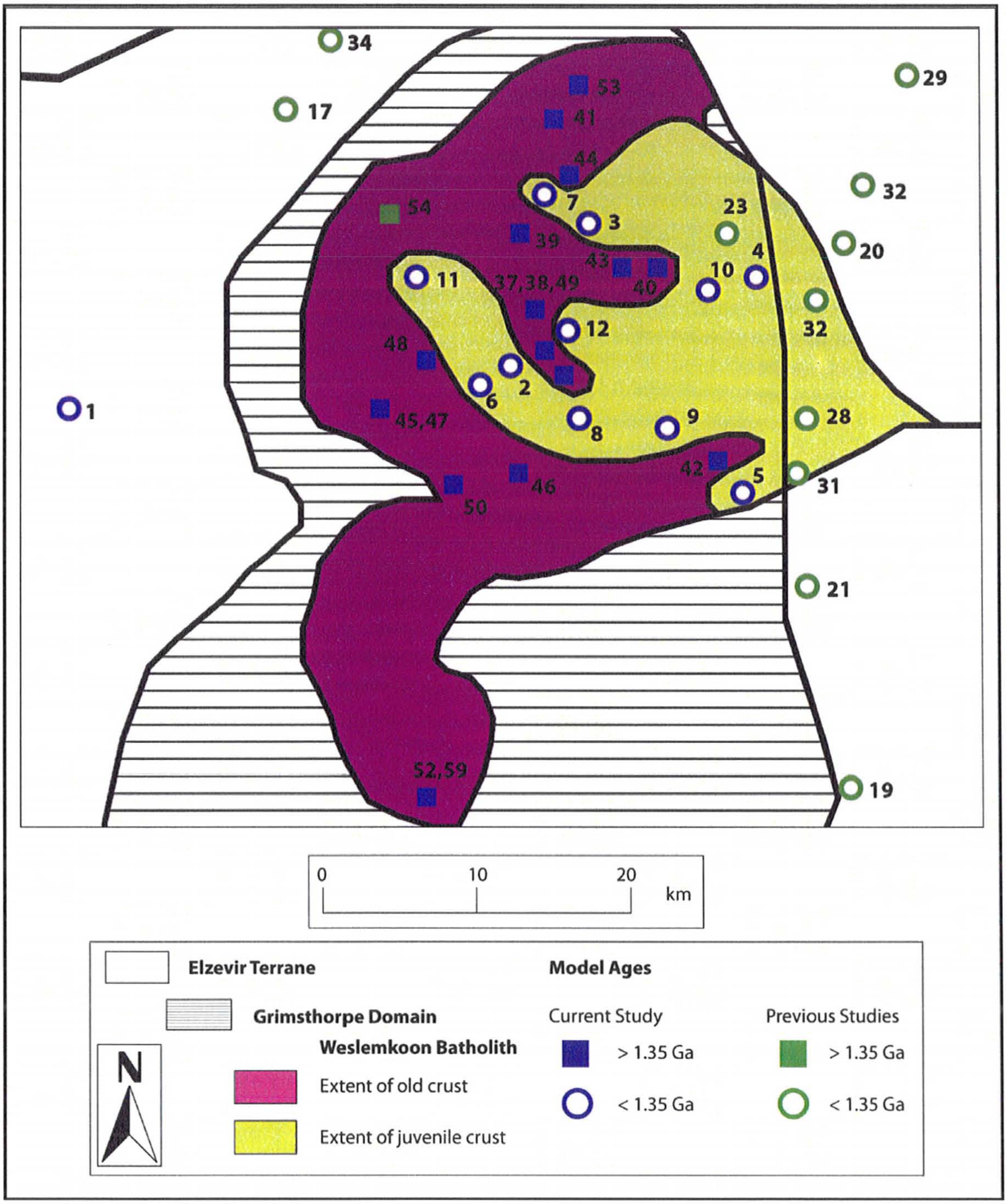

Figure 3.10: Detailed map of the Weslemkoon Batholith. The image has been enlarged to show map numbers referring samples back to table 3.1 and 3.2 and the relationship of the bounding shear zones of the Grimsthorpe Domain in relation to the extent of old and juvenile crust within the Weslemkoon Batholith.

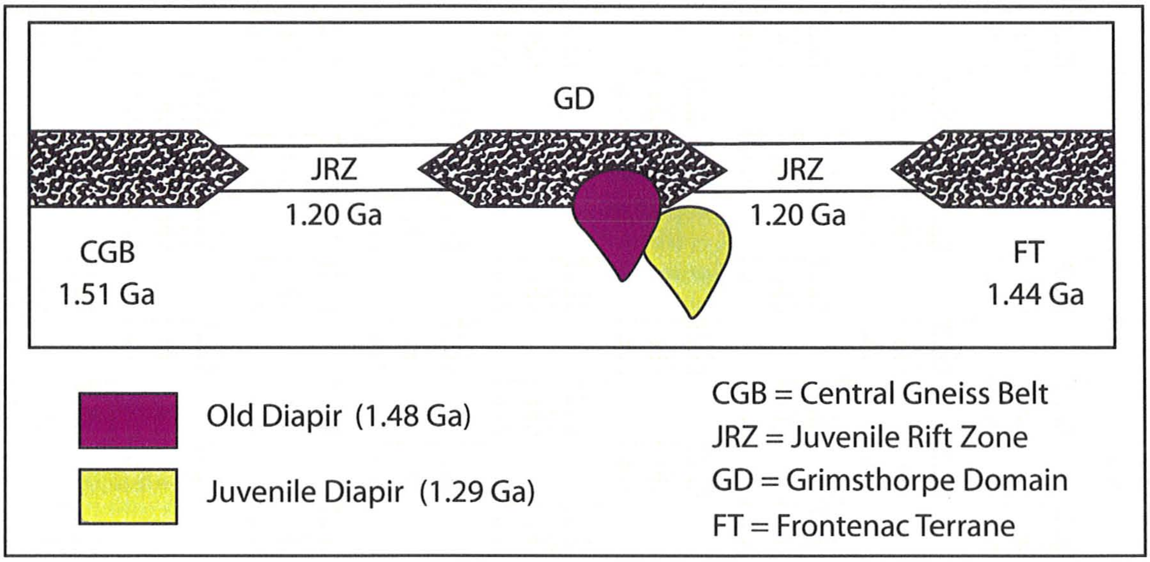

Figure 3.11: Cross section showing the Central Gneiss Belt, Juvenile Rift Zone, Grimsthorpe domain and the magma diapirs of the Weslemkoon Batholith.

Chapter 4: Saguenay and Baie Comeau Study Areas, Quebec

4.1 - Background

The Saguenay and Baie Comeau regions make up a portion of the Central Granulite Terrane and the Baie Comeau Segment of Wynne-Edwards (1972) respectively and are found within the Allochthonous Polycyclic Belt of Rivers et al. (1989). This area in central Quebec has long been considered a 'sea of gneiss', but effort has been extended in the last 40 years to unravel its complex history, identifying a prolonged history of plutonism, dyking, sedimentation, faulting and metamorphism.

Previous studies have put much emphasis on the evolution of the Saguenay region based on anorthosite-mangerite-charnockite-granite (AMCG) magmatism, which dominates the area and is also present to a lesser degree within the Baie Comeau region. AMCG magmatism is expressed as a large belt of plutonic bodies throughout the Allochthonous Polycyclic Belt. This belt was emplaced in several generations of magmatism to be discussed below.

4.1.1 – The AMCG Suites

AMCG magmatism within the Grenville Province occurs in the following sequence of events, as defined by Hebert et al. (2005) and Morisset et al. (2009):

- 1354 Ma Riviere-Pentecote Anorthosite Suite
- 1327 Ma De La Blache Mafic Plutonic Suite
- 1160 – 1135 Ma Lac St. Jean Anorthosite Suite and Morin Massif
- 1082 – 1045 Ma St. Urban – Havre-Saint-Pierre episode which includes the St. Urban Anorthosite, Havre-Saint-Pierre Anorthosite, the La Baie Granite and, the Chicoutimi Mangerite
- 1020 – 1008 Ma Valin Anorthosite Suite which includes the Mattawa Anorthosite and Labrieville Alkalic Anorthositic Massif

The suites from this sequence of events can be identified in figure 4.1. The Riviere-Pentecote anorthosite-leuconorite-leucotroctolite intrusion was dated using U-Pb zircon analysis by Martignole et al. (1993) to between 1350 Ma and 1375 Ma. The above sequence of events from Hébert et al. (2005) and Morisset et al. (2009) summarizes AMCG magmatism resulting from the Shawinigan Orogeny (1140 Ma – 1190 Ma) and Ottawan phase (1020 Ma – 1090 Ma) of the Grenville orogenic cycle and includes both the De la Blache Mafic Plutonic Suite and the Riviere-Pentecote intrusion which correspond with earlier, Elsonian/Elzevirian magmatism in Labrador which spanned the period between 1460 Ma – 1290 Ma (Martignole et al., 1993) and 1250 Ma - 1190 Ma (Rivers, 1997) respectively.

Of the Shawinigan and Ottawan related episodes, the Lac St. Jean Anorthosite episode and the St. Urban – Havre-Saint-Pierre episode are found within the Saguenay area of the present study. The east – west elongated Baie Comeau Anorthosite intrusion (found in the Baie Comeau area of the present study) is found just to the southeast of the De la Blache Mafic Plutonic suite and the Berte and Raudot anorthosites are found to the northeast. While the mineralogy of the Baie Comeau, Berte and Raudot intrusions have been defined (Francis et al., 2000), they remain undated within the literature and thus remain unclassified within the above sequence of events.

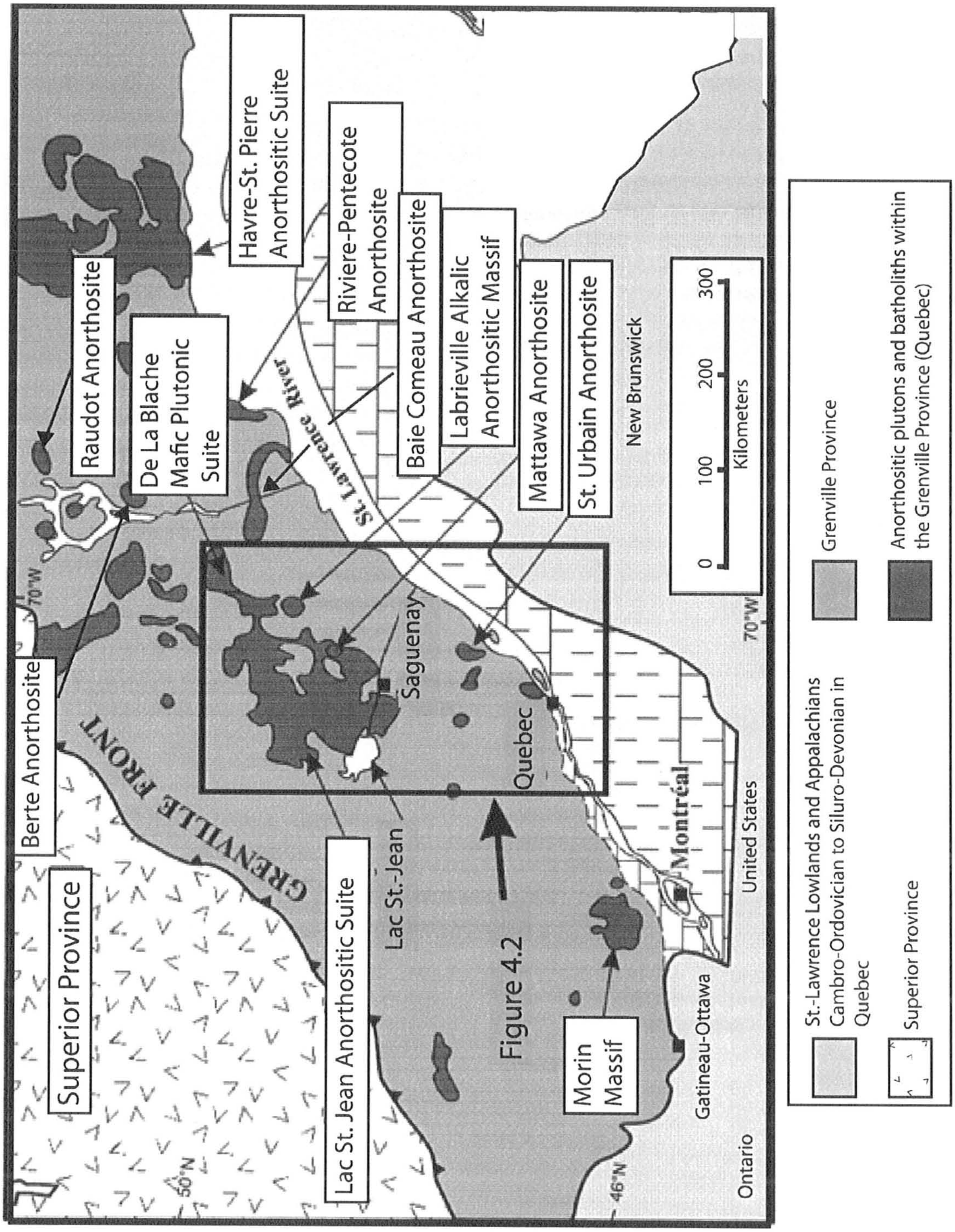

Figure 4.1: Identification of the major AMCG bodies in the Grenville Province (Higgins and van Breemen, 1996); The Raudot Anorthosite and Berte Anorthosite are labelled after Francis et al. (2000). The outline corresponds with figure 4.2.

The De la Blache Mafic Plutonic suite (DBMP), originally considered part of the Lac St. Jean Anorthosite suite (LSJA) (figure 4.1), has been shown by Gobeil et al., (2002) to predate the LSJA and represent an independent mafic plutonic event dated to 1327 Ma. This event was dominated by 'massive labrodorite-type' anorthositic magmatism where felsic rocks comprise less than 5 percent of the pluton (Hébert et al., 2005).

The Lac St. Jean Anorthosite (figure 4.1) was emplaced during the period 1160 – 1135 Ma by several magma injections (Hébert et al., 2005) and is related to the Shawinigan orogeny (1190 – 1140 Ma) (Morisset et al., 2009). The LSJA is further host to several weakly to undeformed 'within plate' granitoid plutons (Higgins and van Breemen, 1996) which will not be considered here. In contrast to the 'massive labrodorite-type' magmatism of the DBMP event, this event was dominated by 95 percent anorthosite and leuconorite magmatism (Hébert et al., 2005).

The St. Urban – Havre-Saint-Pierre episode (related to the Ottawan 1082 Ma – 1045 Ma event) includes the emplacement of the La Baie Granite and the Chicoutimi Mangerite within the Saguenay region, and the St. Urbane Anorthosite and Havre-Saint-Pierre Anorthosite in the Baie Comeau region (figure 4.1).

The youngest of the episodes is represented by the Valin Anorthosite Suite (figure 4.1) which was emplaced between 1020 – 1008 Ma during the collapse of an orogenic plateau formed during Rigolet event (Morisset et al., 2009). While Anorthositic magmatism dominates this suite, there are minor monzonite and charnockite intrusions (Hébert et al., 2005).

The sheer scale of the anorthosite and related intrusions, which can be seen to dominate the area featured within figure 4.2, accounts for the focus of much previous research in central Quebec being on such intrusions. It is proposed that the AMCG magmatism occurred during a time of crustal formation in an ensialic arc. Such a crustal building regime is a typical setting for AMCG magmatism (e.g. Roy et al., 1986; Corrigan and Hanmer, 1997). The tectonic environment prior to this plutonism has only been subject to in-depth study within the past 20 years and is considered to be one of crustal building through ensimatic arc accretion (Dickin and Higgins, 1992; Dickin, 2000; Higgins et al., 2002; Hébert and van Breemen, 2004; Martin and Dickin, 2005; and Dickin et al., 2010).

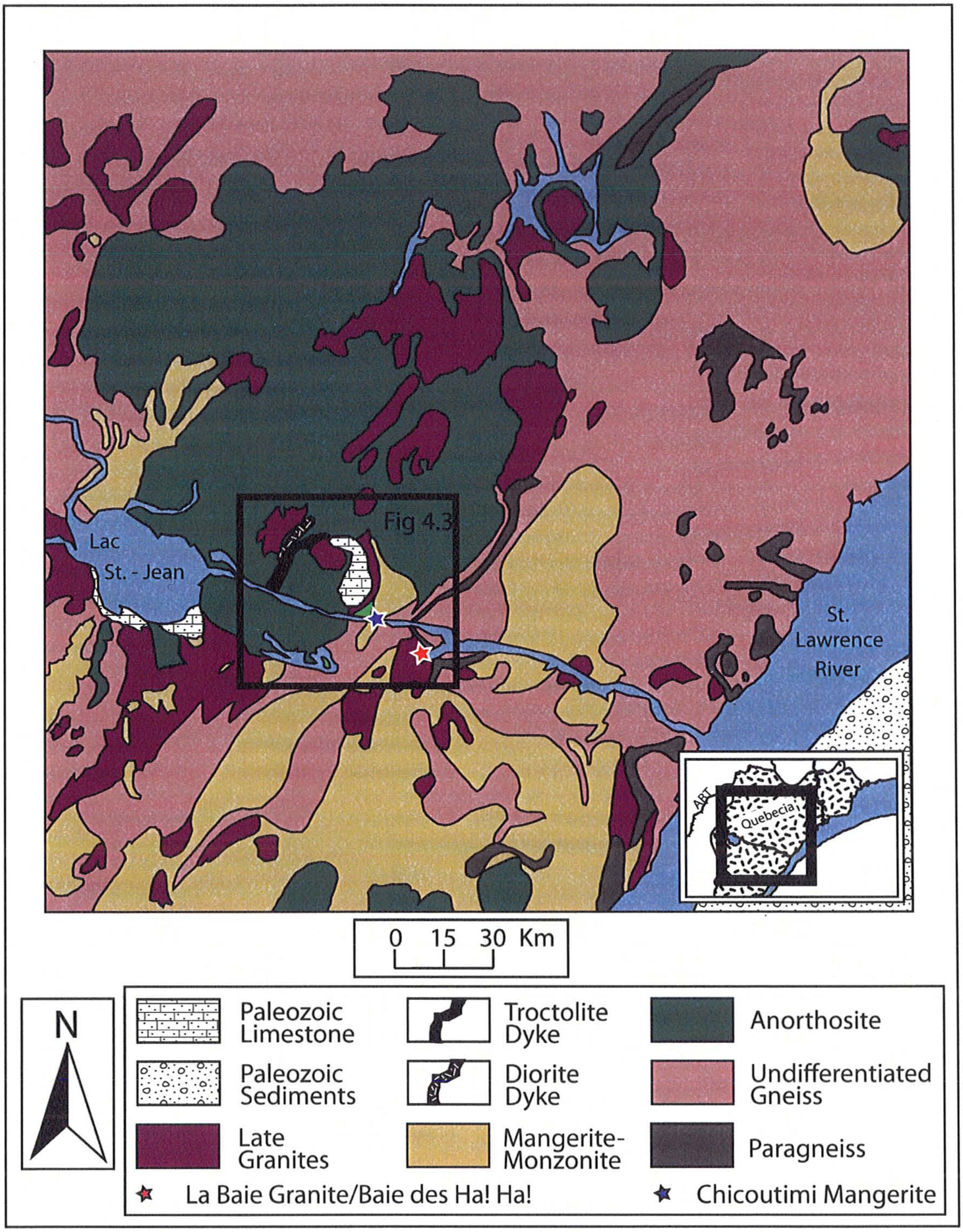

Figure 4.2: Geologic map of the Saguenay region after Dimroth et al. (1981).

Saguenay Region

Hébert and van Breemen (2004) summarize U-Pb ages which define the evolution of the AMCG suite within the Saguenay region. They distinguish three episodes of AMCG magmatism in the area of the current Saguenay study area as well as two events which are recorded in parts of the structural basement (figure 4.3).

Notable intrusions related to the Lac St.-Jean Anorthosite Suite include the mafic, 1157 $\pm$ 3 Ma Bégin Leucotroctolite megadike (black shading in figure 4.3), 1157 $\pm$ 3 Ma Lac Chabot Diorite dyke (dark stipple in figure 4.3), 1155 Ma - 1135 Ma Kénogami charnockite (ken if figure 4.3), and 1148 $\pm$ 4 Ma monzonite (8 km directly south of brq in figure 4.3) as well as the felsic 1146 $\pm$ 3 Ma Labrecque Granite (brq in figure 4.3) dated by Hébert and van Breemen (2004) which are all found in the northwest quadrant of figure 4.3.

Four post-Lac St.-Jean suite emplacement events are expressed within the Saguenay Study area. The 1020 +4/-7 Ma St. Ambroise Pluton is located within the LSJA suite (amb in figure 4.3). The Chicoutimi Mangerite (chc in figure 4.3) occurs as an elongated body northeast of the La Baie Granite. The Chicoutimi Mangerite was intruded at 1082 $\pm$ 3 Ma (as dated by Higgins and van Breemen, 1996). The La Baie Granite (lba 1 and 2 in figure 4.3) is the youngest intrusive suite in the area at 1067 $\pm$ 4 Ma (dated by Higgins and van Breemen, 1992) which has already been established as being associated with the 1082 – 1045 Ma AMCG episode that includes the St. Urbane Anorthosite. A monzonite body (l2f in figure 4.3) which is also surrounded by the LSJA has not been dated but is assumed to be post-LSJA emplacement as it is hosted by this suite (Hebert and van Breemen, 2004).

The La Baie Granite is defined as a 'within plate granitoid' by Nb and Rb concentration, plotting on A-type granitoid discrimination diagrams (Higgins and van Breemen, 1996). This granite is hosted by the Chicoutimi Mangerite, which is also classified by Higgins and van Breemen as a 'within plate granitoid'. The classification of Higgins and van Breemen is consistent with the low initial $^{87}Sr/^{86}Sr$ ratio found for this unit by Eby (1990). These intrusions are related to the Ottawan collisional orogeny (1080 – 1020 Ma as defined by Rivers, 2008) (Morisset et al., 2009).

Four units identified in figure 4.3, the Cyriac Rapakivi Granite (cyr), Saguenay Gneiss Complex (sag), Cap de la Mer (cmr) and Cap à l'Est Gneiss Complex (cpe) are older than the AMCG suites and represent portions of the Saguenay region basement. These units will be discussed in the following section.

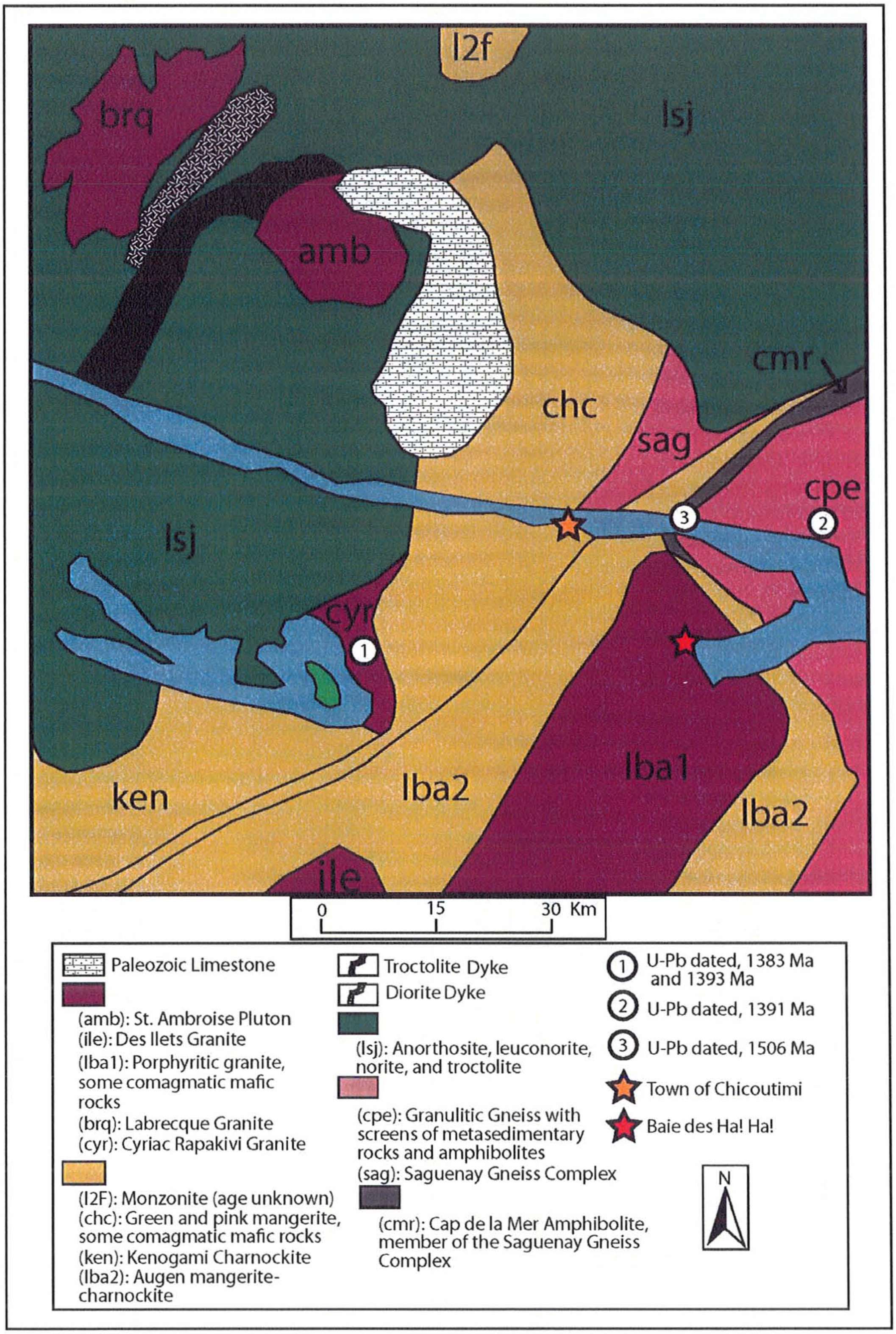

Figure 4.3: Geology of the Saguenay region with known crystallization dates for local basement rocks. Ages and abbreviations from Hebert and van Breemen (2004) (figure adapted from Hébert and van Breemen, 2004).

4.1.2 – Saguenay Basement

While there has been little emphasis on identifying the actual basement (i.e. pre- AMCG rocks) of the Saguenay and Baie Comeau regions (save for the Nd isotope mapping of Dickin and coworkers which will be discussed in section 4.1.4), there are isolated references to the basement (i.e. host rocks) of the Saguenay study area by other authors.

Prior to the 1970's, geologic research within the Grenville Province was largely conducted as reconnaissance work, since the discipline was lacking in reliable tools such as precise isotope determination methods on a whole-rock scale, through there were early attempts at geochronology which have now largely been superseded.

Frith (1971) considered the isolated bodies of migmatites and grey gneiss peripheral to the anorthosite suite to represent reworked 3000 Ma Archean basement. However, this was later shown to be Proterozoic by Frith and Doig (1975). Frith and Currie (1975) explored how anorthosite can be formed as an anatectic residue from metamorphism of a tonalitic basement; Laurin and Sharma (1976) noted the AMCG suite was intruded into migmatitic gneisses and Woussen et al. (1981) explored the gneisses surrounding the anorthosite suite, considering the units to be basement gneiss.

In an attempt at isotope dating within the Saguenay region, Frith and Doig (1973) used Rb-Sr isotopes to date several lithologic bodies of the Lac St.-Jean anorthosite suite (large green body in figure 4.2) and surrounding gneisses. They defined an Rb-Sr isochron for the Baie des Ha! Ha! paragneisses (starred location in figure 4.2) of 1482 $\pm$ 72 Ma which they say reflects a major thermal event. Frith and Doig (1973) further state that this event is preserved because the rocks were effectively dehydrated, making the Rb-Sr isotope system of these samples resistant to resetting by the ca. 1100 Ma Grenville Orogeny.

In another early attempt to unravel the history of the Saguenay region, Dimroth et al. (1981) used degree of metamorphism to divide the 'sea of gneiss' into three distinct age groups based on decreasing migmatization and degree of deformation, using the stratigraphic context of two generations of mafic dykes and their cross-cutting relationships with various gneisses and mobilizates. Dimroth et al. (1981) noted that the isochron produced for the Baie des Ha! Ha! paragneiss is actually a pseudo-isochron due to wide scatter. The scatter is said to be a result of a post depositional metamorphic event which sealed the Rb-Sr system from the metasomatism of younger events and thus represents neither the age of deposition nor the age of the most recent metamorphism. Similarly, Hébert and van Breemen (2004) view the 1482 $\pm$ 72 Ma date as representative of an averaged provenance. Dimroth et al. (1981) reference a personal communication with R. Doig who, using a low initial $^{87}Sr/^{86}Sr$ ratio, estimates the provenance of the Baie des Ha! Ha! paragneiss at ca. 1800 Ma.

While the paper by Dimroth et al. (1981) provided an early synthesis of understanding in the Saguenay region which expanded the detailed mapping work of Laurin and Sharma (1975) and Franconi et al. (1975), one cannot assume that a body more deformed is older than a body less deformed as each unit can have a vastly different evolutionary history due to many complex factors. Thus, the geochronological findings of the paper by Dimroth et al. (1981) have largely since been superseded as a result of advancing U-Pb and Sm-Nd dating methods.

A mapping program that occurred between 1994 and 1996 in the Saguenay region is reported on by Hébert and van Breemen (2004) and establishes both a terminology for the identified lithologic units and (as already stated) an overview of U-Pb ages in the Saguenay region determined up until the point of their study.

Hébert and van Breemen (2004) indentified several bodies which pre-date the AMCG magmatism in the Saguenay region. The Cap de la Mer Amphibolite, Cap à l'Est Gneiss Complex and, Cyriac Rapakivi Granite have all been interpreted as basement rocks.

A U-Pb date for the Cap de la Mer Amphibolite(cmr amphibolites in figure 4.3) has an upper intercept age of 1506 $\pm$ 13 Ma (Hébert and van Breemen, 2004) which defines the age of the igneous precursor corresponding with Pinwarian arc formation. This sample is a foliated gabbroic amphibolite (Hébert and van Breemen (2004).

The Cap à l'Est Gneiss Complex (denoted as 'cpe' in figure 4.3) is found within the vicinity of the Baie des Ha! Ha!. This complex is composed of charnockitic gneiss and metasedimentary rocks. A date obtained for a sample of green charnockitic gneiss had an upper intercept date of 1391 +7/-8 Ma, interpreted as dating magmatic crystallization (Hébert and van Breemen, 2004).

The Cyriac Rapakivi Granite (cyr in figure 4.3) has been dated at 1383 ± 16 Ma by U-Pb (Hébert and van Breemen, 2004). An old date of 1714 Ma was returned for a single inherited zircon and a young date of 1349 for an igneous zircon that underwent Pb loss during the Grenville Orogeny. The date of 1383 Ma represents the weighted mean of dates returned for igneous zircon and thus was interpreted to represent the time of igneous crystallization (Hébert and van Breemen, 2004). A kilometre to the south of the Cyriac Rapakivi Granite, a date of 1393 +22/-10 Ma was obtained for the Ruisseau a Jean-Guy Mafic Intrusion (Hervet et al., 1994).

4.1.3 - Baie Comeau

The corridor from Baie Comeau to the Manicouagan Reservoir is also host to several anorthosite intrusions (including the Raudot and Berte in the north and the De la Blache, Baie Comeau and, Riviere-Pentecote in the south (figure 4.1)) which occur in isolated bodies on a much smaller scale than the Lac St.-Jean anorthosite suite. This benefits the study of the basement in this area, as noted by Dickin and Higgins (1992), since the grey gneiss host rock does not suffer the whole scale replacement by younger intrusions as seen in the Saguenay area. Only one such intrusion, the Baie Comeau anorthosite, occurs within the confines of the current study area (green, east – west elongated body in figure 4.4). This intrusion is dominantly leucotroctolite and anorthosite and contains occurrences of rhythmic layering (Francis et al., 2000) and is irregularly surrounded by charnockite, mangerite and orthogneiss (figure 4.4).

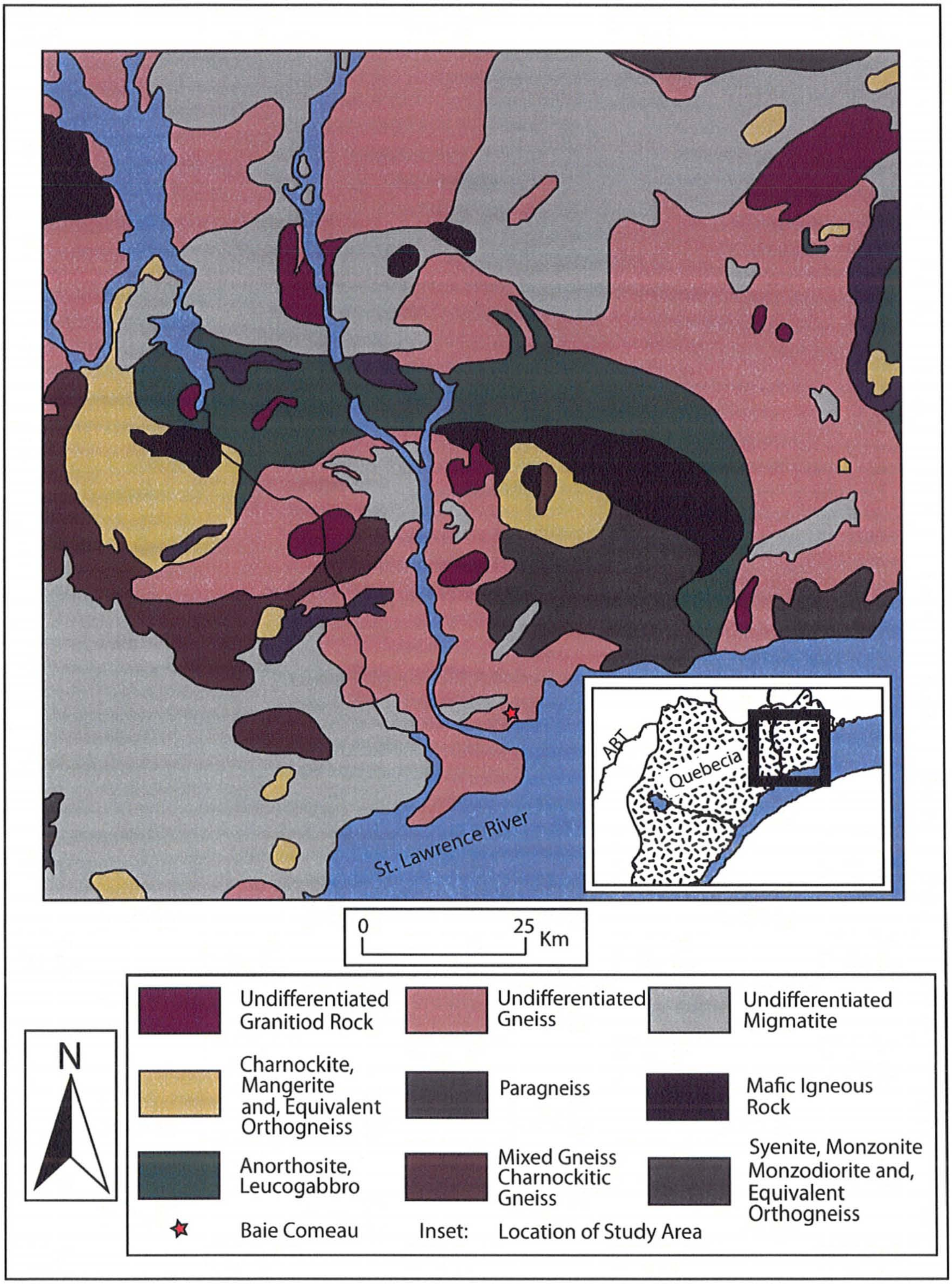

Figure 4.4: Geologic map of the Baie Comeau study area (after Davidson, 1998)

4.1.4 - The Basement Rocks: Nd Isotope Evidence

Dickin and Higgins (1992), through reconnaissance work covering 80 000 km^2 in central Quebec identified a distinct signature in Sm-Nd isotope data, indicating a common basement for a broad area. A Sm-Nd isochron yielding an age of 1.53 (±0.07) Ga was defined by a large number of samples taken from the Saguenay River to the Manicouagan River and as far north as the ABT. The samples that fit to the 1.53 Ga isochron have an average model age of 1.57 Ga which reflects their crustal extraction age. These samples defined a distinctly arc-related petrological assemblage which is confirmed by immobile trace element analysis and shows the arc-related affinity of these rocks or their protoliths (Dickin and Higgins, 1992). This terrane was termed Quebecia (figure 4.5) by Dickin (2000) who extended the term, which was originally applied by Rondot (1986) to a crustal terrane located just north of Quebec City, to refer to this area of central Quebec.

Dickin and Higgins (1992) classified their samples in central Quebec (which fall between the Saguenay and Manicouagan Rivers) via a chemical-mineralogical classification (after Debon and Lefort, 1983) which shows that grey gneisses from the Quebecia terrane define a trend typifying the rock associations known from arc terranes and "contrast[ing] sharply with the trend of the plutonic orthogneisses from Ontario" (Dickin and Higgins, 1992). The arc terrane petrological association spans the tonalite, granodiorite, adamellite, to granite fields. Dickin and Higgins (1992) also found that Y-Nb concentrations for the majority of their samples plotted within the volcanic arc granitoid/syn-collisional granitoid field.

Martin (1995) also plotted Y-Nb element data for 1.55 Ga tonalitic gneisses from samples of the Quebecia terrane, largely to the north and west of Lac St.-Jean and the Saguenay River. Of 23 samples, 15 plotted within the volcanic arc granitoid/syn-collisional granitoid field, which allowed Martin (1995) to further strengthen the argument for an oceanic subduction-related model for the creation of the Quebecia arc (which was first suggested by Dickin and Higgins, 1992). It is noted that between 1.46 and 1.40 Ga there was voluminous A-type granitoid plutonism in Ontario probably produced by an ensialic arc. This limits the timing of the accretion of the Quebecia arc terrane to within 100 Ma of extraction from the mantle (Dickin and Higgins, 1992) assuming that the same tectonic regime applies to the two areas.

Subsequent studies (Dickin, 2000; Martin and Dickin, 2005; Dickin et al., 2010) have aimed to sample this area in greater detail to define the eastern and western limits of Quebecia. This Mesoproterozoic arc terrane reaches from the Tawachiche shear zone (TSZ in figure 4.5) to Port Carter. At the western extreme of this area, the TSZ separates charnockite gneiss of more alkaline affinity (La Bostonnais complex) in the west from more silica enriched grey gneisses in the east (Dickin, 2000). At Port Carter the eastern boundary is marked by a change in age from crust averaging 1.55 Ga to older Labradorian crust (Dickin, 2000).

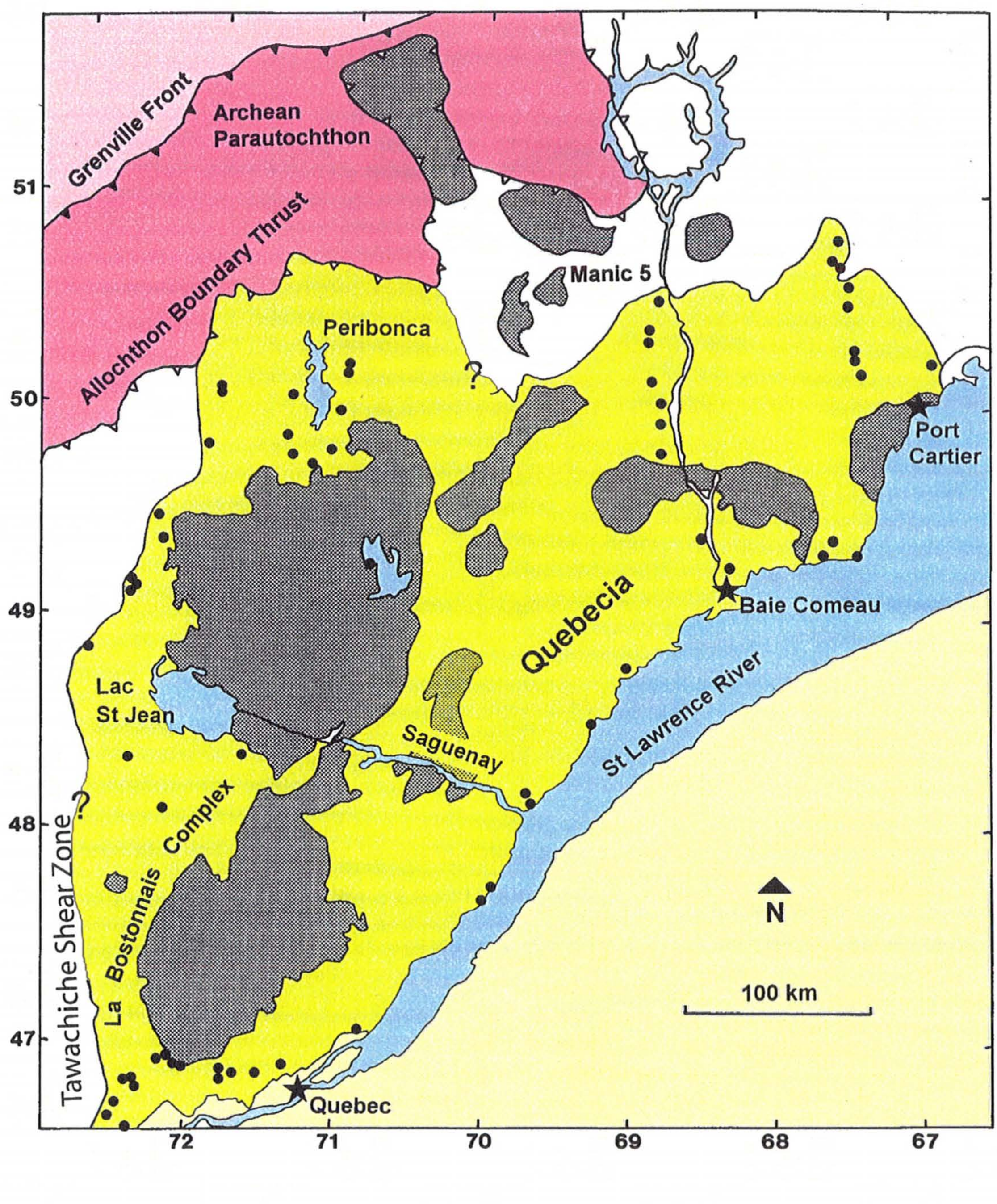

Figure 4.5: Map of Quebecia showing the location of Quebecia aged (1.5 Ga – 1.6 Ga) samples as defined by Dickin (2000) as well as anorthosites and related rocks (indicated by shading).

4.1.5 – La Bostonnais Complex

Understanding the La Bostonnais Complex has further helped distinguish the Quebecia terrane as an accreted arc. The La Bostonnais Complex cross cuts the rocks of the Montauban Group which are composed of metasedimentary and metavolcanic rocks (Sappin et al., 2009) deposited and erupted in an shallow marine environment during a time of weakly bimodal (andesitic to felsic) volcanism typical of an island-arc setting (Corrigan and van Breemen, 1997). The Montauban Group has been dated, using zircon from tuff deposits, to 1.45 Ga (Nadeau and van Breemen, 1994). The La Bostonnais complex however, is calc-alkaline in nature and has geochemical signatures typical of a continental magmatic arc in a subduction related tectonic regime (Corrigan and van Breemen, 1997). Plutons of the La Bostonnais Complex have ages of 1.40 Ga, as identified by Nadeau and van Breemen (1994) using U-Pb dating.

Through major element analysis for the Montauban Group and comparison with major element analysis from modern analogs of island- and continental- arc environments, Sappin et al. (2009) confirm the subduction-related tectonic regime and confirm the island arc affinity of this formation. Sappin et al. (2009) proposed that the La Bostonnais Complex formed by plutonism in an extensional ensialic arc environment behind the volcanic front of the Montauban Group. The ages of the Montauban Group and the La Bostonnais Complex limit the time of accretion of the Quebecia terrane, while their tectonic associations are consistent with an environment where such arc accretion would occur.

4.1.6 – Description of Tectonic Model

Sappin et al., (2009) envision a conceptual model where the Montauban Group was accreted to Laurentia via a northwest-dipping intraoceanic subduction zone and the plutonism that gave rise to the La Bostonnais Complex was intruded into the Montauban Group before and after this accretion. However, Martin and Dickin (2005) invoke a subduction flip model to accommodate the formation and accretion of the juvenile Quebecia arc and the subsequent ensialic arc magmatism responsible for the formation of the La Bostonnais Complex (figure 4.6). This model describes the following stages:

1. between 1.5 Ga and 1.45 Ga there is south-dipping subduction which results in the magmatism that fed the Quebecia arc
2. around 1.43 Ga they suggest that the Laurentian craton attempted to subduct beneath Quebecia, causing a build-up of stress, resulting in a flip to north-dipping subduction beginning at 1.40 Ga and the
3. formation of an ensialic arc which is preserved in the La Bostonnais Complex

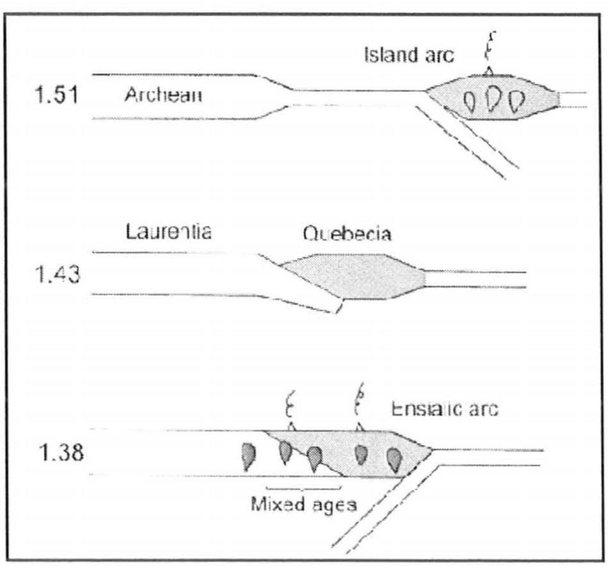

Figure 4.6: Model for accretion of the Quebecia terrane and formation of La Bostonnais Complex – the ensialic arc (after Martin and Dickin, 2005).

4.1.7 – Study Focus

This portion of the present study aims to map in greater detail the basement of two areas in central Quebec using Sm-Nd analysis. The sampling in the Saguenay area was spurred by U-Pb date of 1506 $\pm$ 13 Ma for the Cap de la Mer Amphibolite found by Hébert and van Breemen (2004). In the Baie Comeau area, sampling was directed by reconnaissance work by Dickin and Higgins (1992) who noted a clustering of samples that predate the Quebecia terrane near the mouth of the Manicouagan River. It is hoped that with greater sampling density it will be possible to define the extent of the older crust.

4.2 - Results

The present study adds thirty seven new samples to the eighty one samples previously analyzed using Sm-Nd mass spectrometry by Dickin and colleagues for the central Quebec area. The results from the present study, along with previously published data have been compiled into three tables. Table 4.1 gives model age results found to be younger than the Quebecia terrane (<1.46 Ga), Table 4.2 gives the results for model ages that fall within the age range corresponding to the Quebecia terrane (1.46 – 1.65 Ga) as defined by Dickin and Higgins (1992), and Table 4.3 gives the results for model ages that are pre-Quebecia (>1.65 Ga). Samples from the present study which returned model ages which were older than expected were reanalysed to confirm that the results indicated the true age of the rock. Such samples were subject to duplication using more than one dissolution or confirmed via a duplicate analysis for $\frac{^{143}Nd}{^{144}\mathrm{Nd}}$ ratios ('test tube repeat'). These duplicate results are indicated by '*' and '**' respectively.

Table 4.1

Post-Quebecia (<1.46 Ga)

MAP #	SAMPLE	EASTING	NORTHING	Nd (ppm)	Sm (ppm)	147Sm/144Nd	143Nd/144Nd	E(t) at 1.45	Tdm (Ga)
This Study: Quebecia - Saguenay Samples									
1	SG20	19331355	5306390	90.91	16.81	0.1118	0.512072	4.7	1.45
This Study: Juvenile - Baie Comeau Samples									
2	BC16	19544299	5443161	85.06	16.03	0.1139	0.512121	5.2	1.40
From Dickin (2000): Juvenile Samples									
	sm24			104.01	16.56	0.0963	0.511914	4.4	1.46
From Dickin and Higgins (1992): Juvenile - Manicouagan River Samples									
	CDP4			54.77	10.09	0.1115	0.512130	5.9	1.36
	ma114			20.36	2.78	0.0835	0.511855	5.7	1.39
	LU5			30.34	4.45	0.0886	0.511894	5.5	1.40

Table 4.2

Quebecia (1.46 - 1.65 Ga)

MAP #	SAMPLE	EASTING	NORTHING	Nd (ppm)	Sm (ppm)	147Sm/144Nd	143Nd/144Nd	E(t) at 1.45	Tdm (Ga)
This Study: Quebecia - Saguenay Samples									
3	SG 16	19347996	5357910	171.27	27.4	0.0967	0.512022	4.2	1.49
4	SG23	19333927	5248453	83.80	17.74	0.1280	0.512193	4.0	1.51
5	SG15	19375247	5351593	29.35	4.56	0.0938	0.511855	3.7	1.51
6	SG11	19421449	5309967	55.48	11.09	0.1208	0.512117	3.9	1.52
7	SG19	19334272	5321122	81.24	13.95	0.1038	0.511923	3.2	1.55
8	SG12	19423373	5326665	81.08	17.47	0.1302	0.512186	3.5	1.56
9	SG10	19438297	5316224	12.81	3.00	0.1411	0.512291	3.5	1.57
10	SG7	19421736	5354983	14.40	3.17	0.1329	0.512201	3.3	1.58
11	SG14	19382873	5348851	73.91	16.90	0.1383	0.512253	3.3	1.59
12	SG6	19418128	5356126	6.12	0.87	0.0857	0.511701	2.2	1.60
13	SG18	19333358	5330727	56.2	11.09	0.1193	0.512051	2.9	1.60
14	SGØ	19345000	5367000	64.27	12.19	0.1146	0.511990	2.5	1.62
15	SG1	19357290	5368607	55.22	12.89	0.1411	0.512262	3.0	1.63
16	SG22	19331699	5269174	34.13	7.72	0.1368	0.512220	3.0	1.63
This Study: Quebecia - Baie Comeau Samples									
17	BC18	19531199	5450239	105.63	14.51	0.0830	0.511758	3.9	1.50
18	BC7	19550412	5462131	26.00	5.47	0.1271	0.512169	3.7	1.54
19	BC17	19531313	5450153	52.55	11.03	0.1269	0.512156	3.5	1.55
20	BC19	19532420	5438447	46.72	9.91	0.1283	0.512169	3.5	1.56
21	BC9	19554302	5464348	29.16	5.71	0.1184	0.512054	3.2	1.58
22	BC10	19555268	5454828	22.66	5.19	0.1384	0.512258	3.4	1.59
23	BC5	19539298	5468495	18.20	4.05	0.1334	0.512202	3.2	1.59
24	BC8	19554102	5459970	18.83	4.53	0.1455	0.512322	3.3	1.61
From Dickin (2000): Quebecia samples									
	MS6	19286000	5551300	124.90	17.42	0.0843	0.511762	3.7	1.51
	LU6	19344800	5521500	45.51	9.34	0.1240	0.512146	3.8	1.52
	CDP1	19327900	5518500	13.21	2.11	0.0966	0.511868	3.5	1.53
	LU11	19327900	5542000	16.31	2.60	0.0962	0.511863	3.5	1.53
	GL20	19672600	5457600	37.83	7.77	0.1242	0.512128	3.5	1.55
	LU3	19335800	5510200	41.76	8.60	0.1246	0.512135	3.5	1.55
	MS8	19286500	5554000	28.14	6.17	0.1325	0.512211	3.5	1.56
	CDP2	19324000	5531200	38.42	7.83	0.1230	0.512121	3.5	1.56
	LU14	19354200	5560800	22.97	4.14	0.1090	0.511969	3.2	1.56
	GL1	19675400	5443300	41.48	8.60	0.1253	0.512132	3.3	1.57
	GL2	19676900	5449900	35.75	7.00	0.1183	0.512058	3.2	1.57
	RA4	19690800	5485400	26.53	5.13	0.1168	0.512045	3.2	1.57
	MS9	19712500	5523000	40.16	7.42	0.1117	0.511991	3.1	1.57
	CDP5	19326500	5547500	15.30	2.72	0.1073	0.511946	3.0	1.57
	LU12	19352700	5558600	41.73	9.11	0.1320	0.512199	3.4	1.57
	TD1	19664500	5426300	24.36	5.11	0.1269	0.512139	3.2	1.58
	GL3	19673900	5453100	30.52	6.48	0.1283	0.512156	3.2	1.58
	RA1	19693900	5475200	20.35	3.87	0.1150	0.512008	2.8	1.59
	LSJ31	19657000	5412900	33.51	7.13	0.1287	0.512137	2.8	1.62

Quebecia (1.46 - 1.65 Ga) continued

MAP #	SAMPLE	EASTING	NORTHING	Nd (ppm)	Sm (ppm)	147Sm/144Nd	143Nd/144Nd	E(t) at 1.45	Tdm (Ga)
From Dickin and Higgins (1992): Lac St. Jean, St. Lawrence River (north shore) and Manicouagan River samples									
	n29			13.43	2.60	0.1171	0.512081	3.9	1.51
	lsj1			34.16	8.13	0.1438	0.512335	3.9	1.54
	n11			n/a	n/a	0.1044	0.511939	3.4	1.54
	lsj4			23.38	4.25	0.1099	0.511985	3.3	1.55
	ns9			n/a	n/a	0.0993	0.511875	3.1	1.55
	m121			16.07	3.01	0.1131	0.512016	3.3	1.55
	n31			n/a	n/a	0.1208	0.512091	3.4	1.56
	n32a			42.79	7.78	0.1099	0.511981	3.2	1.56
	ma40			27.18	5.46	0.1214	0.512097	3.4	1.56
	m132			39.52	8.60	0.1315	0.512197	3.5	1.56
	m153			4.12	0.71	0.1048	0.511930	3.2	1.56
	m178			28.62	5.20	0.1100	0.511981	3.2	1.56
	m199			16.94	3.41	0.1217	0.512097	3.3	1.56
	n20			12.28	2.31	0.1143	0.512014	3.1	1.57
	n32b			32.07	6.29	0.1186	0.512059	3.1	1.57
	ma12			4.38	0.85	0.1167	0.512045	3.2	1.57
	m103			45.43	9.32	0.1241	0.512116	3.2	1.57
	m182			41.32	7.45	0.1089	0.511964	3.1	1.57
	n18			34.45	6.85	0.1202	0.512072	3.1	1.58
	lsj2			53.47	10.84	0.1226	0.512093	3.1	1.59
From Dickin (2000): Montauban Samples									
	m10			38.76	6.61	0.1030	0.511947	3.8	1.51
	m11			23.62	5.30	0.1357	0.512263	4.0	1.52
	mb7			17.45	3.78	0.1309	0.512208	3.8	1.53
	mb1			9.09	1.78	0.1180	0.512072	3.5	1.54
	mb2			14.90	3.35	0.1359	0.512255	3.8	1.54
	mb9			14.29	2.68	0.1134	0.512029	3.5	1.54
	m17			18.06	3.20	0.1072	0.511959	3.3	1.55
	m16			34.19	4.98	0.0880	0.511757	2.9	1.56
	m15			7.10	1.10	0.0935	0.511791	2.6	1.59
	mb3			34.15	7.43	0.1315	0.512171	2.9	1.61
	m13			44.69	8.30	0.1122	0.511971	2.6	1.61
	mb8			18.55	4.24	0.1380	0.512232	2.9	1.62
From Dickin (2000): Quebec samples									
	qb4			45.74	10.15	0.1342	0.512245	3.9	1.53
	qb7			39.46	8.58	0.1314	0.512211	3.7	1.54
	ns1			n/a	n/a	0.0774	0.511654	2.9	1.55
	q11			25.38	5.36	0.1277	0.512156	3.4	1.57
	qb6			37.44	8.26	0.1334	0.512207	3.3	1.58
	qb9			44.83	8.84	0.1192	0.512040	2.7	1.61
	ns2			n/a	n/a	0.0950	0.511785	2.2	1.61
	qb8			42.17	9.28	0.1330	0.512183	2.9	1.62
	qb3			14.65	3.64	0.1502	0.512363	3.2	1.63
	q10			48.24	9.30	0.1165	0.512000	2.4	1.63
From Dickin (2000): Sept Iles - Port Cartier samples									
	c10			60.04	11.78	0.1185	0.512066	3.3	1.56
	c12			36.40	6.82	0.1132	0.512000	3.0	1.58
	c17			39.89	7.21	0.1092	0.511951	2.8	1.59
	c19			19.12	4.11	0.1299	0.512168	3.2	1.59
	c13			19.06	4.05	0.1285	0.512146	3.0	1.60
	c21			27.30	5.07	0.1122	0.511975	2.7	1.60
	cs8			17.65	3.71	0.1271	0.512126	2.9	1.61
	cs9			48.97	8.92	0.1102	0.511949	2.6	1.61
	sm8			44.73	8.86	0.1197	0.512027	2.3	1.64

Table 4.3

Pre-Quebecia (>1.65 Ga)

	SAMPLE	EASTING	NORTHING	Nd (ppm)	Sm (ppm)	147Sm/144Nd	143Nd/144Nd	E(t) at 1.45	Tdm (Ga)
This Study: Pre-Quebecia - Saguenay Samples									
25	SG3	19375471	5365838	56.25	11.93	0.1281	0.512103	2.2	1.67
	SG3**					0.0160	0.512170		
26	SG21	19334438	5286577	28.32	5.67	0.1210	0.512022	2.0	1.67
	SG21**						0.512040		
27	SG2	19361401	5367258	48.40	10.05	0.1255	0.512066	2.0	1.69
	SG2*			64.09	13.28	0.1252	0.512054	1.8	1.70
	SG2*			64.09	13.28	0.1252	0.512054	1.8	1.70
28	SG13	19405072	5340652	32.68	6.20	0.1148	0.511932	1.4	1.71
29	SG4	19379869	5363873	26.89	6.57	0.1478	0.512188	0.3	1.98
	SG4*			26.89	6.57	0.1478	0.512189		1.97
3	SG5	19387750	5363883	32.12	6.34	0.1194	0.511809	-1.9	1.99
This Study: Pre-Quebecia - Baie Comeau Samples									
31	BC6	19547332	5461716	26.03	4.77	0.1107	0.511922	1.9	1.66
	BC6*			25.99	4.78	0.1111	0.511927		1.66
32	BC2	19522132	5491939	49.60	9.74	0.1187	0.511881	-0.4	1.68
33	BC14	19567568	5461078	15.23	2.83	0.1123	0.511891	1.0	1.73
	BC14**						0.511871		
34	BC4	19532935	5480324	22.29	4.97	0.1348	0.512135	1.6	1.75
35	BC15	19548989	5448591	9.64	2.09	0.1312	0.512051	0.6	1.83
36	BC13	19563067	5458506	20.25	3.92	0.1170	0.511827	-1.1	1.92
	BC13**						0.511838		
37	BC1	19520718	5490084	50.32	10.08	0.1210	0.511852	-1.4	1.96
	BC1**						0.511854		
From Dickin (2000): Pre-Quebecia Samples									
	MB1			9.09	1.78	0.1240	0.511957	0.1	1.84
From Dickin and Higgins (1992): Pre-Quebecia - Manicouagan River Samples									
	NS27			14.12	2.44	0.1045	0.511808	0.8	1.71
	MA25.8			26.90	5.40	0.1212	0.511911	-0.2	1.86
	MA42.7			14.94	3.11	0.1257	0.511960	-0.1	1.87
	MA67			42.21	8.56	0.1226	0.511925	-0.2	1.87
	MA58.1			49.16	9.50	0.1168	0.511791	-1.8	1.97

The results for the ratios $\frac{^{143}Nd}{^{144}\mathrm{Nd}}$ and $\frac{^{147}Sm}{^{144}\mathrm{Nd}}$ which are presented in tables 4.1 through 4.3 have been plotted on an Sm-Nd isochron diagram in figure 4.7. This figure shows an isochron of 1.51 Ga established for the Quebecia terrane which was found using all the previously published samples for this terrane. This diagram provides the justification of the division of data into the three age groups: <1.46 Ga, 1.46 - 1.65 Ga and, >1.65 Ga.

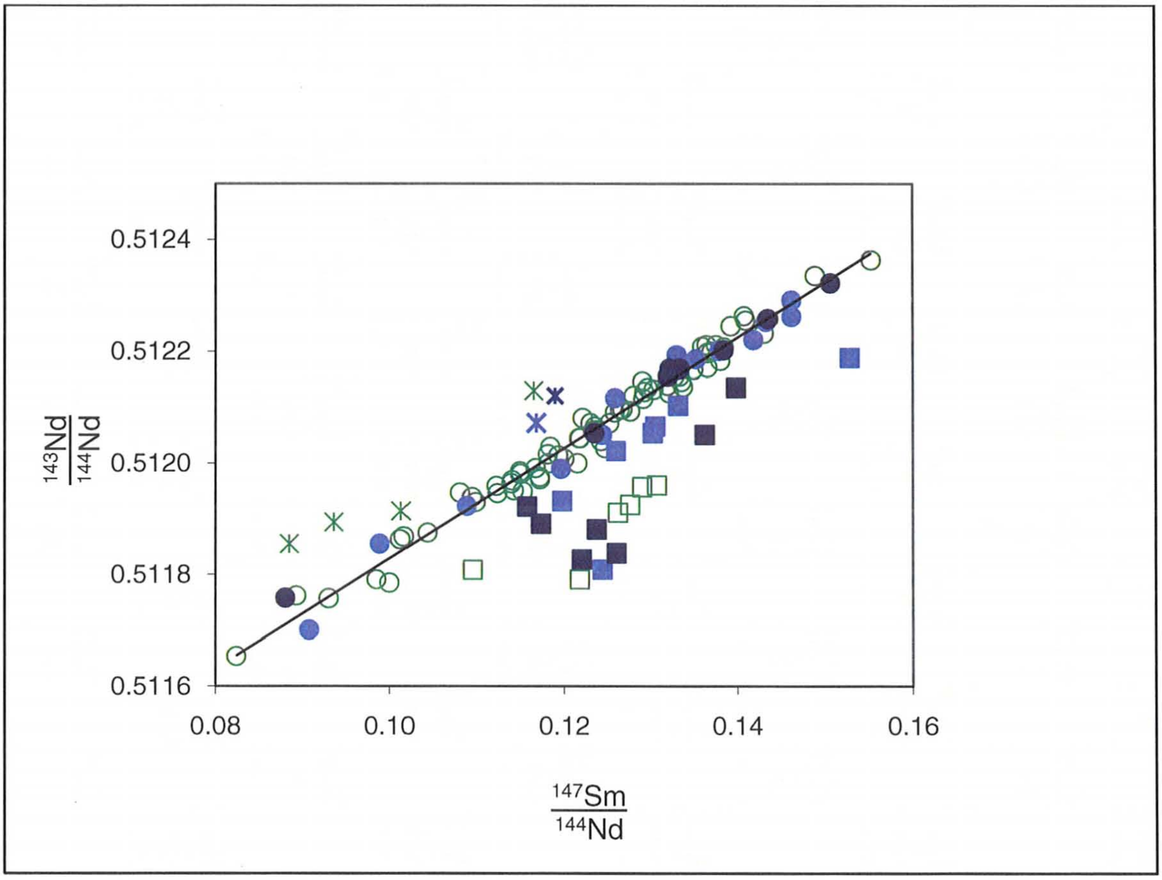

Figure 4.7: Isochron diagram for the Quebecia terrane. Blue symbols represent samples analyzed in the present study (dark blue symbols represent samples taken along the Manicouagan River in the Baie Comeau area, light blue symbol represent samples in the Saguenay area), green symbols represent samples from previous studies. Model ages are defined by symbols where asterisks are < 1.46 Ga, circles are between 1.46 Ga and 1.65 Ga and, squares are > 1.65 Ga.

Quebecia samples from the current study are strongly collinear with the previously published Quebecia results which produced the 1.51 Ga isochron reference line of Dickin et al. (2010), is shown in figure 4.7. There are a few samples that plot above the 'Quebecia array' whose ages of 1.36 Ga – 1.46 Ga are attributed to post-Quebecia plutonism that also resulted in the development of the La Bostonnais complex (dated at 1.40 Ga by Nadeau and van Breemen, 1994). Only two samples from the current study (SG 20 and BC16) fall within this range. Model ages > 1.65 Ga plot below the 'Quebecia array' in figure 4.7. For the Saguenay suite, model ages predating Quebecia range up to 1.99 Ga. The Baie Comeau suite model ages predating Quebecia range up to 1.96 Ga.

Figure 4.8 presents a series of histograms illustrating the frequency of model ages for previous studies conducted in central Quebec as well as the Saguenay and Baie Comeau study areas for comparison. Data was organized into bins of 50 My (e.g. 1.45 Ga - 1.49 Ga; 1.50 Ga – 1.54 Ga ...) which are appropriate relative to the estimated analytical error of $\pm$ 20 My. The data distribution shows a marked peak between 1.55 Ga and 1.60 Ga which is apparent in all three data suites. This heavy concentration of samples around this peak (from 1.45 Ga – 1.64 Ga) accounts for 77 percent of all the samples. Right skewing is also apparent in all three data suites, accounting for the occurrence of model ages that represent a crustal forming event older than the Pinwarian-aged Quebecia terrane.

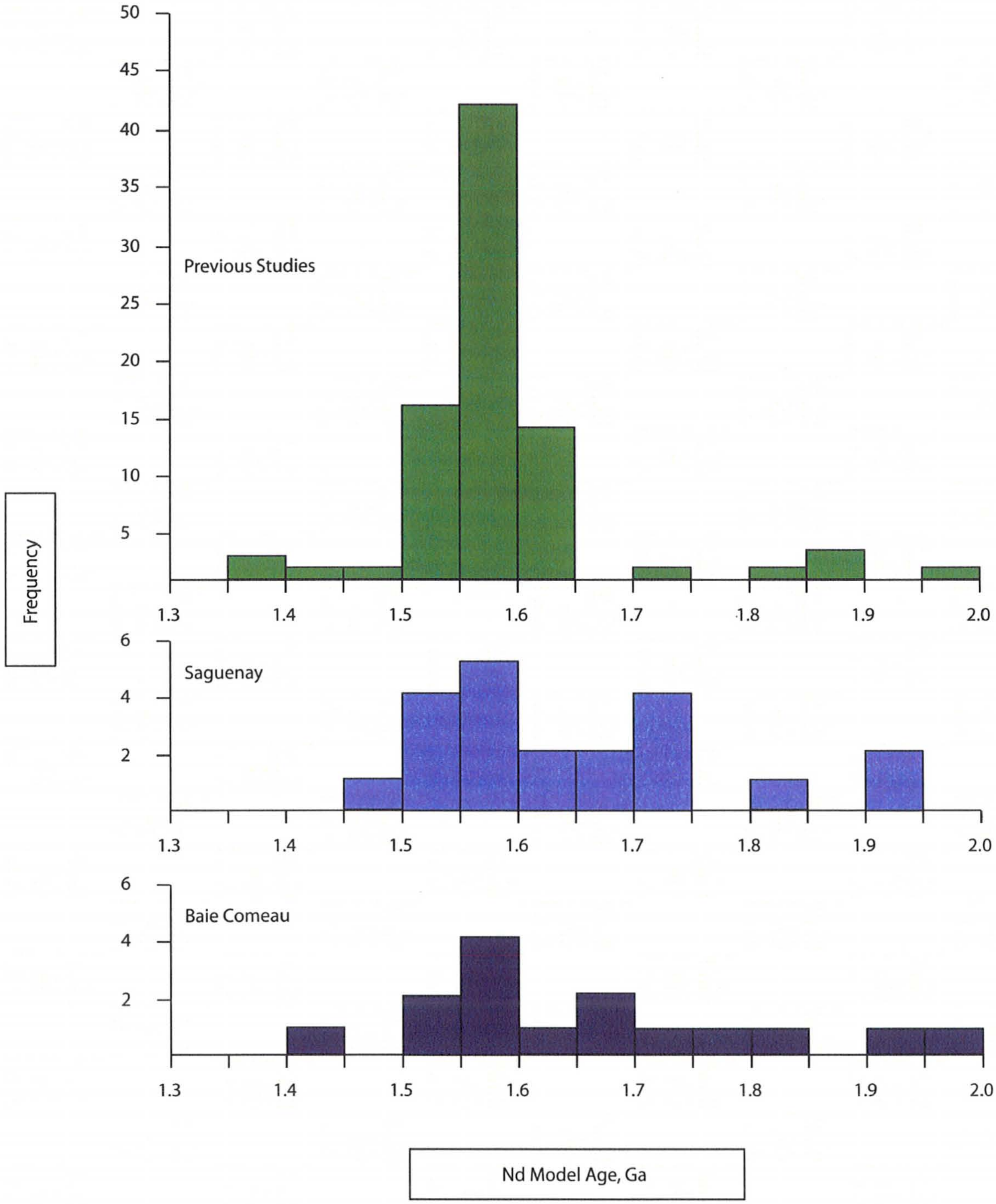

Figure 4.8: Frequency plot of Nd model ages for samples from the previous studies (green), Saguenay area (light blue) and, Baie Comeau area (dark blue).

To further compare the results from the present study to previously published results from central Quebec, εNd values which reflect isotope enrichment or depletion relative to crust formed at 1450 Ma have been plotted against Nd concentration (in ppm) in figure 4.9. The reference age of 1450 Ma was utilized to calculate εNd values as it corresponds with a major known magmatic event in the Grenville Province which gave rise to the La Bostonnais Complex.

The previously published data for Quebecia-aged samples form a distinct cluster between the εNd values of +2 and +4. Quebecia-aged samples from the current study (green circles and dark and light blue symbols respectively in figure 4.9) also plot between +2 and +4. When considering only the results of the current study, there is relatively large variation in Nd concentraion amongst samples with model ages between 1.65 Ga and 1.46 Ga (blue circles in figure 4.9) while there is considerably less variation in Nd concentration amongst samples with model ages > 1.65 Ga (blue squares in figure 4.9). Previously published data where model ages are < 1.46 Ga (green asterisks in figure 4.9) have low concentration of Nd and a high positive εNd value (which is expected for a juvenile magma) in comparison with the rest of the data.

Previously published data with model ages > 1.65 all have εNd values near 0, the majority of which are between 0 and -1 typical of old crust while, only three samples from the current study (all within the Baie Comeau study area) have negative εNd values. The majority of the samples with model ages > 1.65

Ga from the current study have εNd values between 0 and +2 which could reflect a small degree of reworking by juvenile magmatism subsequent to their extraction from the mantle.

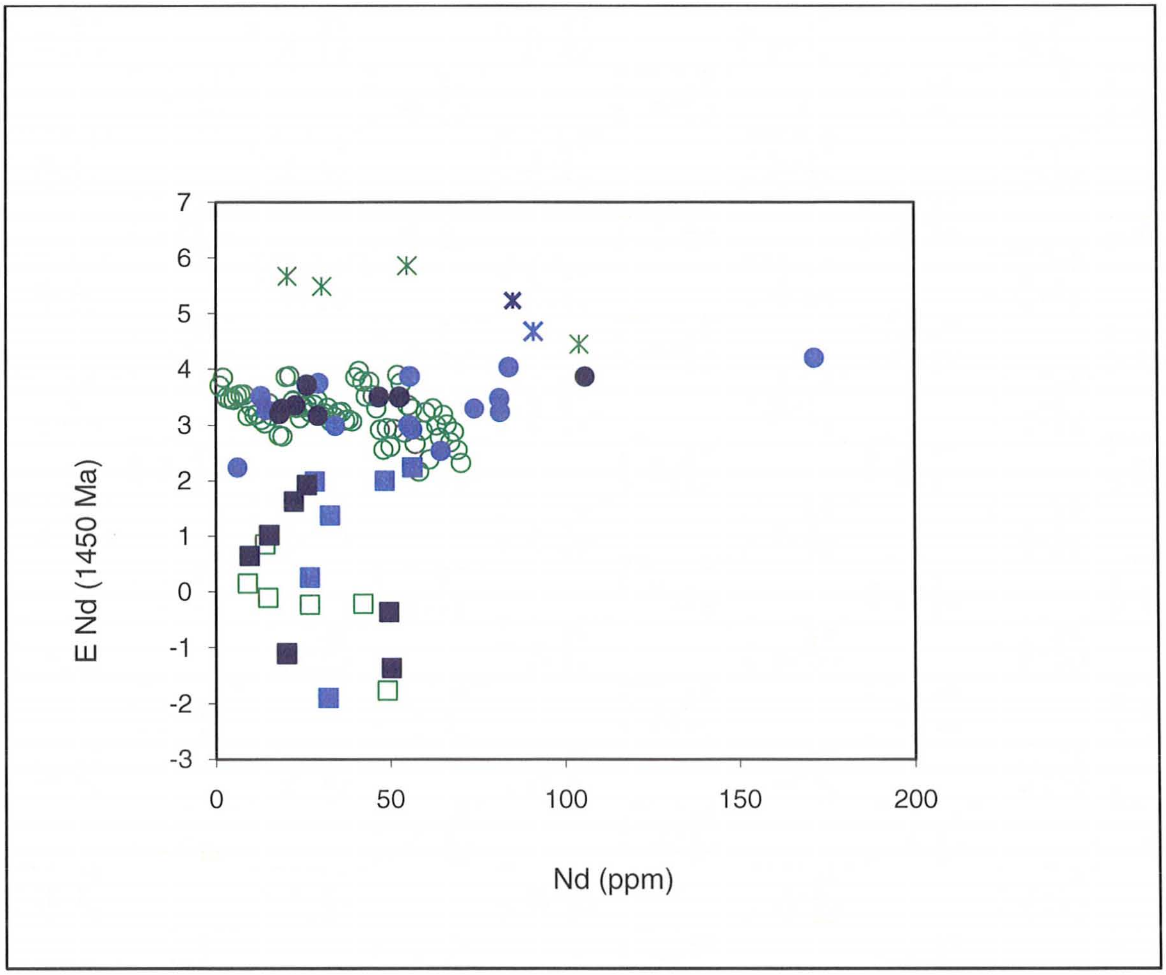

Figure 4.9: εNd (at 1450 Ma) against the concentration of Nd (in ppm) for samples from central Quebec. Blue symbols represent samples analyzed in the present study (dark blue symbols represent samples taken along the Manicouagan River in the Baie Comeau area, light blue symbol represent samples in the Saguenay area), green symbols represent samples from previous studies. Model ages are defined by symbols where asterisks are < 1.46 Ga, circles are between 1.46 Ga and 1.65 Ga and, squares are > 1.65 Ga.

4.3 – Discussion

The current study aimed to investigate the extent of pre-Quebecia (> 1.65 Ga) model ages defined by Nd analysis by Dickin and Higgins (1992) in the Baie Comeau region and U-Pb crystallization ages that pre-date AMCG magmatism found by Hervet et al. (1994) and Hébert and van Breemen (2004) within the Saguenay region. The results of the present study are illustrated in figure 4.10 for the Saguenay study area and figure 4.11 for the Baie Comeau study area.

Figure 4.10 is a map of the Saguenay study area showing sample locations and their respective model ages. Surrounding the town of Chicoutimi (at star #3), there is a relatively large block of older crust geographically coincident with U-Pb dates that pre-date the AMCG magmatism in the area (termed the Baie des Ha! Ha! Block in the present study). Admittedly there is no Nd data for the area surrounding the Cyriac Rapakivi Granite (cyr in figure 4.3), but the extent of older crust has been stretched to include this area to account for the U-Pb dates of 1383 Ma and 1393 Ma (star #1 in figure 4.10 as dated by Hebert and van Breemen, 2004 and Hervet et al., 1994 respectively).

One sample with a model age of 1.67 Ga is found in the southwest of the study area which is geographically isolated from other Nd model age defined pre-Quebecia samples and the U-Pb defined pre-AMCG samples. There is question as to the reliability of the 'old distinction' of this isolated block. Several analyses were performed to confirm the > 1.65 model age of this sample (two of which are reported in table 4.3). A complete analysis with the lowest analytical error was accepted and is reported in table 4.3 however, two other $\frac{^{143}Nd}{^{144}\mathrm{Nd}}$ results returned that were an average of 0.512025 which is only slightly higher than the value 0.512022 which was used in the calculation of the model age. Higher results from the ratio $\frac{^{143}Nd}{^{144}\mathrm{Nd}}$ cause younger ages, but the difference here is not large enough to cause rejection of the 1.67 Ga model age from the >1.65 sample group although, it is close to the cut off. Further sampling and analysis will be necessary to confirm the existence and extent of this older block.

The model ages that are >1.65 Ga in the Saguenay study area are found for samples from an area distinguished by the Geologic Map of the Grenville Province (Davidson, 1998) to have lithologic units that are both pre-Grenvillian and Grenville related. This indicates that while the Grenville orogenic cycles effectively overprinted many of the units, resetting their U-Pb systems, some of the units with Grenvillian U-Pb ages retained traces of their true provenance in the Sm-Nd system.

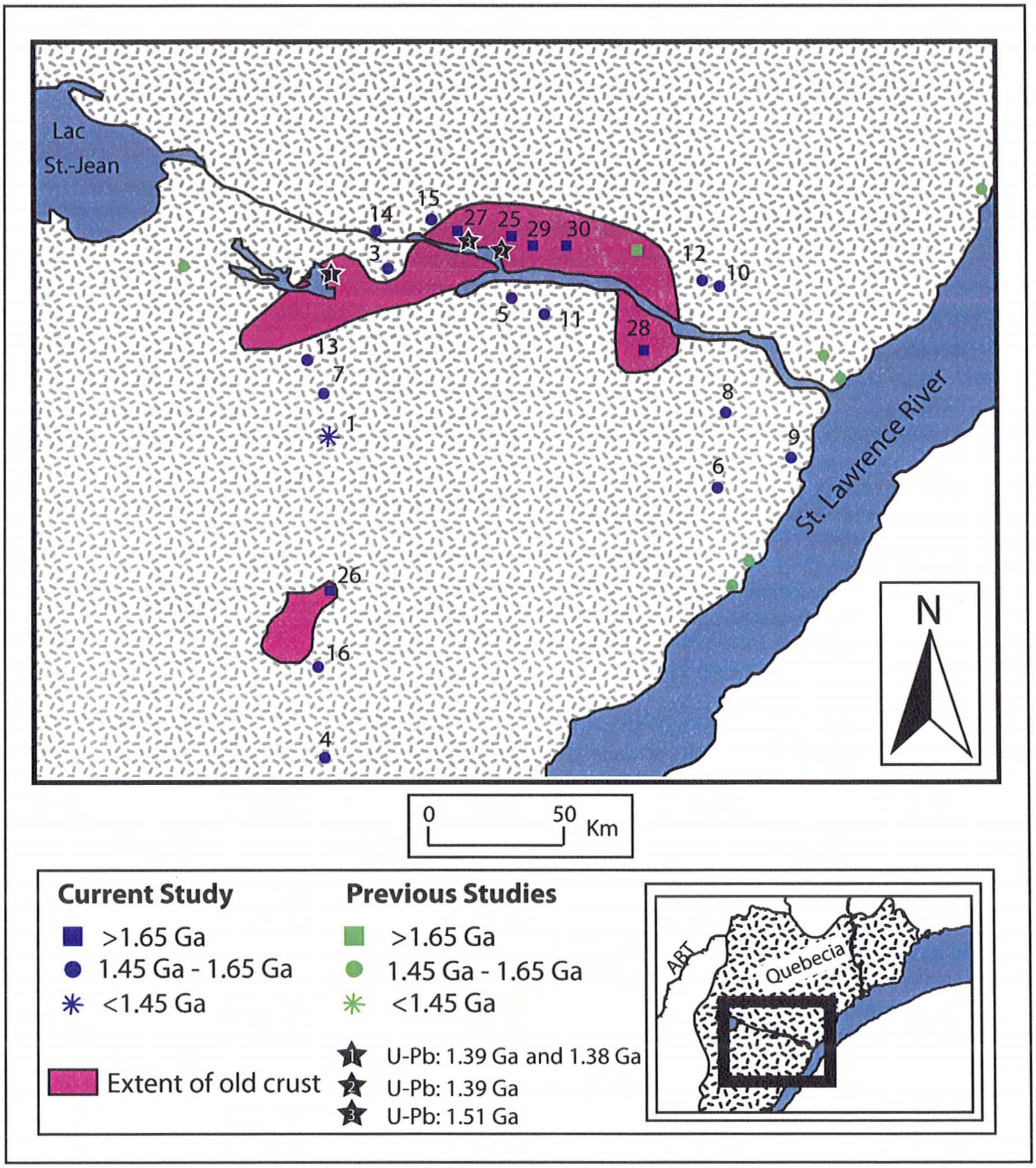

Figure 4.10: Geographic extent of old crust in the Saguenay study area.

Model ages from the Baie Comeau study are summarized in figure 4.11. There is a continuous block of pre-Quebecia crust as defined by model ages > 1.65 Ga. This area is termed the Baie Comeau Block. The southern portion of this block (along the St. Lawrence River) has fairly well constrained boundaries by the distribution of Quebecia aged samples which surround it, however the northwestern extent of this block lacks sample density (limited by road access) and thus the location of the boundaries are inferred according to lithology.

All of the samples in the Baie Comeau area that are >1.65 Ga, fall within a unit of undifferentiated gneiss defined as pre-Grenvillian by the geologic map of the Grenville Province (Davidson, 1998) and thus, the contours of the Baie Comeau Block follow the outline of this lithologic unit (identifiable in figure 4.3 as the light pink unit between the St. Lawrence River in the south and the elongated anorthosite unite in the north and northeast). Like the Baie Comeau anorthosite to the north and northeast, this body of undifferentiated gneiss is folded around a body of charnockitic gneiss.

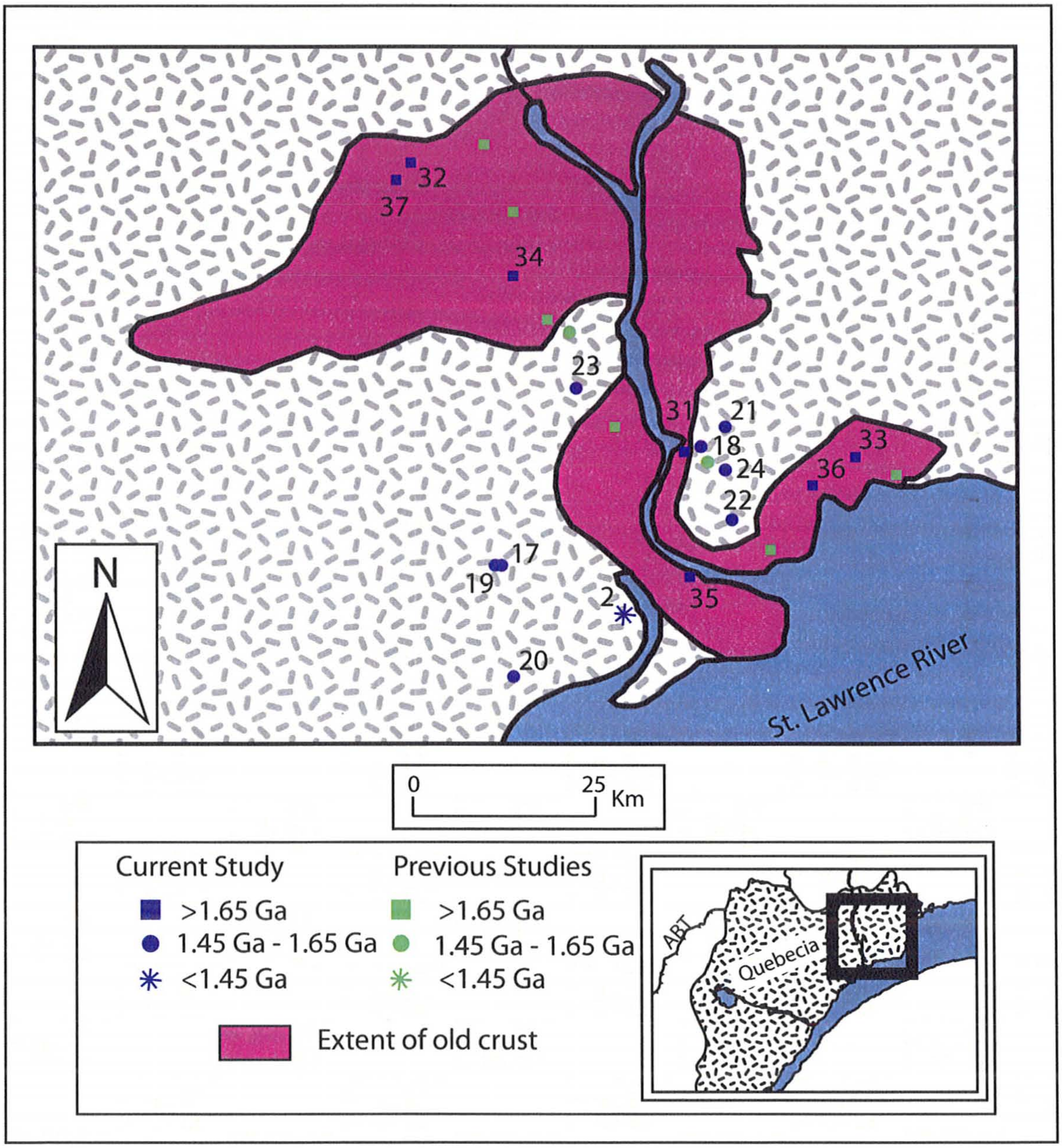

Figure 4.11: Geographic extent of old crust within the Baie Comeau study area.

The tectonic implications of the blocks of old crust in the Saguenay and Baie Comeau study area must be considered in the context of Quebecia. This broad area of central Quebec has undisputedly homogenous Nd-Isotope characteristics which are interrupted by the Baie des Ha! Ha! and Baie Comeau blocks of older crust. The isotope data for these blocks of older crust is comparable with data from the northern extent of a wedge-shaped ensialic arc defined by Martin and Dickin (2005), whose boundaries coincide with the ABT to the northwest and the juvenile Quebecia terrane to the southeast. This arc is composed of model ages between 2.10 Ga and 1.65 Ga and εNd values between -5.0 and +1.7 (Martin and Dickin, 2005) which encompasses the model ages and εNd values for the old crust in the present study and contrasts the distinctly younger, and less radiogenically enriched Quebecia terrane.

It is possible that the Quebecia arc represents a similar situation to the geology of the southwest Japan arc. This modern analogue has a tectonic setting where fragments of old lithosphere were rifted from the Eurasian continent during the expansion of the Sea of Japan and later incorporated in the younger arc terrane formed by subduction-related magmatism (Senda et al., 2006).

In the context of the Japan arc analogue, one would expect that the fragments of old crust found in the Saguenay and Baie Comeau areas would be isotopically and geochronologically similar to an area in the foreland of Laurentia, but surrounded by juvenile crust formed during arc creation. Since the old blocks identified in the present study are shown to be surrounded by an expansive arc terrane representing extensive formation of juvenile crust, the present study presents the conditions of composite arc formation to satisfy the existence of older blocks within Quebecia.

The fragments of old crust defined in the Saguenay and Baie Comeau regions are possibly connected to one another to form a 'panel' of old crust running through the younger Quebecia arc. Figure 4.12 represents a possible model for the extent of such a panel. The boundaries of this panel have been drawn to include the fragments of old crust defined for the Saguenay and Baie Comeau regions and follow the contour of pre-Grenvillian gneiss defined by the geologic map of Davidson (1998).

There are several roads which access the central area of the panel lying above the town of Forestville, but such sampling was outside the scope of the present study. The available access roads present an opportunity to test this model in subsequent studies and provide an area for future investigation into the central Grenville Province of Quebec to further understanding of this area.

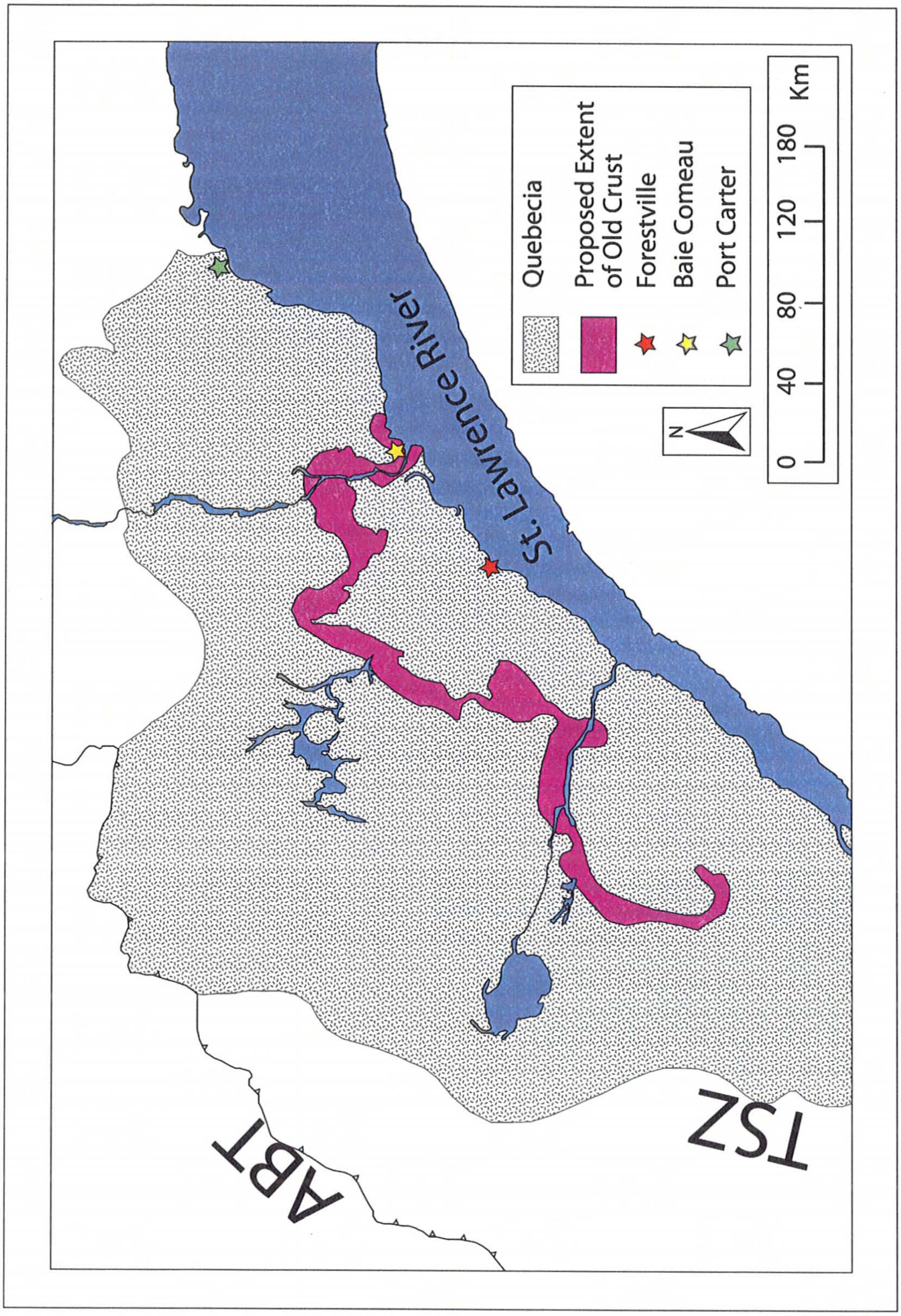

Figure 4.12: Proposed extension of old crust within Quebecia. ABT = Allochthon Boundary Thrust, TSZ = Tawachiche Shear Zone.

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Appendix A: Analytical Procedure

A.1 – Introduction

Analytical procedures for Sm-Nd analysis involves several steps which can be classified into three categories: field collection, laboratory processes, and mass spectrometry procedures. Each of these steps follow a precisely defined methodology. Careful adherence to the methodology is crucial to establish criteria for repeatable and valid results.

A.2 – Sampling and Rock Crushing

Orthogneiss samples were collected at road cuts and from outcrops within the study areas. The sampling distribution was controlled by the accessibility established by a network of logging roads, highway road cuts as well as river shores. With the use of a 12 lb. sledge hammer, 5 to 10 kg of rock was extracted at each location. Care was taken to acquire only fresh (unweathered), homogeneous rocks from a coherent outcrop so that whole-rock integrity could be maintained for accurate representation in the results. At each sample location a GPS reading was taken and the site was recorded on a map of the area and in a field catalogue.

Crushing and powdering took place in the rock crushing room at McMaster University. A single sample was first scrubbed with a wire brush to remove any soil or moss which may contaminate the sample. Samples were then split into 5 cm^3 pieces using a hydraulic splitter. At this stage any weathered sections or impurities were removed. These pieces were then processed through a jaw crusher, which ground the sample into gravel sized grains of about 1 cm^3 or smaller. The jaw crusher was first contaminated with some of the sample to avoid contamination of dust from previous samples. Using a table top sample divider to homogenize the sample and separate out 100 ml to 200 ml of gravel. In order to produce a fine rock powder suitable for dissolution in acid during later steps, the gravel was loaded into a tungsten carbide disc mill which was then placed in a shatterbox. After 5 minutes of pulverization, a find sand was produced which was then poured onto a clean sheet of paper. Approximately one half of the powder was discarded and the other half loaded back into the disc mill for further pulverization. After 5 to 10 more minutes of pulverization a fine powder (approximately 300 mesh size) was transferred back to the paper and 80 ml to 100 ml of the sample was transferred into a clean glass container. Due to careful cleaning and separation techniques, the powdered rock retrieved at the end of this process is still representative of the whole-rock source.

A.3 – Dissolution and Cation Chromatography

Weighing

First, Teflon coated, plastic bombs were labelled for each sample and then treated to remove static to avoid measurement inaccuracies in finding mass from static build up. Each bomb was then placed on an analytical scale and weighed twice to ensure that all the static had been removed, its mass then recorded. Gradually, 100 mg of sample powder was added to each bomb with a clean spatula.

Dissolution

Dissolution of the rock powder took place in the Spectrochemisty Clean Lab at McMaster University. Strict WHIMS protocol for handling hazardous chemicals was followed at all times. Bombs were lined up in a fume hood where 10ml of Hydrofluoric Acid (HF) was added to each. After the lids had been secured, bombs were placed in protective Teflon jackets and loaded into an oven. After 3 days in the oven at 140 degrees Celsius the bombs were removed, cooled and each loaded with approximately 5ml of concentrated (16 molar) nitric acid (HNO_3) then placed on a hotplate for evaporation. To complete the dissolution, 5ml of 6 molar hydrochloric acid (HCl) was added to the bomb and loaded back into the oven for 24 hours to complete the dissolution process. Once samples were removed, they were checked for any undissolved residues. If the samples were fully dissolved they were ready to be split and spiked.

Splitting and Spiking

The splitting process began by making two aliquots allowing for both isotope ratio analysis (IR) and isotope dilution (ID) analysis. Samples were diluted with 10ml of de-ionized water. Each bomb was then placed on the analytical scale and a mass was found for the bomb, sample, and lid and recorded. Each sample was then split among two beakers, one with sample for IR and one for ID. Samples marked for isotope dilution were then spiked with a ^{150}Nd-^{149}Sm enriched solution. This process began with weighing of the spike bottle. This mass was tarred and approximately 200mg of spike was added to a sample followed by reweighing of the spike bottle and the measurement recorded. Beakers for both ID and IR samples were placed back on hotplates for evaporation. Samples were then redissolved in 2 mL of 2.5 molar HCl and transferred into plastic test tubes and centrifuged for 10 minutes. Samples were then ready for cation chromatography.

Cation Exchange Chromatography

At this stage samples were loaded into cation columns which separate the rare earth elements based on their binding affinities to the resin contained within the columns. This resin substrate contains a permanent negative charge which causes a cation binding affinity to the resin. These affinities are based on the pH conditions and ionic strength thus, by using eluents with differing strengths materials can be preferentially rendered as stationary phased or mobile phase material, the latter which is eluted from the columns using strong acid and collected for further separation. A pipette was used to load 1 mL of the sample into the cation columns, which was eluted with 2 mL of 2.5 HCl. Another 36 mL of 2.5 HCl was added along with 12 mL of 2M HNO_3, which removes Na, Ca and other major elements. 7.5 M HNO_3 was then added, which collects the REEs. This was evaporated under heat lamps and 1 mL of 0.3 M HCl was added in order to load the sample on the next set of columns.

REE Chromatography

A pipette was used to load 1 mL of 0.3 M HCl solution into the REE columns, which was then washed in with 2 mL of 0.3 M HCl. Another 24 mL of 0.3 M HCl was added, followed by 12 mL of 0.3 M HCl, responsible for collecting the Nd. Subsequently, 2.5 mL of 1 M HCl was added after which, 12 mL of 1 M HCl was used to collect the Sm. The resulting solutions are evaporated under a heat lamp. One drop of 0.0003 M H_3PO_4 was then added to the residue, and evaporated down until near dryness.

A.4 – Mass Spectrometry

Isotopic analysis was carried out on a VG isomass 354 mass spectrometer in the McMaster Isotope Geochronology lab. Double, rhenium tantalum filament beads were fabricated and then out-gassed in preparation for the sample loading. A measured 0.4 μL of 0.2 molar H_3PO_4 was added to the sample and the solution was added to the centre Rhenium filament. A 2.0 amps current was then passed through the sample to dry it. The bead was then ready to be loaded into the mass spectrometer for analysis.