ND ISOTOPE DELINIATION OF ARCHEAN AND PALEOPROTEROZOIC CRUSTAL TERRANES: CRYPTIC SUTURING AND ENSIALIC ARC FORMATION IN THE PARENT-CLOVA REGION OF SOUTH-CENTRAL QUEBEC

By

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ABSTRACT

One of the key components in the crustal evolution of the Canadian Shield was the ~1.0 Ga Grenville orogeny, which resulted in major northwest directed thrusting of pre-Grenvillian crustal allochthons against the Laurentian foreland. This orogenic episode resulted in extensive metamorphism, terminal collisional uplift and subsequent erosion, such that current surface geology expresses mid- to deep- crustal components.

Originally distinguished from adjacent provinces in the Canadian Shield based on isotopic, structural and metamorphic signatures; the first-order crustal terranes of the Grenville Province in Quebec are primarily comprised of the relatively stationary (Archean - Paleoproterozoic) Parautochthonous Belt and the more laterally transported (Paleoproterozoic - Mesoproterozoic) Allochthonous Belts. Although a first-order crustal formation map for most of the Grenville has already been compiled, 50,000 km^2 of south-central Quebec has remained unmapped, with weak constraints on boundary locations as well as an overall lack of understanding of crustal mixing processes within the region.

Over 90 new Nd-isotope analyses provide crustal formation age constraints for granitoid orthogneisses from south central Quebec, and are used to delineate three principal crustal terranes, interpreted respectively as reworked Archean, a mixed ensialic arc, and juvenile Mesoproterozoic crust. The resistance of the Sm-Nd isotope system to metamorphic resetting has provided a reliable method to investigate the ages of these pre-Grenvillian terranes, as age of initial extraction from the mantle provides the best possible protolith indication.

Nd-isotope and major element analysis has indicated the presence of reworked Archean crust in the north, bounded by the ABT, and a juvenile Mesoproterozoic terrane to the south (Quebecia). A block of mixed ages, of possible ensialic arc origin, constitutes the central section and may overlie a diffuse cryptic Archean-Proterozoic boundary. The tectonic evolution of the region can be explained through a subduction flip model, in which a 1.5 Ga oceanic arc terrane became obliquely sutured onto the continental margin, resulting in a flip to north-dipping subduction under the new composite margin. This subduction flip caused ensialic arc formation in a 50 km wide zone subparallel to the ABT, which reworked Quebecia rocks through continental arc magmatism.

To the south of this region, back arc spreading within the ensialic arc led to the development of a rift zone that was filled by clastic and carbonate sedimentation, forming the Central Metasedimentary Belt. Some of these rocks were later thrust northwards over older crust during the Grenville Orogeny, forming the Cabonga Nappe complex. The extent of this terrane has also been further constrained by Nd isotope mapping in this study.

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CHAPTER 1
THE GRENVILLE PROVINCE

1.1 Introduction

The Canadian Shield is one of the fundamental pieces that make up the world's cratonic suite and represents over 2 billion years of crustal formation, growth and change. The youngest geologic province within the shield is interestingly enough one of the least understood, the Grenville Province.

Formed during the amalgamation of Rodinia, the Grenville Province represents a long-lived ancient orogenic belt which comprises the southwestern margin of the Canadian Shield. Once an active convergent continental margin, new continental crust was intruded and sutured onto the Laurentian foreland for nearly a billion years until terminal collision of the Grenville Orogeny at 1.1 Ga halted subduction and crustal growth. The continent-continent collision that formed the Grenville Province is analogous to that of the Himalayas (Easton, 1992), and resulted in considerable crustal shortening and thickening. However, the multiple tectonic pulses and subsequent terminal uplift essentially erased much of the region's geologic history, which has led to great debate when trying to decipher the original 'growth history' of the province.

Although crustal components associated with the Grenville Orogeny can be found globally, the Canadian portion of the Grenville Province is located along the southeastern margin of the Canadian Shield, and appears as a longitudinal belt stretching from the Atlantic coast in the northeast to Georgian Bay in the southwest, where it is overlain by Paleozoic sedimentary rocks. The northwestern limit of the Grenville Province is defined by the Grenville Front, where rocks associated with the Grenville orogeny are juxtaposed against the Archean aged Superior Province (Figure 1.1). Approximately 400 km wide, 2000 km long, and nearly 1,000,000 km^2 in area, the Canadian component forms a significant portion of the Canadian Shield. However, large areas of the province have not been studied in detail, due to its complexity and lack of mineral resources.

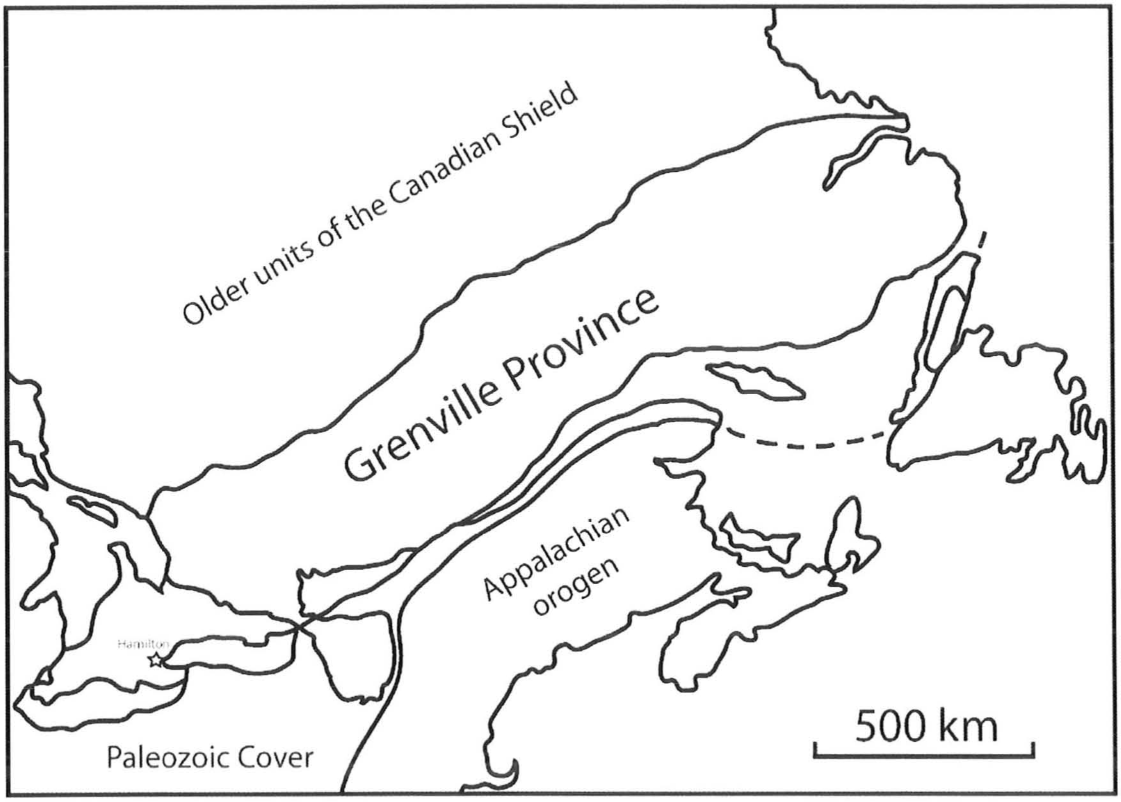

Figure 1.1 – Extent of the Grenville Province within the eastern portion of the Canadian Shield (modified from Dickin et al., 2007).

Due to its relatively long and complex geologic history, early studies lacked sufficient insight to formulate complete theories of the Grenville orogen. Logan's (1847) early observations of the rock types in central Quebec led to a somewhat superficial label as the "sea of gneisses", reflective of the complex geology that comprised that section of the Grenville Province. Only with the refinement in understanding of isotopic and geochemical systems could multi-component studies be employed to unravel the true evolutionary provenance of these rocks.

The aim of this contribution is to correlate first-order crustal terranes using Nd isotope analysis of orthogneisses from the Parent-Clova region of central Quebec to fill in one of the last remaining gaps in the crustal formation map of the Grenville Province.

1.2 Structural Divisions of the Grenville Province

With the beginning of modern geochronological studies, further insight into the internal structural divisions of the Grenville Province emerged. Stockwell (1964) utilized widespread K-Ar isotopic evidence to investigate cooling trends within the Grenville, and defined the extent of the ca. 1.0 Ga orogenic expression. Although this provided a basis for interpreting the Grenville as a unified orogeny, Stockwell recognized that the Grenvillian event had potentially overprinted the effects of earlier pre-Grenvillian orogenies.

Less than a decade later, Wynne-Edwards (1972) used structure, metamorphism and lithology to divide the Grenville Province into geological segments based primarily on metamorphic character. This allowed the Grenville Province to be divided into seven distinct areas, which are in part still recognized today: the Grenville Foreland Belt, the Grenville Front Tectonic Zone, the Central Gneiss Belt, the Central Metasedimentary Belt, the Central Granulite Terrain, the Baie Comeau Segment and the Eastern Grenville Province (Figure 1.2). Although this provided a better understanding of the distinct metamorphic characteristics expressed by each, geochronologic studies were needed to decipher the polycyclic history suffered by each individual segment of the orogeny, demonstrating that provenance cannot be discerned by metamorphic variation alone.

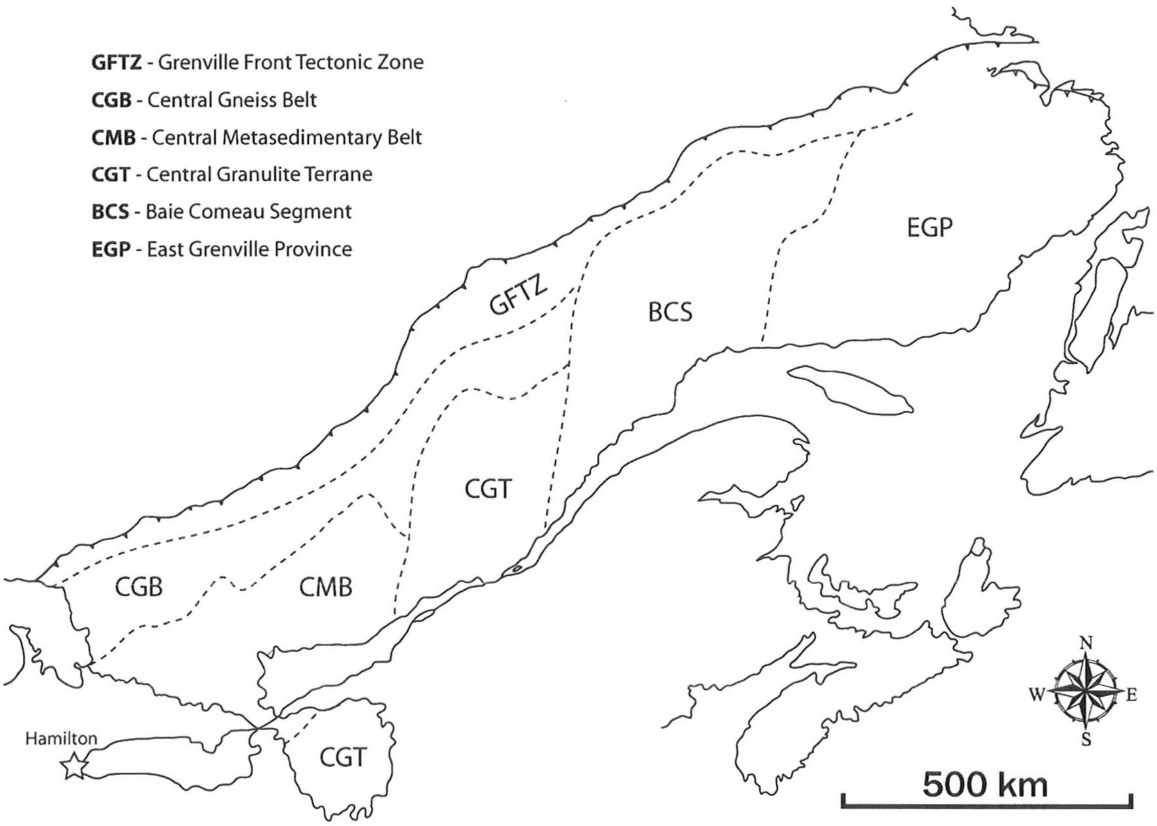

Figure 1.2 – Lithotectonic domains of the Grenville Province based on the nomenclature proposed by Wynne-Edwards (1972).

Following advances in understanding the regional structure of the Grenville Province in the early 1980s, the importance of recognizing large scale ductile shear zones and their kinematics added to a refinement of Grenvillian crustal architecture. Rivers et al. (1989) built upon these models in their analysis of the whole Grenville Province, using modern aeromagnetic and U-Pb isotope analysis to establish more fundamental divisions of the Province based on geologic, geophysical and geochronological evidence. These properties allowed Rivers et al. (1989) to identify three first-order longitudinal tectonic belts that are separated by three first-order tectonic boundaries; divisions which make up the present day nomenclature of the Grenville Province (Figure 1.3).

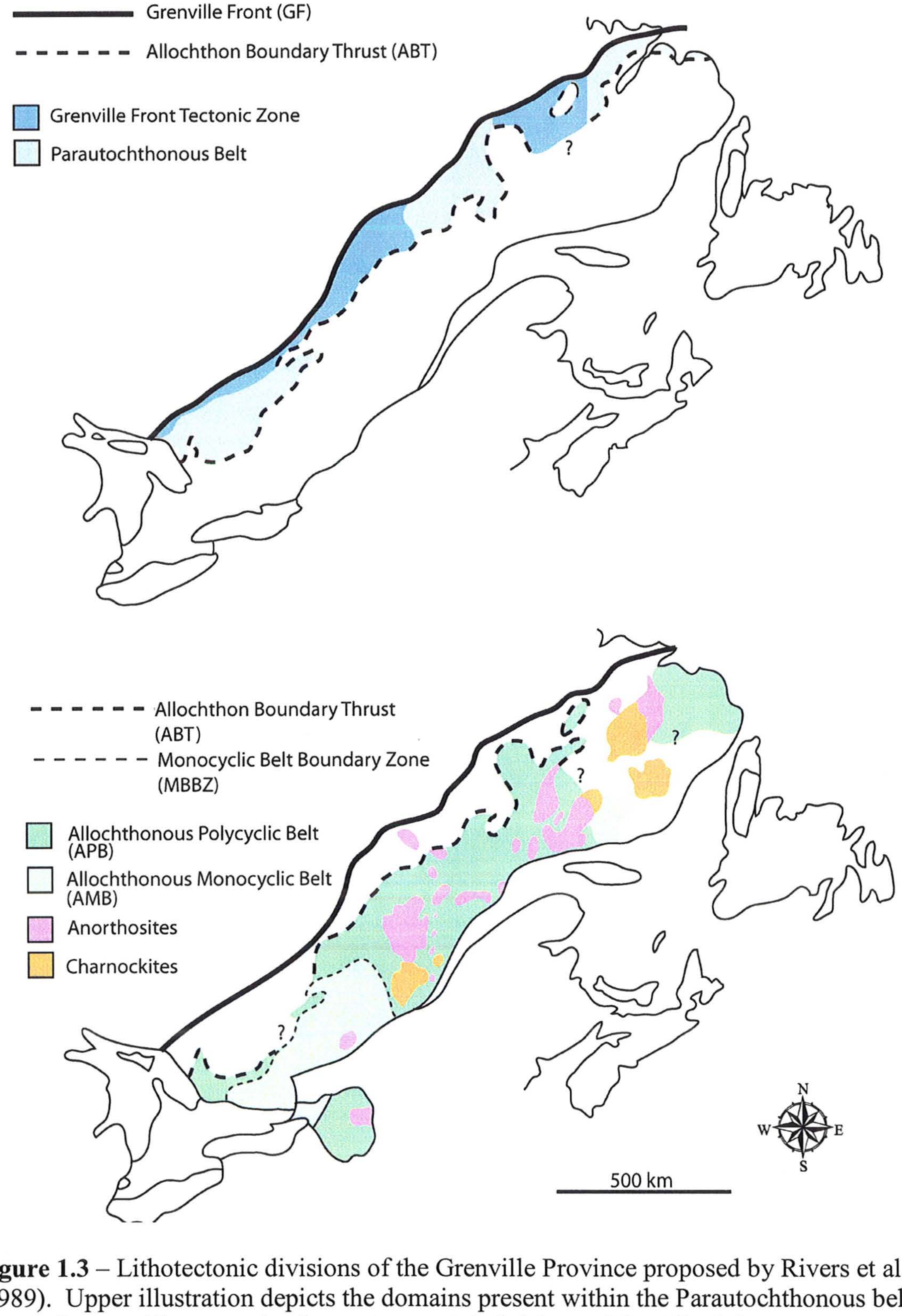

Figure 1.3 – Lithotectonic divisions of the Grenville Province proposed by Rivers et al. (1989). Upper illustration depicts the domains present within the Parautochthonous belt. Lower diagram illustrates the first-order crustal divisions of the Allochthonous Monocyclic Belt (AMB) and Allochthonous Polycyclic Belt (APB), along with major Anorthosite-Mangerite-Charnockite-Granite (AMCG) plutonic bodies.

1.3 Belts and Boundaries

Traversing from northwest to southeast across the Grenville Province, the three first-order crustal belts proposed by Rivers et al. (1989) are the Parautochthonous Belt (PB), Allochthonous Polycyclic Belt (APB) and the Allochthonous Monocyclic Belt (AMB). These are separated by the Grenville Front (GF), Allochthon Boundary Thrust (ABT) and the Monocyclic Belt Boundary Zone (MBBZ), respectively. The Grenville Front is the zone that separates the Archean craton to the northwest from rocks of Archean provenance that were metamorphosed by crustal burial effects associated with the terminal Grenville orogeny. It is recognized as a major crustal discontinuity that truncates the adjacent Archean Superior Province and is identified by major uplift, a change in metamorphic grade, faulting and mylonitization.

The hanging wall to the Grenville Front and the oldest first-order longitudinal belt within the Grenville is known as the Parautochthonous Belt. This belt ranges in width up to 150km, is characterized by a degree of lithological continuity with the Superior Foreland northwest of the Grenville Front, and exhibits limited lateral crustal movement. Modern aeromagnetic data has proved to be of some use when distinguishing the extent of the PB, as it is generally represented by a subdued aeromagnetic signature. Frith and Doig (1975) were the first to document an isotopic age boundary coinciding with a magnetic discontinuity in the central Grenville Province, where low relief magnetic patterns defining Archean-aged tonalitic gneisses are truncated by high relief intense swirling patterns in Paleoproterozoic crust to the southeast.

The Allochthon Boundary Thrust (ABT) is a first-order structural boundary, formed by low angle thrust faulting, which separates the PB to the northwest from the

APB in the southeast. It has been mapped along almost the entire length of the Grenville, and is generally subparallel to the Grenville Front. Although the ABT exhibits a more complex trajectory than the Grenville Front, its location is fairly well established in much of Labrador and eastern Quebec. However, several regions remain in Ontario and western Quebec where better definition is needed.

Although the ABT sometimes exhibits metamorphic grade inversions caused by thrusting (Rivers et al., 2002), the intense polycyclic nature of metamorphism that is associated with the suturing and accretionary amalgamation of younger crustal terranes onto the PB has led to difficulties in accurately mapping its location. However, the ABT often coincides with breaks in isotopic age between the Archean and Paleoproterozoic aged PB and the younger Mesoproterozoic crustal terranes of the APB. As a result, the Sm-Nd isotopic system has been able to accurately map the location of the ABT throughout much of the Grenville Province, due to its ability to represent the age of initial crustal extraction from the mantle. This allows the 'break' in isotopic ages to be used as a mapping tool to identify major crustal boundaries.

The APB is the largest of the longitudinal belts in the Grenville Province. It is formed of terranes that have been thrust to the northwest over the PB, and represents the hanging wall to the ABT (Rivers et al., 1989). The polycyclic nature of this belt is demonstrated by supracrustal rocks that show evidence of having undergone more than one metamorphic event during pre-Grenvillian tectonic collisions. The resulting geology is that of high-grade (upper amphibolite to granulite facies) metamorphic rocks such as orthogneisses and paragneisses which host younger plutons.

The MBBZ is a first-order tectonic boundary that separates the APB and the AMB, dividing the late middle Proterozoic monocyclic supracrustal rocks from the older polycyclic rocks. However, in contrast to the ABT, the MBBZ shows no evidence of regional inversion of metamorphic grade (Rivers et al., 1989). This boundary has been mapped into south central Quebec and is identified immediately to the south of the study area.

The youngest of the first-order belts is the AMB, which hosts crustal units that have only been subjected to a single (Grenvillian) metamorphic episode, and are invaded by plutonic rocks only during that time. The second-order terranes that comprise the AMB are primarily supracrustal rocks of lavas and sediments, deposited prior to the terminal collision of the Grenville orogeny. While these rocks were locally thrust further to the north in the Cabonga region of western Quebec (Rivers et al., 1989), Paleozoic sedimentary rocks in southern Ontario define their southwestern limit.

As a result of both orogenically associated exhumation and subsequent erosion, at the present day the Grenville exposes mainly crystalline rocks that were subject to deformation and metamorphism at lower to mid-crustal levels. Due to the extensive lateral transport experienced by various allochthonous crustal units and subsequent erosion, certain regions in the Grenville Province host structural windows and klippen that result in isolated groupings of rocks respectively older and younger in age than the surrounding crust. Exemplified by the delineation of the Lac Gordon klippe (Herrell et al, 2006), the recognition of these structures allows for more accurate boundaries to be drawn, however requiring more detailed sampling and mapping efforts.

1.4 Styles of Crustal Addition in the Grenville Province

In order to accurately reconstruct the crustal growth history within the Grenville Province, it is necessary to obtain crustal formation ages, which represent the time when new crust was produced in arc systems, where water released by subduction of hydrated oceanic crust facilitates widespread mantle melting and voluminous calcalkaline magmatism. Over time, this magmatism can generate large volumes of thickened mafic arc crust, typically observed in island arc systems, and also produces the necessary heat flux to partially re-melt earlier mafic crust to generate more silicic granitoid upper crust.

The new crust produced is of ensimatic nature, as it is formed on or very near to oceanic crust. This subduction-driven mechanism allows for the generation of 'juvenile' crustal terranes in island arc systems that can contribute to continental growth if they are accreted onto a cratonic nucleus in some form of orogenic collision. This was the case for the Abitibi Belt in the southern segment of the Superior Province, in which, prior to 2.7 Ga, juvenile arc crust was rapidly generated through island arc systems and accreted together within a few tens of millions of years, resulting in rapid continental growth (Hoffman, 1989).

Juvenile crustal generation can also occur through back arc continental rifting, as established continental crust is stretched and ruptured, allowing for basaltic magmatism to fill in these zones with thin oceanic crust. The propagation of the rifting generally results in the formation of an oceanic basin; however occasionally the rift may fail before the continent has fully ruptured, resulting in a rift zone with a juvenile crustal signature within the pre-existing continental crust. This rift zone eventually fills in with sediments and/or basalts such that it approaches original continental crust thickness, and can be exemplified by the 1.1 Ga Keweenawan (Midcontinental) Rift Zone of the United States.

Another more complicated manner of crustal formation is through the establishment of an Andean type ensialic arc, where arcs are produced intracontinentally, or just along a continental margin. This may result in the production of hybrid geochemical signals as the established pre-existing continental crust is reworked by younger magmatism which results in varying degrees of crustal mixing.

With widespread agreement on terrane accretion being the largest contributor to crustal growth in the development of the Grenville Province, Hanmer et al. (2000) published a case against post 1.4 Ga accretionary tectonics in the Grenville which correlated geological, geochronological and petrological evidence to disprove the notion that island arc accretion was the fundamental means of crustal growth shortly before the Grenville orogeny. Hanmer et al. (2000) observed that there was no opportunity to accrete new terranes within the Ontario-Quebec-Adirondack segment of the Grenville after ca 1.2 Ga, and attributed much of the crustal addition at this time to the long-lived reworking of the southeast facing, Andean-type margin of Laurentia.

Martin and Dickin (2005) showed that isotopic and geochemical evidence near the Lac St. Jean region of Quebec produced a zone with a mixed isotopic signature, indicative of this manner of crustal addition. They determined that the zone was a reworked portion of Laurentia that had been the result of ensialic arc-type magmatism, associated with the docking of the Mesoproterozoic aged first-order terrane of Quebecia onto the Laurentian foreland. This has implications for the current study area, as Martin and Dickin (2005) sampled directly to the northeast of this area, and a continuation of the mixed ensialic signature would further support Andean-type ensialic arc formation as a result of the docking of Quebecia onto the Laurentian foreland.

1.5 Geochronologic Studies of the Grenville Province

Due to the polycyclic history suffered by much of the Grenville Province, most nuclide systems cannot accurately record the age of crustal formation. Various isotopic systems have been used to model the history of the Grenville, but some traditional methods such as K-Ar dating are subject to metamorphic resetting, yielding ages ca. 1.0 Ga (Easton, 1986) that are more representative of time of exhumation, uplift and orogenic cooling, rather than of the formation age of the rock.

Although the geologic complexity proves problematic, other isotopic systems such as U-Pb can still be useful in their own respect. U-Pb is capable of producing an accurate measure of the time of crystallization within unique geologic units, and thus establishes a younger limit on the formation age of any particular crustal terrane. Krogh (1989) and Krogh et al. (1992), exhibited the usefulness of U-Pb dating by recording a range of Archean U-Pb ages south of the Grenville Front, illustrating that multiple metamorphic/intrusive events can be recorded in the Grenville Province by the various crystallization ages within regional terranes. However, this can be problematic when addressing the overall growth history of the Grenville, where the wide range of U-Pb crystallization ages observed in reworked Archean rocks southeast of the Grenville Front fail to tightly constrain the formation age of crustal domains, which is needed to define first-order crustal divisions within the Grenville Province (Dickin, 2000).

In order to establish the formation age of the crust, U-Pb isotope evidence must be paired with a metamorphic resistant isotope system that can date the upper limit of the time of crustal extraction from the mantle. Such an age can be generated by the Sm-Nd method, by producing Nd model ages that are an estimate of the time at which the crust was extracted from the mantle, representing the oldest event in the history of a crustal terrane. This method proves to be an ideal tool because of the lack of significant Sm/Nd fractionation during most erosional, sedimentary and metamorphic processes.

The Grenville Province has been the focus of Sm-Nd crustal formation research for over twenty years, with a multitude of studies using the Nd model age method (in combination with other geologic evidence) to decipher pre-Grenvillian reconstructions (e.g. Dickin and McNutt, 1989; Dickin and Higgins, 1992; Dickin, 2000; Martin and Dickin, 2005; Dickin et al., 2009). Due to the extensive metamorphic histories of the Grenvillian rocks in the study area, the Sm-Nd method was preferred as it is resistant to isotopic resetting, and has already been successfully used to map much of the crustal formation of the Grenville (Dickin, 2000).

The aim of this thesis will be to use Sm-Nd isotopes to define the position of the ABT in the south central portion of Quebec, and investigate the provenance of rocks found within this region. This will help to complete the first-order crustal formation map of the Grenville Province, as well as investigating the continuation of different crustal belts that have previously been recognized in areas adjacent to the present study area. For example, ensialic arc signatures were observed by Martin and Dickin (2005) directly to the northeast, juvenile 1.5 Ga crust (Quebecia) was identified by Dickin (2000) to the southeast, while a proposed back arc rift was identified in the Central Metasedimentary Belt to the southwest of the current study area (Dickin et al., 2009).

CHAPTER 2
SM-ND ISOTOPE METHODOLOGY

2.1 Introduction

4.57 billion years ago, the early Earth was a molten planet covered by an ocean of lava. Some short while after planetary coalescence, lighter elements in the mantle began to 'melt off' from their more dense counterparts as magmas were extracted from the upper mantle, forming buoyant new continental crust. The onset of oceanic crustal subduction in the early Earth resulted in focused areas of mantle melting to produce microcontinents, and over time macrocontinents.

2.2 Sm-Nd Use in Geochronology

It has been known for some time that some radiometric isotope systems can play an important role in unraveling the geologic past, considering that during the cooling of the solar nebula conditions existed such that all solar system bodies were formed with homogenous ratios of most isotopes (Grossman et al., 1974).

The value of the Sm-Nd isotope system as a tool for studying continental evolution was first recognized by DePaolo and Wasserburg (1976), when they made the first Nd isotope determinations on terrestrial igneous rocks. They investigated the variations in the Sm/Nd ratio that is observed on earth due to differentiation. This occurs as continental crust forms, resulting in fractionation and Nd-enrichment of continental crust while depleting the mantle, showing a strong correlation to the Chondritic Uniform Reservoir (CHUR) evolution line that was determined from meteorites. This work facilitated the increased potential for the Sm-Nd system to be used as a viable geochronometer, aiding in long lived geologic reconstructions.

Due to the long half-life of ^{147}Sm (ca. 106 Ga), Sm-Nd analysis of terrestrial rocks requires the measurement of minute variations in the daughter isotope ratio over time, and is well suited for the age range of crustal extraction experienced in the Grenville. Adhering to the law of radioactivity, the Sm-Nd isotopic system can be used to calculate the age of a rock, using the following formula:

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

Where: λ = radiometric decay constant
t = time in years

In order to derive ages from this equation, the present day isotopic ratios of $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ are needed, along with the initial isotopic ratio of $^{143}Nd/^{144}Nd$. Present day ratios are measured through conventional mass spectrometry, but the initial ratio of $^{143}Nd/^{144}Nd$ can only be determined through the use of isochrons or a model for the composition of the magma source. In order for an isochron to provide the initial ratio, present day values of $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ are plotted on the isochron, with the slope of the line equaling λt. This isochron line provides suitable results, but requires a large sample suite for rocks of the same age and is both cost and time inefficient.

Crustal extraction ages can also be determined by an Nd-model age, which is calculated by assuming that the initial $^{143}Nd/^{144}Nd$ ratio of the rock is equal to the $^{143}Nd/^{144}Nd$ ratio of the mantle at the time of extraction (Arndt and Goldstein, 1987).

This method allows for discrete Nd model ages to be generated through the use of CHUR, taken from chondritic meteorites representing the original Sm-Nd ratio in the mantle, as both Sm and Nd have similar chemical properties and only undergo slight relative fractionation during crystal-liquid processes (Figure 2.1).

The epsilon (ϵ) Nd notation was developed by DePaolo and Wasserburg, whereby initial $^{143}Nd/^{144}Nd$ isotope ratios could be represented in parts per 10^4 deviations from the CHUR evolution line. The ϵ notation allows for all data to be normalized to CHUR, hence removing effects of different fractionation corrections which have been applied for Nd analysis. εNd can therefore be represented by the following formula:

$$\varepsilon Nd(t) = [\, (^{143}Nd/^{144}Nd)_{sample}(t) \,/\, (^{143}Nd/^{144}Nd)_{CHUR}(t) \;-\; 1 \,] \times 10^4$$

DePaolo and Wasserburg (1976) noted that if the CHUR evolution line defines the initial ratios of continental igneous rocks through time, then measurements of $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ in any crustal rock would yield a model age of the formation of the rock. This is true given that there was sufficient Nd/Sm fractionation during the process of crustal extraction from the mantle to give a reasonable divergence of crust and mantle evolution lines. The model age is then given as:

$$T_{CHUR} = (1/\lambda) \times \ln [1 + ((^{143}Nd/^{144}Nd)^0_{sample} - (^{143}Nd/^{144}Nd)^0_{CHUR})) \,/\, ((^{147}Sm/^{144}Nd)^0_{sample} - (^{147}Sm/^{144}Nd)^0_{CHUR}))]$$

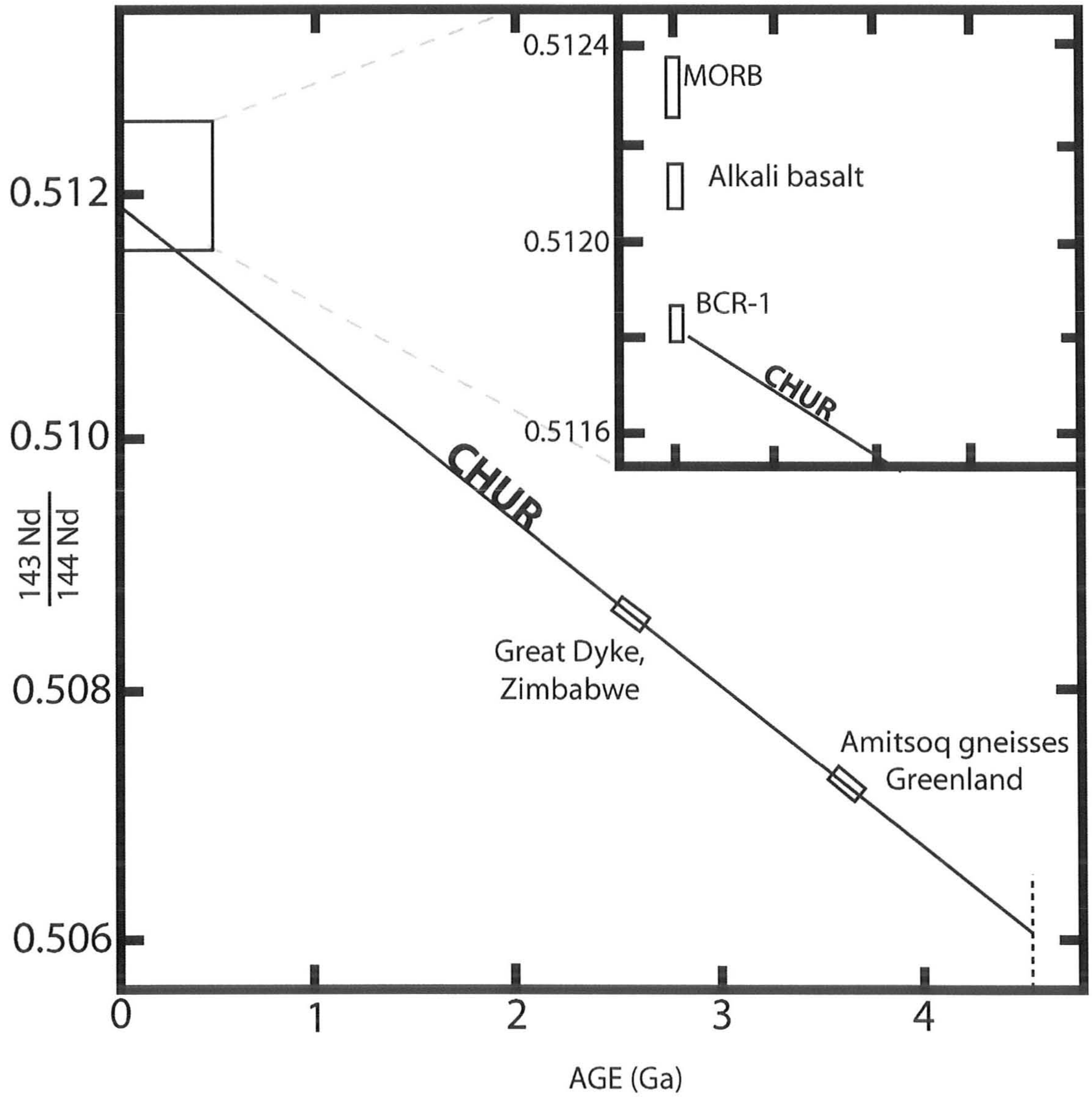

Figure 2.1 – Chondritic Uniform Reservoir (CHUR) evolution curve after DePaolo and Wasserburg (1976).

While observing the good fit of Archean plutons to CHUR, DePaolo and Wasserburg (1976) noted that young mid ocean ridge basalts (MORB), representing present day mantle derived material, exhibit a highly positive ϵ deviation from the CHUR evolution line. This evidence, along with subsequent analysis of Proterozoic metamorphic basement rock from the Colorado Front Range, led to the development of the Depleted Mantle model, whereby deviations from the CHUR line, measured in ϵ Nd, indicate the degree of differentiation in the mantle (DePaolo, 1981).

DePaolo was able to represent the Nd isotope evolution of a progressively depleted reservoir; a curve that is close to the CHUR evolution line in the Early Archean, but diverges progressively to the present day. The increase of ϵ Nd over time is the result of the progressive loss of Nd relative to Sm from the mantle, resulting in a CHUR baseline that is less relevant with each magmatic event. The Depleted Mantle model (T_{DM}) proposed by DePaolo (1981) shows that as time passes, the difference in T_{CHUR} and T_{DM} increases, yielding different model ages (Figure 2.2).

The determination of ϵ Nd allows for the evolution of the depleted mantle to be represented, where the composition of the depleted reservoir, relative to CHUR, at time T, is given as:

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

(Dickin, 1995)

Sm-Nd model ages calculated using this depleted mantle curve are denoted T_{DM}, which is a more accurate indicator of crustal formation ages than T_{CHUR}, which does not take into account the progressively depleting mantle source. This allows for the Depleted Mantle model (T_{DM}) to determine crustal formation ages through the use of Nd-isotope analysis in juvenile mantle-derived rocks of different ages.

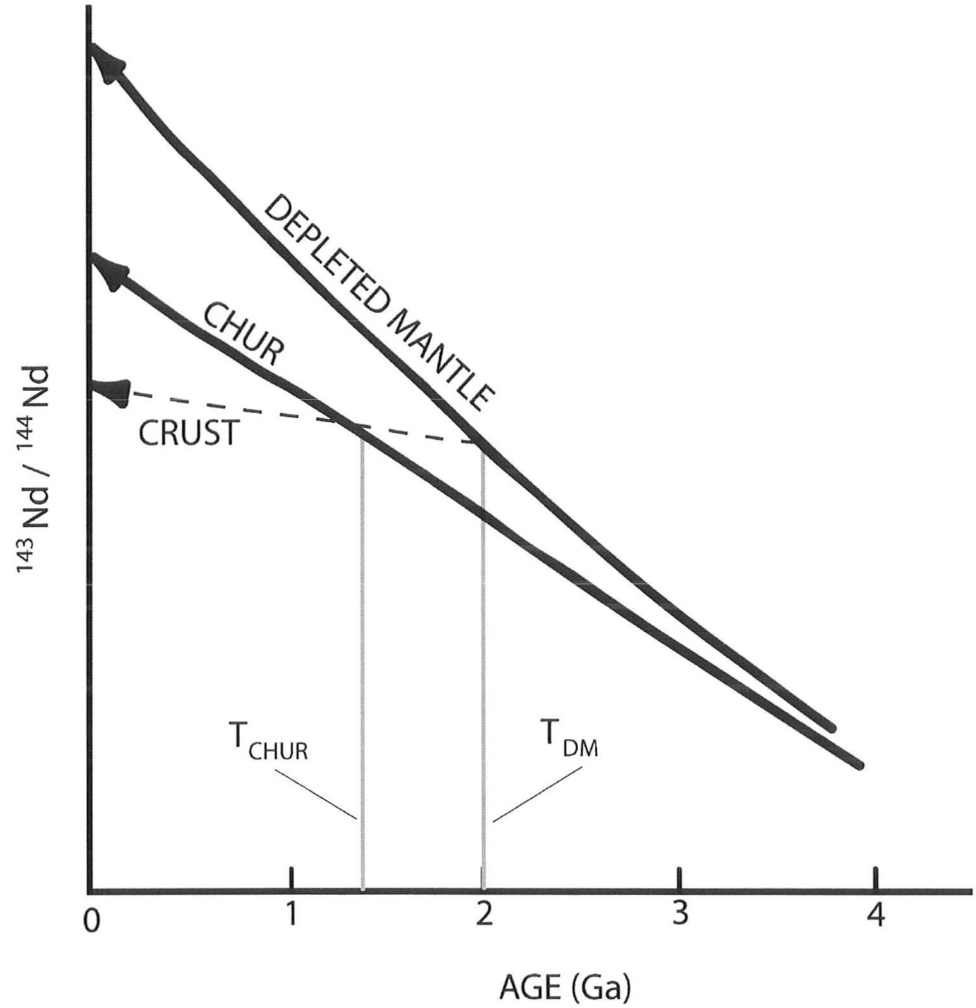

Figure 2.2 – Depleted mantle evolution curve in terms of $^{143}Nd/^{144}Nd$, after DePaolo (1981).

Although the resistance to metamorphic resetting of the Sm-Nd system is well established, many researchers became hesitant of the validity of Nd model ages, as problems regarding contamination effects from the mixing of various units were still poorly understood. Arndt and Goldstein (1987) highlighted fundamental assumptions that must be made when using Nd model ages to correlate time of crustal segregation from the mantle. These assumptions are as follows: (1) It is necessary to recognize the continental isotopic evolution from a Depleted Mantle source, (2) a short occurrence between emplacement of a sample in the continental crust and the acquisition of the representative Sm-Nd ratio, and (3) the Sm-Nd ratio of the sample cannot be modified by succeeding intracrustal events. Although this could prove problematic for the polycyclic history of much of the Grenville, Nelson and DePaolo (1985) pointed out the validity in using Nd model ages to represent the average age of mixed sources, such that crust-mantle differentiation events can be identified by model age groupings when corresponded to known geologic events. Despite various concerns about the accuracy of samples with mixed origin and zircon inheritance (McCulloch, 1987), the Sm-Nd method provided a solid basis on which to construct representative crustal formation assemblages, especially when combined with additional geologic and isotope evidence.

CHAPTER 3
REGIONAL GEOLOGIC CONTEXT

3.1 Introduction

Many Sm-Nd isotopic studies have been conducted over the years, focusing on developing a first-order crustal formation map of the entire Grenville Province. The current study area remains as one of the last remaining gaps in this crustal formation map, as various studies have only been conducted in the surrounding regions (Dickin, 2000; Guo and Dickin, 1996; Martin and Dickin, 2005; Dickin et al., 2009). The following is a brief review of previous Sm-Nd isotopic studies documenting crustal formation in their respective regions (Figure 3.1), and will help to provide further insight into the present study area represented by the void in the crustal formation map.

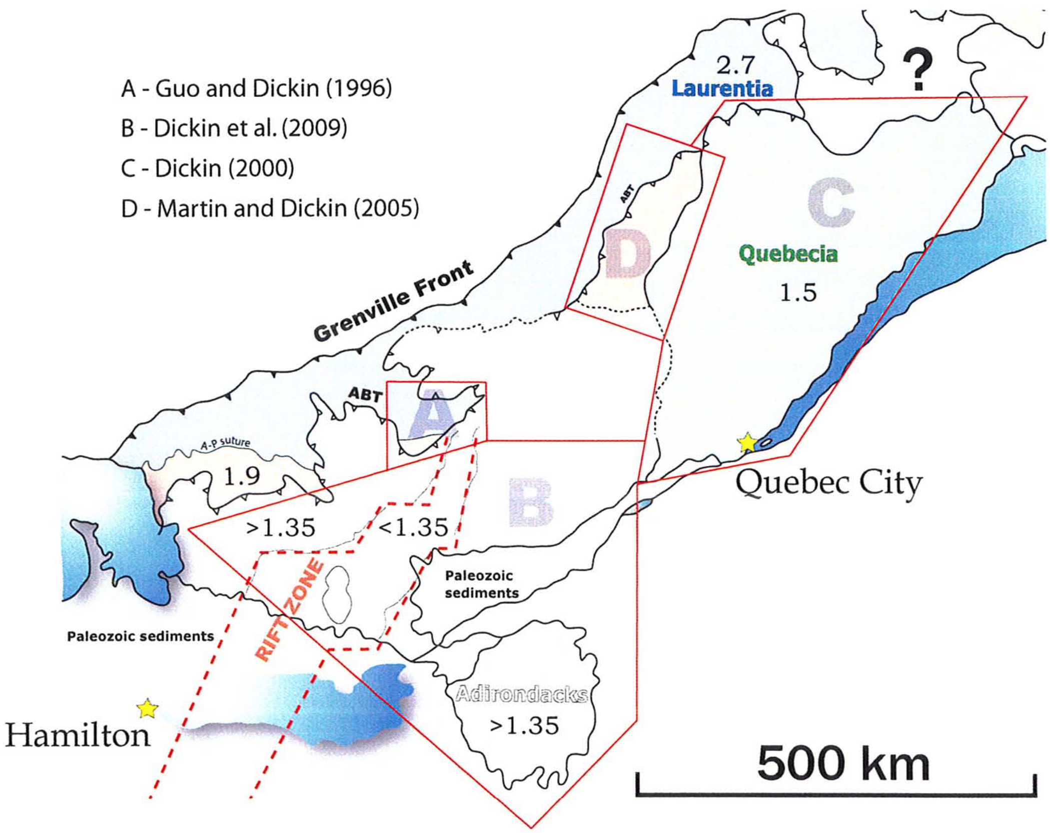

Figure 3.1 – Map of various past crustal formation studies in the southern portion of the Grenville Province surrounding the current study area.

3.2 Northwest of the Study Area

Dickin and McNutt (1989) began work on establishing a Penokean aged suture running across Ontario and western Quebec, separating Archean and Proterozoic aged crustal terranes within the PB. The Sm-Nd evidence collected from orthogneisses across the region were used to produce a crustal formation map showing that 1.9 Ga model ages south of the suture represented an oceanic island arc formed over a southerly dipping subduction zone, which had collided with the cratonic foreland during the Penokean orogenic event. This ability to delineate internal boundaries within the PB, based on crustal extraction ages, allowed the Sm-Nd method to chart the early crustal history of the Grenville Province. However, the use of crustal extraction ages to determine the growth history of the Grenville was still in its infancy, as only regional studies were being conducted. A greater swath of data from across the entire Grenville was needed to complete a representative picture of the orogeny, such that all first-order crustal units can be characterized in terms of age of crustal extraction/formation.

Later works (Guo and Dickin, 1996; Dickin, 2000; Dickin and Guo, 2001) continued to follow the Archean-Proterozoic suture through Ontario and southwestern Quebec, while refining the southern limits of Archean crust and the position of the ABT in Ontario and western Quebec. Sm-Nd evidence showed that the main trace of the ABT, separating the parautochthonous and allochthonous rocks in the Mattawa region near the Ontario-Quebec boarder, was further south than previously proposed (Davidson, 1998; Ketchum and Davidson, 2000), and that constraints on the ABT boundary based on the extent of 1.16 Ga coronitic metagabbros could not sufficiently demarcate the extent of allochthonous terranes, due to the limited distribution of matabasic outcrops.

The Archean-Proterozoic suture was also traced throughout the region, and generally follows the Mattawa fault until it disappears beneath polycyclic allochthonous rocks associated with the Lac Wilson nappe, located in southwestern Quebec (A-P suture in Figure 3.1). These boundary interactions allowed for insight regarding crustal architecture, where the shallowly dipping ABT marked the extent of transported allochthonous material juxtaposed over the cryptic Archean-Proterozoic suture beneath it, as well as showing the presence of allochthonous klippen within the reworked Archean foreland, reaffirming its low angle nature.

The continuation of the Archean-Proterozoic suture was identified further to the east in Quebec where it reappears in the Baskatong region (Figure 3.1, A), exhumed from beneath the Lac Dumoine Thrust Sheet of the APB to the southwest. Guo and Dickin (1996) traced a distinct step in Nd model ages and mapped a northeast trending sliver of Paleoproterozoic crust, until it disappeared beneath the AMB of south-central Quebec (Figure 3.2). Considering that nearly 500 km of the Archean-Proterozoic suture has been mapped at surface throughout Ontario and southwestern Quebec with a northeasterly trend, it is plausible that the Archean-Proterozoic suture remains as a cryptic suture beneath allochthonous terranes within the study area in the Parent-Clova region to the northeast. Here it may affect the isotopic composition of younger plutonic rocks by providing a magma source during crustal melting.

Two other notable geological features of the Baskatong area (Figure 3.2) are the presence of charnokitic rocks within the Renzy Shear Belt, interpreted as a klippe of the APB, and the large Cabonga nappe in the north, identified as an overthrust terrane of metasedimentary rocks correlated with the AMB (Guo and Dickin, 1996).

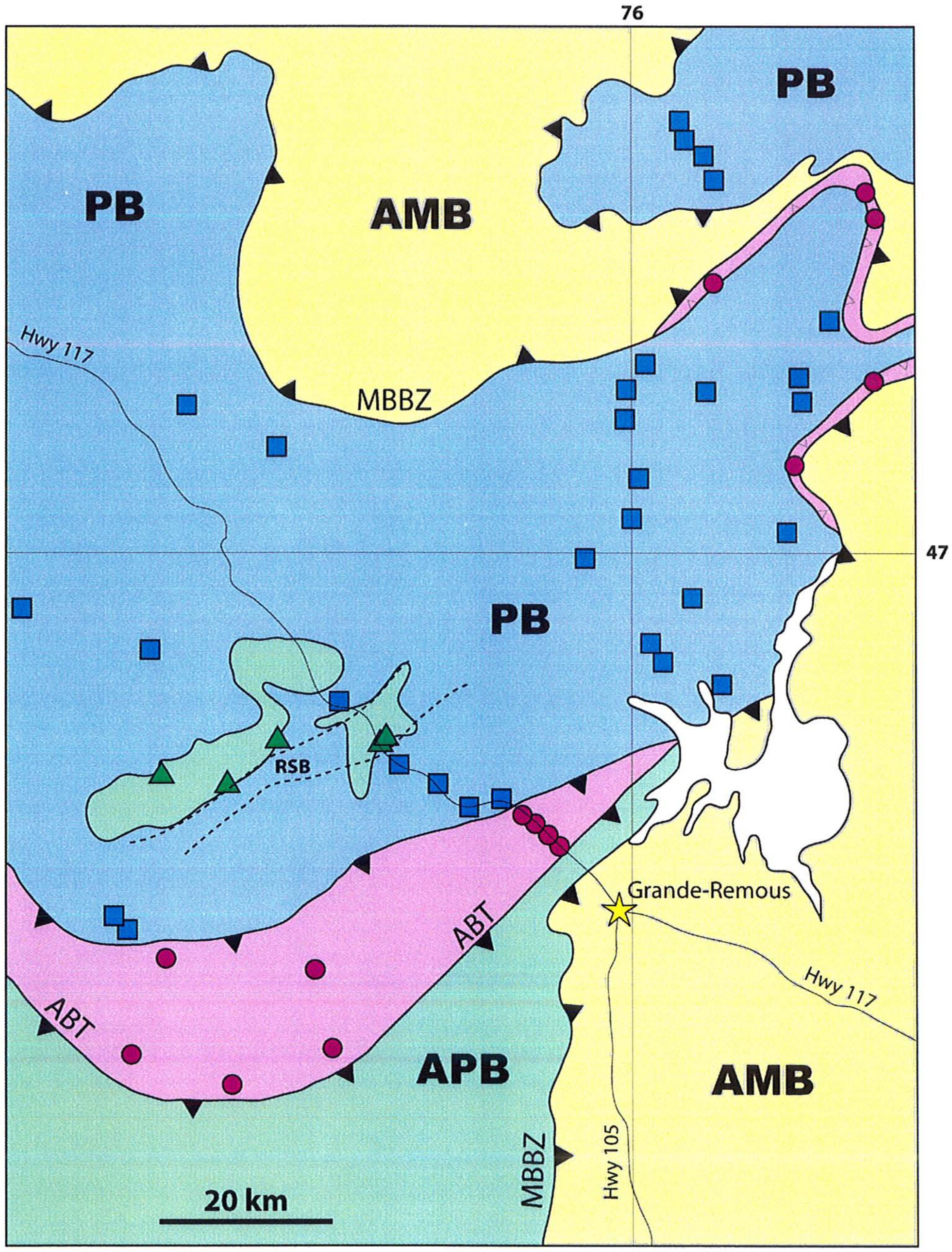

Figure 3.2 – Modified map of crustal terranes investigated by Guo and Dickin (1996). ■ – Plutonic/gneissic rocks with 2.2 - 2.5 Ga model ages; ● – Plutonic/gneissic rocks with 1.8 - 2.0 Ga model ages; ▲ – Rocks form the Renzy Shear Belt (RSB). PB – Parautochthonous Belt, APB – Allochthonous Polycyclic Belt, AMB – Allochthonous Monocyclic Belt. Refer to figure 3.1 A for regional location.

3.3 Southwest of the Study Area

Recent work by Dickin et al. (2009) presented a large Nd isotope data set which was used to generate a crustal formation map for much of the southwest Grenville Province (Figure 3.1, B). Previous studies had already shown that much of the crust in the central and eastern parts of the province is pre-Grenvillian, comprising of distinct 1.5, 1.7, 1.9 and 2.7 Ga arc terranes that were partially reworked by later ensialic arcs and collisional zones. However, Dickin et al. (2009) showed that the juvenile monocyclic crust identified within the CMB can in fact be interpreted as a failed back-arc rift zone exhibiting an *en echelon* geometry, with pre-Grenvillian crust flanking it on either side (Figure 3.3). The flanks show evidence of an earlier 1.5 Ga Pinwarian event, as well as a later 1.4 - 1.3 Ga continental margin arc that is associated with the Elzevirian orogeny.

Dickin et al. (2009) interpreted the pre-Grenvillian (1.5 – 1.7 Ga) Grimsthorpe domain (Elzevir Block) as a horst between two ensimatic rift segments that formed a subparallel graben structure. Much of this juvenile crust in Ontario is regarded as ensimatic, however the juvenile crust within the Marble Domain of Quebec (between the Cayament and Heney shear zones) returned Nd model ages >1.35 Ga which is indicative of pre-Grenvillian crust. This led Dickin et al. (2009) to suggest that the CMB transitions from an ensimatic to ensialic rift zone in this area, which is consistent with the notion that juvenile crust of the CMB (<1.35 Ga) was emplaced in a failed rift environment, shortly before the onset of the Grenvillian orogenic cycle.

This geographic distribution of Nd model ages led to a new tectonic model for describing the emplacement of this juvenile crust, where back-arc spreading created a rift zone behind a (pre-Grenvillian) Elzevirian subduction zone that was obliquly straddled the Mesoproterozoic continental margin. The collisional geometry can be defined by the *en echelon* character of the CMB, and resulted in the rift zone dying out as it met cold Archean crust to the northeast, directly to the southwest of the current study area. Subduction along this continental margin was probably halted by the accretion of a 1.5 Ga Andean-type arc (recognized as the Shawinigan orogeny) and then finally terminated by the collision of a major continental block (Amazonia) during the Ottawan orogeny.

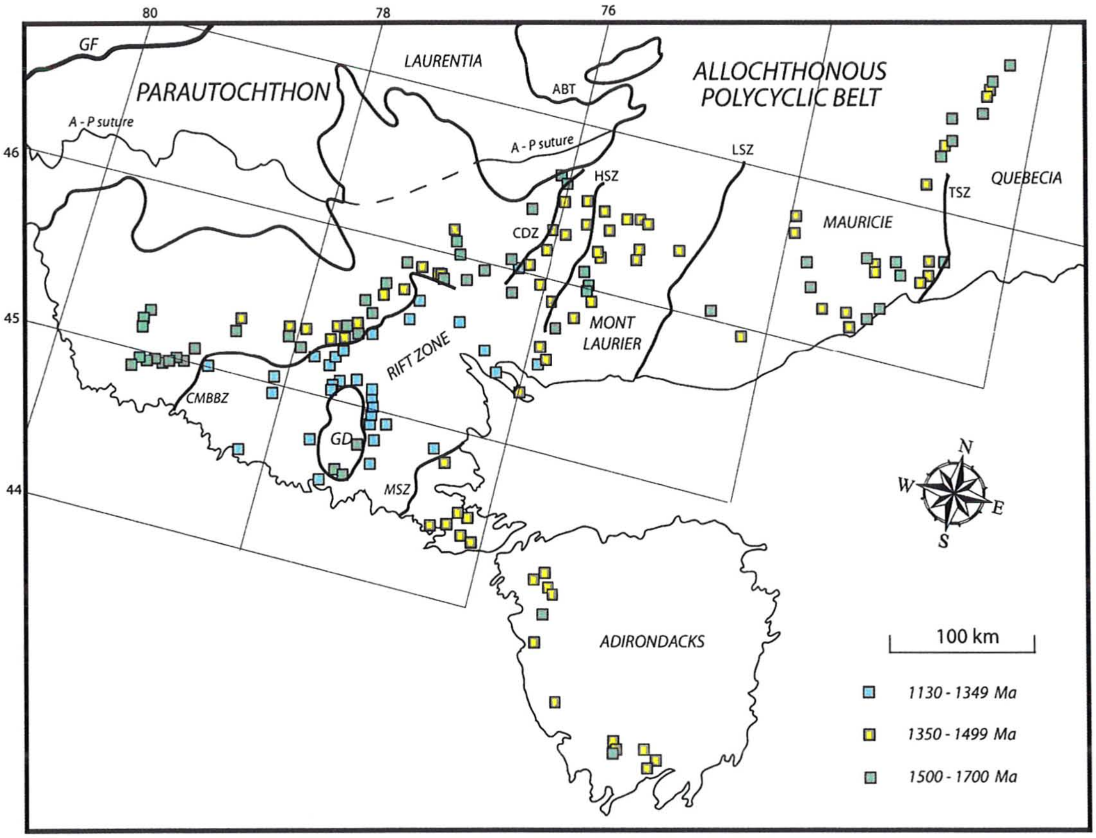

Figure 3.3 – Modified map of crustal formation ages and major terranes defining the extent of juvenile crust in the southwestern Grenville Province (Dickin, 2000 and Dickin et al., 2009). CMBBZ – Central Metasedimentary Belt Boundary Zone; MSZ – Maberly Shear Zone; CSZ – Cayament Shear Zone; HSZ – Heney Shear Zone: LSZ – Labelle Shear Zone; TSZ – Tawachiche Shear Zone; A-P suture – Archean-Proterozoic Suture; GD – Grimsthorpe Domain. Refer to figure 3.1 B for regional location.

3.4 Southeast of the Study Area

Dickin (2000) created a relatively complete crustal formation map based on over 300 Nd model ages across much of the Grenville, with a focus on characterizing the parautochthon and allochthonous polycyclic belt, notably to the east and southeast of the current study area (Figure 3.1, C). One of the components of the APB that Dickin (2000) investigated was a large block of relatively isotopically homogeneous crust that displayed a high abundance of Nd model ages ca. ~1.55 Ga (Figure 3.4). Initially identified via Nd isotope analysis by Dickin and Higgins (1992), this large terrane was interpreted as a Mesoproterozoic arc that was accreted to the Laurentian foreland within 100 Ma of its formation, which led to the narrow range of Nd model ages seen in the terrane.

This block, termed 'Quebecia' by Dickin (2000), was further defined, based on Nd isotope analysis, petrology and trace element geochemistry, as an oceanic arc of Mesoproterozoic origin that was produced by a crust forming event with a minimum age of 1450 Ma and a maximum age of 1650 Ma.. This rapid accretion and collision of Quebecia is supported by a U-Pb crystallization age of 1.45 Ga determined on a felsic tuff from the Montauban Group (Nadeau and van Breemen, 1994).

Other U-Pb evidence from the La Bostonnais Complex (Figure 3.4) gives a distinctly younger U-Pb age of 1.39 – 1.41 Ga (Nadeau and van Breemen, 1994), which has however been subsequently interpreted as an ensialic arc that reworked the interior of the Quebecia terrane for 150 Ma after its crustal formation, giving rise to granitoid orthogneisses with a more alkaline chemistry (Dickin, 2000). Therefore, on the basis of Sm-Nd model ages the unity of the Quebecia terrane has been confirmed with only a few sections that lack clear boundary definition, notably in the southwest of the terrane.

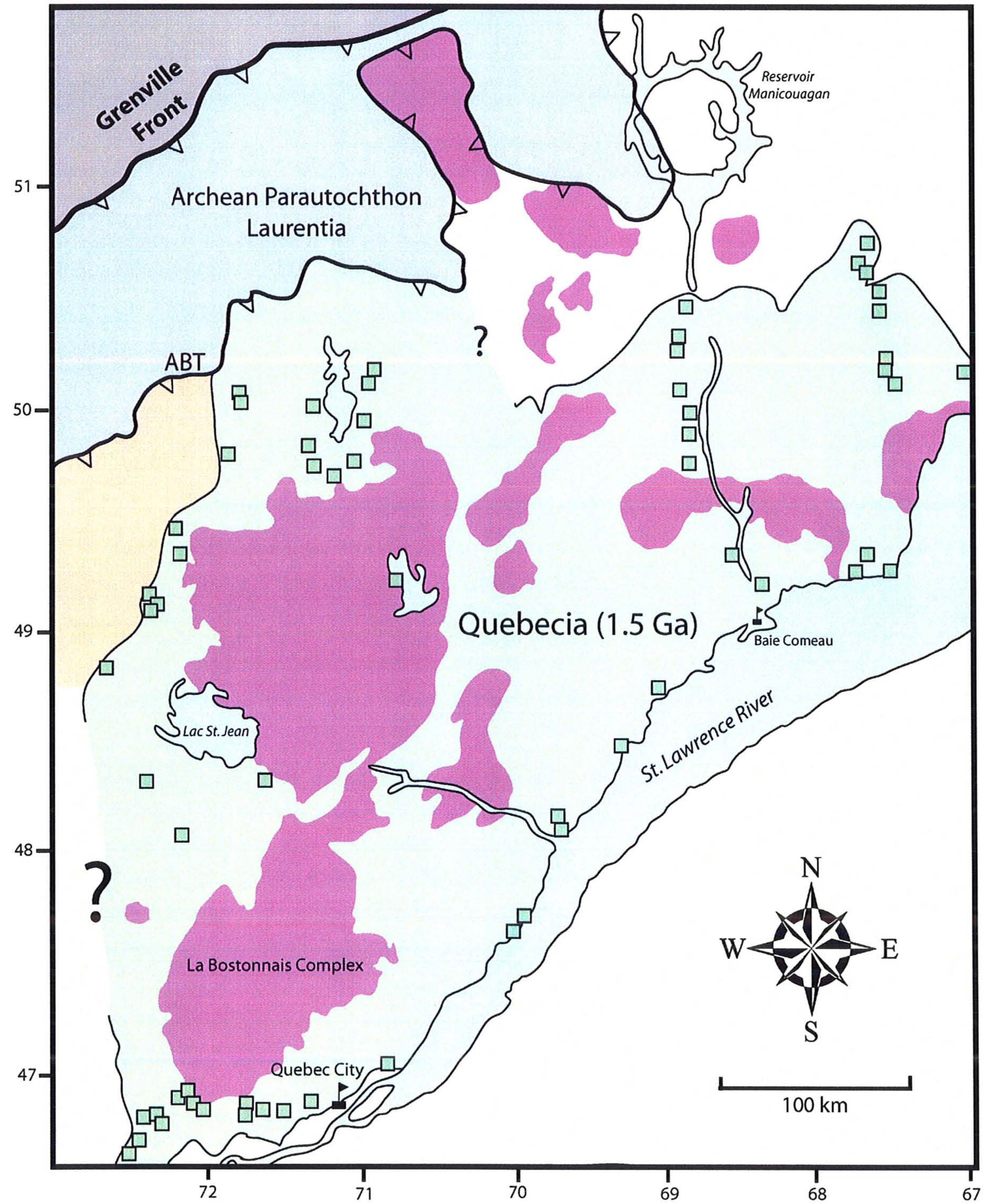

Figure 3.4 – Crustal formation age map for 1.5 Ga crust forming event, termed 'Quebecia'. Blue shading – Archean parautochthon, red shading – Ensialic arc (reworked Archean), green shading – Quebecia and purple shading denotes anorthosites and related rocks from Davidson (1998). ■ – 1.5 to 1.6 Ga Nd model ages. Refer to figure 3.1 C for regional location. Modified from Dickin (2000).

The southwestern tip of Quebecia has only been constrained by Nd model age mapping as far west as the Tawachiche shear zone (TSZ) (Dickin, 2000), and there is a lack of data necessary to constrain this boundary north to the Lac St. Jean region. The present study area will investigate the western extent of the Quebecia terrane in this unknown region, as well as providing information on the amount of crustal mixing between the ~1.55 Quebecia terrane and the younger ensialic arc crust of the APB to the west, a region which encompasses the Mauricie and Morin terranes in south central Quebec.

3.5 Northeast of the Study Area

Dickin (2000) was able to investigate the northwest extent of Quebecia in the Lac St. Jean region, where a continuation of Nd model ages in the range of 1.45 - 1.65 Ga was observed (Figure 3.4). However, Martin and Dickin (2005) later returned to the area (Figure 3.1, D) to better define the ABT between the Archean parautochthon and Quebecia, northwest of Lac St. Jean, where they encountered three distinct blocks (Figure 3.5).

To the northwest is the Archean parautochthon with Nd model ages >2.3 Ga, mainly comprised of tonalitic gray gneisses. To the southeast was a block composed almost exclusively of gneisses that had Nd model ages ranging between 1.5 – 1.6 Ga, regarded as the northwestern limit of the Quebecia terrane. The central block encountered returned a wide range of Nd isotope signatures (1.7 – 2.2 Ga) and showed an alkaline major element chemistry that is characteristic of ensialic arc formation. This wide spread of Nd model ages northwest of Lac St. Jean found by Martin and Dickin (2005) suggested that crustal addition in the region was of ensialic arc origin.

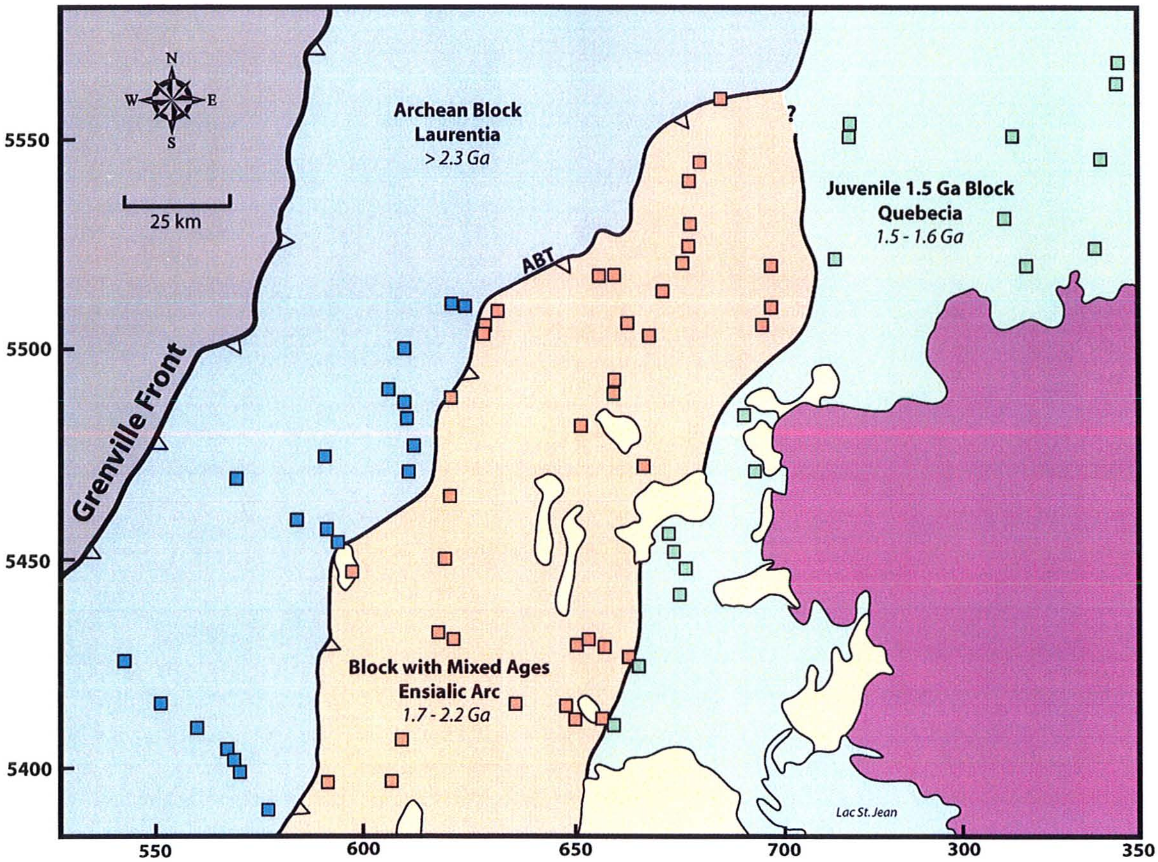

Figure 3.5 – Modified from Martin and Dickin (2005). Simplified crustal formation age map of the region northwest of Lac St.Jean, identifying a ~50km wide ensialic arc subparallel to the margin of Laurentia. Purple shading denotes La Bostonnais Complex (anorthosite), orange shading indicates younger charnockite and granitic plutons. ■ – Juvenile 1.5 Ga Nd model ages (Quebecia), ■ – Ensialic arc with mixed ages, ■ – Archean-aged Laurentia. Refer to figure 3.1 D for regional location.

The mixed Nd isotope signature expressed by the central block is attributed to a change in subduction styles, where a subduction flip model was proposed. Martin and Dickin (2005) suggest that sometime around 1.43 Ga, Quebecia may have become sutured onto the continental margin of Laurentia, at which point stress build-up related to the cessation of subduction provoked a flip, such that a low angle suture was preserved between 2.7 and 1.5 Ga crustal blocks. This suture gave rise to a more gradational age boundary between the two blocks, with north-dipping subduction further complicating the crustal signature through younger magmatism, resulting in the mixing of the crustal components. The southern limit of the ensialic signature is constrained only in the area immediately to the west of Lac St. Jean, with the current study area focusing on establishing the continuation of this zone of mixed signatures as well as mapping the extent of the adjacent Quebecia terrane.

The concept of ensialic arc formation was also seen during the definition of the ABT in the North Bay and Mattawa regions of Ontario, which were initially based on the presence of matebasic rocks suites (Ketchum and Davidson (2000). However lithologic interpretation of the location of the ABT fell short in western Quebec (Central Gneiss Belt) as mafic outcrops become sporadic, requiring wide interpolations between these outcrops.

Dickin et al., (2008) showed that isotopic characterization of the region is necessary to compliment the geologic constraints in more accurately defining the ABT, especially in areas where high grade polycyclic rocks are found on both sides of the boundary. North of the ABT, parautochthonous crust showed a homogeneous Nd isotope signature with a crustal formation age of 1.91 Ga that was attributed to the docking of a juvenile Paleoproterozoic arc terrane (Barillia) to the Laurentian foreland, subsequently reworked by the Killarnian magmatic event. In contrast, allochthonous crust in the region displayed a heterogeneous isotopic signature that was more consistent of ensialic arc formation (Algonquia), which mixed 1.7 and 1.45 Ga sources.

3.6 Geologic Context of the Present Study Area

The field area of this study encompassed a ~50,000 km^2 area of south-central Quebec extending from 46° 90' N, 75° 90' W to 48° 30' N, 72° 75' W (Figure 3.6). Generally bordered by Hwy 167 to the northeast, Hwy 155 to the southeast and Hwy 117 to the southwest, the lack of any major roadways throughout this vast region has hindered mapping efforts, which have thus been neglected to this point. Due to the enormity of the area, reconnaissance scale mapping of crustal formation ages will allow for initial insight of the extent of first-order terranes within the region, and investigate the possible continuation of an ensialic arc signature between Archean and Mesoproterozoic aged blocks.

Much of the field area is dominated by basement lithologies that are high-grade metamorphic in nature, including orthogneisses and minor paragneisses whose precursors have been subjected to granulite to upper amphibolite grade metamorphism. A large portion of the region has been characterized as undifferentiated or mixed gneisses (Davidson, 1998a), attesting to the complex geologic histroy and relative lack of geologic investigation of the region.

Based on major element analysis of rock suites to the immediate northeast (Martin and Dickin, 2005), precursor rocks are generally a mixture of various granitoid lithologies of TTG (tonalite, trondhjemite, granodiorite) association with multiple occurrences of younger AMCG suite rocks (anorthosite-mangerite-charnockite-granite), mostly concentrated in the central and northeastern sections of the study area.

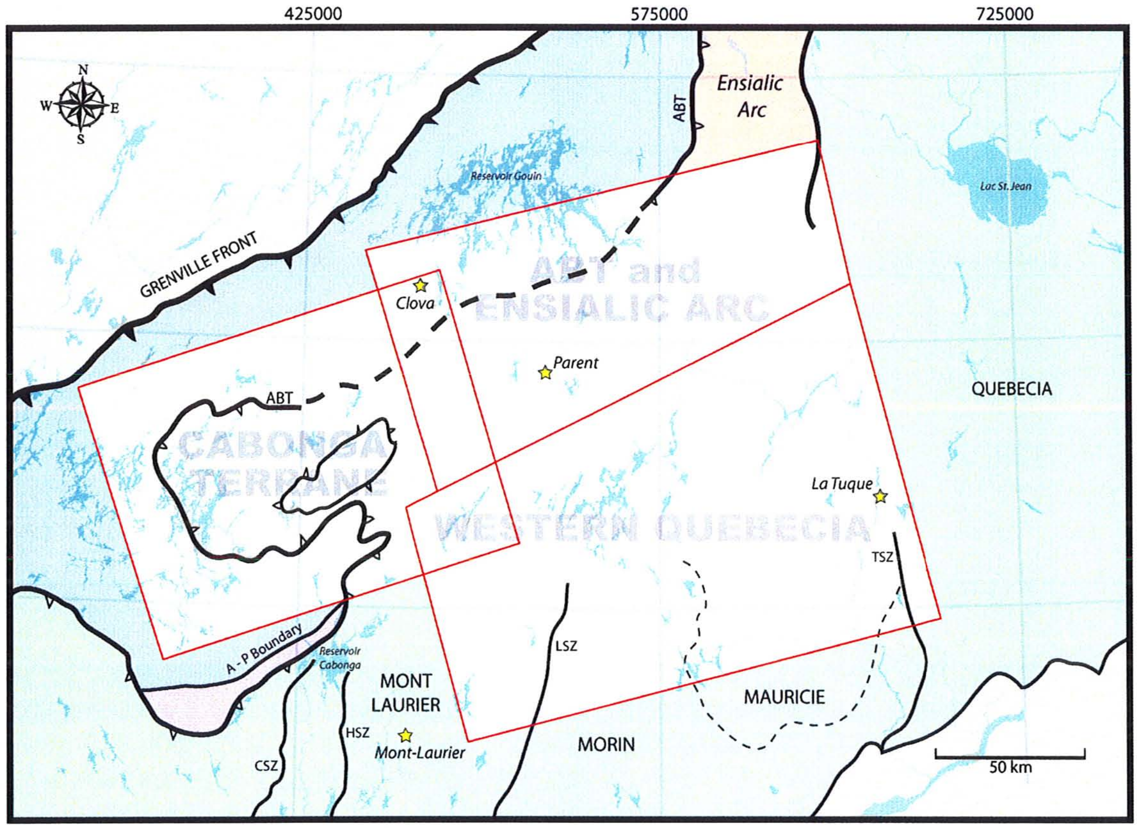

Figure 3.6 - Modified map (Dickin, 2007 and Dickin 2000) showing some of the crustal divisions and important shear zones located within the region. The study areas are separated into: Western Quebecia, ABT and Ensialic Arc, and the Cabonga Terrane. ABT – Allochthon Boundary Thrust; CSZ – Cayament Shear Zone; HSZ – Heney Shear Zone: LSZ – Labelle Shear Zone; TSZ – Tawachiche Shear Zone; A-P suture – Archean-Proterozoic Suture. Blue/Purple – Parautochthonous Belt, Green – Allochthonous Polycyclic Belt, Red – Ensialic Arc.

The western portion of the study area is expected to host rocks of younger affinity comprising mid-Mesoproterozoic aged orthogneisses, plus minor paragneisses and syenite-monzonite-monzodiorite complexes, as well as a few small outcroppings of CMB marbles. Metamorphic grade in the rocks show a slight decrease from granulite to amphibolite facies as they are characteristically of monocyclic provenance.

Important crustal divisions have been identified crossing through the study area, such as the limit of the AMB, the ABT and a ~50 km wide band of mixed crust interpreted as an ensialic arc (Figure 3.6). The addition of isotopic data to the region will aid in further constraining these boundaries and will complete the first-order crustal model for southern Quebec in relation to the Grenville orogenic cycle.

The ABT, which has been traced along much of the Grenville Province, is believed to cross the northern portion of the study area (dashed line in Figure 3.6) and is expected to separate parautochthonous Archean crust to the north from the reworked Proterozoic crust of the ensialic arc to the south, originally identified by Martin and Dickin (2005).

Finally, the western limit of Quebecia has been currently limited to the Tawachiche Shear Zone (TSZ in Figure 3.6) by both U-Pb (Corrigan and van Breemen, 1997) and Sm-Nd (Dickin, 2000) isotopic data. Further sampling to the northwest of the TSZ into the Mauricie and Morin terranes will be used to bridge the remaining gap in Quebecia's southwestern limit, and identify any crustal mixing that may have resulted from the addition of younger (<1.45 Ga) Mesoproterozoic arc terranes.

To allow for more detailed (regionally specific) investigation, the study area has been broken up into three distinct regions, highlighting zones where distinct crustal interactions can be transected and investigated. The sub-divided zones are: Western Quebecia; the ABT and Ensialic Arc; and the Cabonga Terrane, and these will be discussed in turn in the next chapter.

CHAPTER 4
RESULTS: WESTERN QUEBECIA

4.1 Geologic Context

Originally identified as Quebecia by Rondot (1986), and defined as part of the Allochthonous Polycyclic Belt by Rivers et al. (1989), Quebecia is a first-order crustal terrane primarily comprised of Mesoproterozoic mixed gneisses and AMCG (anorthosite–mangerite–charnockite–granite) suite rocks. The definition of this large Mesoproterozoic arc terrane is mostly attributed to isotopic work (Dickin and Higgins, 1992; Dickin, 2000), where results have shown that the gneissic equivalents are interpreted as a Mesoproterozoic arc system that was accreted onto Laurentia within 100 Ma of its formation. Evidence from petrology and trace element geochemistry has shown that Quebecia has granitoid compositions that are typical of the tonalite-adamelite-granodiorite (TTG) suite (Dickin, 2000). This results in the suite having a more silica rich and alkali poor composition than that observed in continental arc complexes and is generally associated with crustal formation on oceanic crust.

Dickin (2000) made initial definition of the extent of Mesoproterozoic Quebecia crust based on Nd model ages and allotted an Nd model age range of 1450 – 1650 Ma, for the crust forming event defining Quebecia. However, it was also noted that even though the Nd data shows strong correlation and clustering around the 1.55 Ga average model age for Quebecia, a greater spread of εNd values are generally seen along the margins, as compared to the interior of Quebecia. This was the evident case in the Montauban area, where sediments of ancient provenance are found as well as evidence for post 1.4 Ga plutonism (Nadeau and van Breemen, 1994). This mixing of sources can result in variable degrees of crustal contamination and can make boundary definition difficult.

The northwestern extent of Quebecia has been defined by Martin and Dickin (2005) based on petrological and isotopic work, where Quebecia is obliquely juxtaposed against Archean aged Laurentian crust. Dickin et al. (2009) further investigated the continuation of Quebecia crust throughout the Mauricie region, where the trend of 1.5 Ga crustal formation ages has only been mapped east of the Tawachiche Shear Zone (TSZ), with reworked Quebecia crust with Nd model ages <1450 observed throughout the Mauricie region.

Due to the reconnaissance level of sampling throughout the region, and the close association of Nd model age ranges between Quebecia and other domains of the APB, it is likely that Quebecia will share an ambiguous boundary with the more juvenile crust of the APB. Therefore, sampling in this region will be used to define trends within Mesoproterozoic aged crust through isotopic and petrochemical analysis, relating them to published isotopic data from the Mauricie terrane (Dickin et al., 2009) and Quebecia (Martin and Dickin, 2005; Dickin et al., 2009) to better discern the extent of Quebecia in this region.

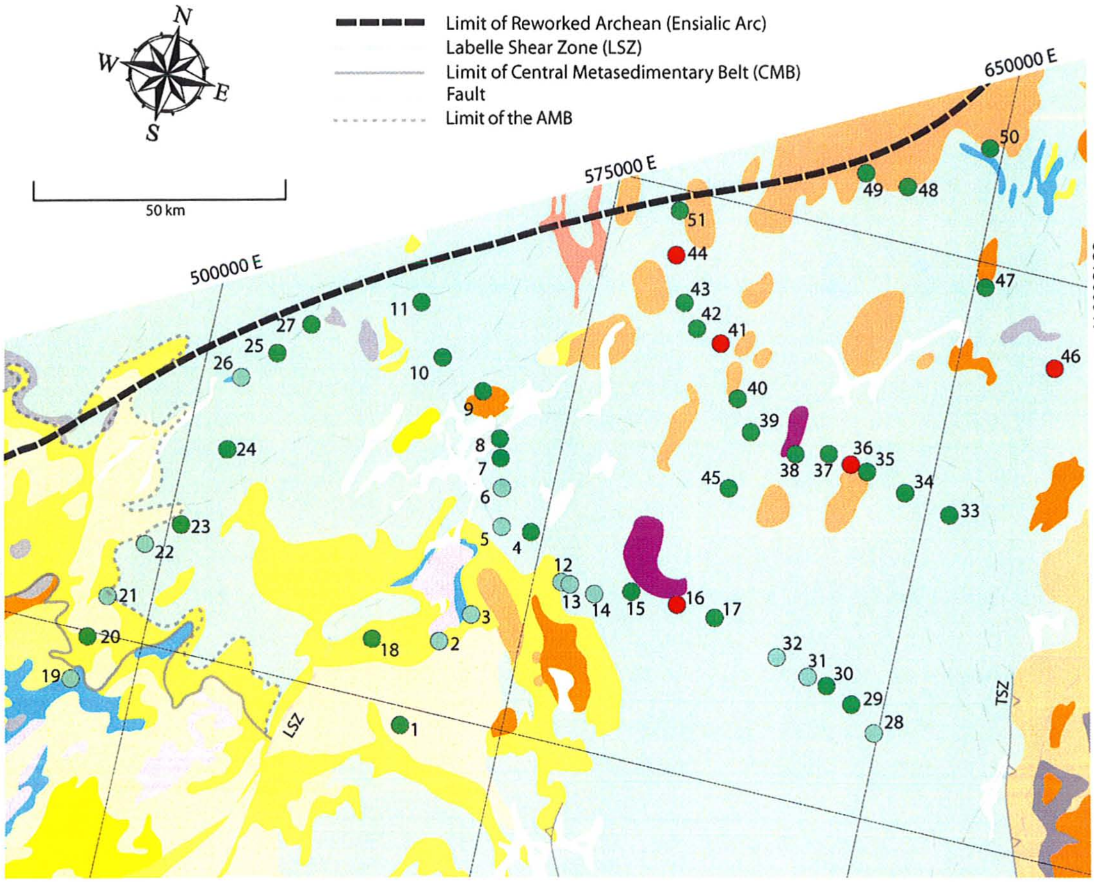

Figure 4.1 – Geology and sampling locations within the section of the study area defining Western Quebecia. LSZ – Labelle Shear Zone, TSZ - . Tawachiche Shear Zone. • – Reworked Crust (<1450 Ma), • – Western Quebecia (1450 – 1650 Ma), • – Inherited Older Crust (>1650 Ma). Refer to APPENDIX B for lithologic key.

4.2 Nd Model Age Mapping

51 new Nd model ages were determined for orthogniesses to further define the crustal formation history of this section of the Grenville Province (Figure 4.1). Nd analyses conducted by Martin and Dickin (2005) investigated the northwestern segment of Quebecia as it appeared to be thrust against the ABT, near Lac St. Jean, Quebec. In this region, a unique trend in Nd model ages showed the presence of Archean crust in the west, Mesoproterozoic Quebecia crust in the east and a block of mixed model ages which were interpreted as an ensialic arc. Mapping within the current study area will focus on delineating the extent of Mesoproterozoic crust through Nd model age analysis, and will be used to look at any identifiable crustal mixing process that may have occurred between Quebecia (1450 – 1650 Ma) and younger units of the APB (<1450 Ma). Spatial distribution of the sampling locations can been seen in Figure 4.1, with corresponding isotopic data presented in Table 4.1. Supplementary data used to define Quebecia (Martin and Dickin, 2005; Dickin et al., 2009) and Mauricie (Dickin et al., 2009) are also used (Appendix C), and provide a reference for the Mesoproterozoic arc terrane.

Table 4.1 - Sm-Nd isotopic data for western Quebecia.

Sample	Northing	Easting	Nd ppm	Sm ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	error	εNd 1450	T_{dm} (Ma)
Western Quebecia: T_{dm} ages 1450 - 1650 Ma									
1 - LK 01	5199069	556421	35.02	7.12	0.1229	0.512126	0.013	2.8	1534
4 - LK 07	5244174	570779	30.48	6.12	0.1214	0.512120	0.013	2.9	1521
7 - LK 10	5256375	564270	49.32	10.04	0.1230	0.512117	0.020	2.6	1553
8 - LK 11	5259424	563191	44.75	9.45	0.1276	0.512196	0.011	3.3	1497
9 - LK 13	5268687	557192	111.44	17.69	0.0959	0.511919	0.010	3.4	1453
10 - LK 15	5273224	549785	35.55	6.49	0.1104	0.512053	0.012	3.5	1458
11 - LK 17	5281989	547011	119.57	19.19	0.0970	0.511824	0.015	1.4	1590
15 - LK 24	5236819	597455	56.18	10.21	0.1098	0.512027	0.011	3.1	1487
17 - LK 26	5236356	611698	33.96	7.09	0.1261	0.512114	0.016	2.0	1614
18 - LK 27	5214951	548657	32.34	7.20	0.1346	0.512193	0.010	2.1	1633
20 - PT 04	5205454	488784	40.25	7.84	0.1177	0.512007	0.012	1.3	1643
23 - PT 09	5230424	502055	77.55	11.34	0.0884	0.511837	0.010	3.1	1466
24 - PT 10	5247061	507356	20.80	3.69	0.1072	0.511933	0.014	1.7	1585

25 - PT 12	5267045	515455	22.08	5.03	0.1378	0.512290	0.016	3.4	1507
27 - PT 14	5274042	520503	38.96	8.44	0.1309	0.512191	0.012	2.7	1564
29 - RR 02	5231514	645627	50.49	9.07	0.1086	0.511986	0.012	2.5	1532
30 - RR 03	5232775	641429	46.58	8.05	0.1044	0.511967	0.012	2.9	1499
33 - SM 01	5267158	654073	16.13	2.71	0.1016	0.511942	0.012	2.9	1496
34 - SM 03	5269598	644006	50.29	10.75	0.1292	0.512161	0.012	2.3	1588
35 - SM 04	5270537	636270	76.78	14.75	0.1161	0.512067	0.009	2.8	1521
37 - SM 06	5271843	629711	17.56	3.03	0.1043	0.511971	0.017	3.0	1492
38 - SM 07	5272071	623013	40.57	8.69	0.1294	0.512156	0.012	2.2	1601
39 - SM 09	5273331	612022	23.71	4.06	0.1035	0.511926	0.011	2.2	1543
40 - SM 11	5279366	608043	13.08	2.26	0.1046	0.511962	0.013	2.7	1508
42 - SM 14	5290464	597932	35.31	6.42	0.1099	0.511995	0.013	2.5	1537
43 - SM 15	5293515	594962	13.98	2.57	0.1110	0.512001	0.017	2.4	1544
45 - SM 18	5261686	610490	36.42	5.71	0.0948	0.511931	0.012	3.8	1424
47 - SM 23	5311667	649863	32.83	6.38	0.1174	0.512063	0.011	2.5	1548
48 - SM 24	5328908	631079	38.22	7.90	0.1249	0.512096	0.011	1.8	1623
49 - SM 26	5333109	621877	120.00	20.75	0.1045	0.511910	0.012	1.7	1579
50 - SM 50	5339960	645205	133.07	21.14	0.0960	0.511878	0.012	3.9	1506
51 - SM 67	5308878	588859	16.52	3.29	0.1204	0.512054	0.020	2.8	1612

Reworked Crust: T_{dm} ages <1450 Ma

2 - LK 02	5217669	560395	70.24	13.48	0.1160	0.512121	0.011	3.9	1435
3 - LK 03	5224338	563232	84.16	14.99	0.1076	0.512054	0.012	4.0	1419
5 - LK 08	5245498	566212	12.37	1.86	0.0909	0.511951	0.014	4.9	1355
6 - LK 09	5250482	564596	71.74	11.13	0.0938	0.511921	0.012	3.8	1425
12 - LK 20	5236188	581232	5.01	1.06	0.1284	0.512296	0.016	5.1	1333
13 - LK 21	5236132	581708	20.32	4.01	0.1192	0.512155	0.010	4.0	1430
14 - LK 22	5234673	586649	22.11	4.68	0.1279	0.512272	0.010	4.8	1367
19 - PT 01	5194645	487766	60.06	10.85	0.1092	0.512072	0.010	4.1	1414
21 - PT 06	5212886	491489	10.88	2.09	0.1159	0.512174	0.009	4.9	1353
22 - PT 08	5223870	495015	79.25	11.77	0.0898	0.511892	0.014	3.9	1414
26 - PT 13	5263282	509264	44.53	8.11	0.1101	0.512060	0.010	3.7	1443
28 - RR 01	5229796	649883	31.66	7.71	0.1472	0.512449	0.014	4.9	1355
31 - RR 04	5232599	638010	11.76	1.55	0.0798	0.511773	0.026	3.3	1444
32 - RR 05	5233633	629851	6.91	1.88	0.1641	0.512606	0.034	5.0	1334

Inherited Older Crust: T_{dm} ages >1650 Ma

16 - LK 25	5236788	603276	77.37	15.90	0.1242	0.512015	0.011	0.4	1747
36 - *SM 05*	5270808	634350	82.43	16.88	0.1237	0.511968	0.012	-0.4	1817
41 - SM 13	5289216	601260	127.52	22.24	0.1054	0.511860	0.011	0.6	1663
44 - SM 16	5302094	589326	28.63	7.94	0.1678	0.512372	0.010	-0.2	2232
46 - *SM 20*	5297854	668804	36.24	9.08	0.1514	0.512352	0.014	2.2	1686

(italicized samples were duplicates)

Figure 4.2 shows a series of histograms illustrating the frequency of Nd model ages in the current study area, along with samples collected from the Mauricie region (Dickin et al., 2009) and Quebecia (Dickin et al, 2009; Martin and Dickin, 2005). The two histograms depicting Quebecia show a strong peak at 1.55 Ga, consistent with the average crustal formation age for the terrane. Samples defining the Mauricie region show a larger range in model ages, with a peak occurring around 1.4 Ga. The newly collected samples defining western Quebecia show a similar range in ages to those of Mauricie, but have a peak approaching 1.55 Ga, similar to those of Quebecia. Samples from this region can therefore be regarded as the mixture of pristine Quebecia crust that has acquired juvenile crustal input from younger magmatism to the south.

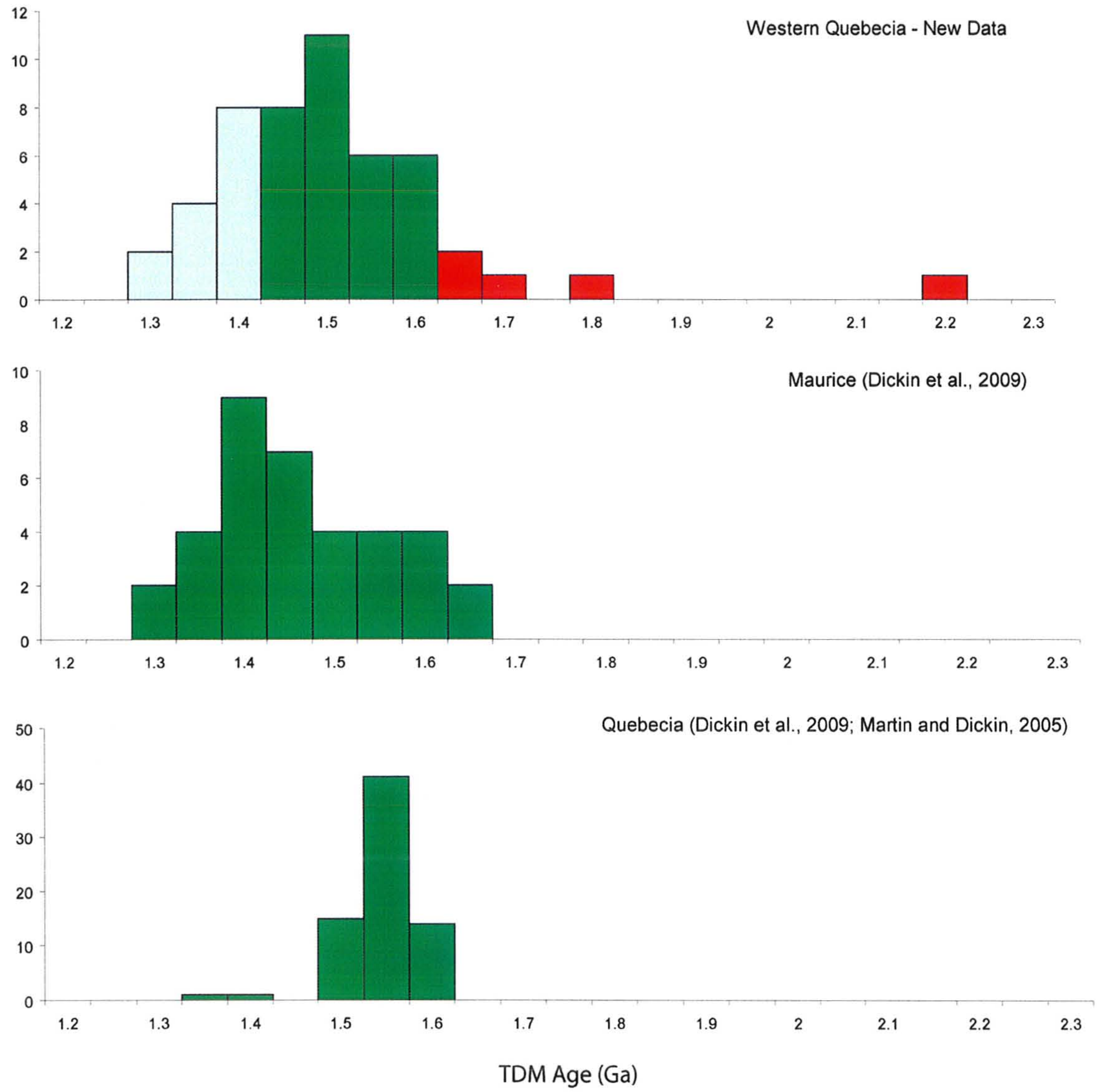

Figure 4.2 – Histogram of Nd model age frequency for the samples defining Western Quebecia, compared to Nd model ages distributions defining the Mauricie region and Quebecia. Light Green – Reworked Crust (< 1450 Ma); Green – Western Quebecia (1450 – 1650 Ma); Red – Inherited Older Crust (1650 – 2300 Ma).

The $^{143}Nd/^{144}Nd$ versus $^{147}Sm/^{144}Nd$ isochron diagram for the samples from the region of western Quebecia are presented in Figure 4.3, and show a strong clustering with samples defining Quebecia (Martin and Dickin, 2005; Dickin et al., 2009) and the Mauricie region of Dickin et al. (2009). A reference line of 1.51 Ga is given, representing the isotopic evolutionary trend for Quebecia, with a majority of the samples closely clustered around this line, and clustering similar to that of Quebecia defined by Martin and Dickin (2005) and Dickin et al. (2009). Data from the Mauricie region collected by Dickin et al., (2009) show a very strong overlap with the majority of samples collected in the present study, which can be regarded as a continuation of similar Mesoproterozoic crustal material with some juvenile crustal contamination. This provides evidence for the presence of the 1.55 Ga accretionary arc of Quebecia west of the Tawachiche Shear Zone. Out of the 5 samples with Nd model ages greater that 1650 Ma, only sample SM 20 plots above the 1.51 Ga reference line. The older model ages of these 5 samples are attributed to the incorporation of older crustal sediments within the melt, and will be considered to be aberrant as they are surrounded by Mesoproterozoic ages that are consistent with an origin as part of the Quebecia terrane.

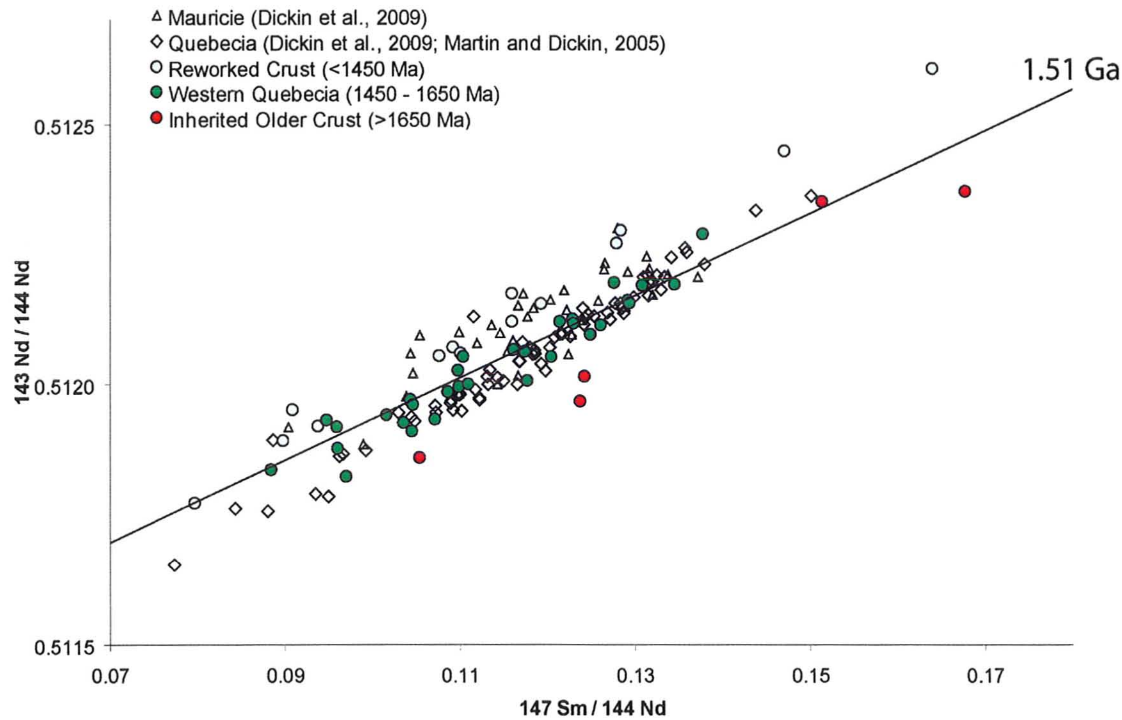

Figure 4.3 – Isochron diagram of $^{143}Nd/^{144}Nd$ versus $^{147}Sm/^{144}Nd$ for samples characterizing Western Quebecia. Indicated on the graph is the 1.51 Ga reference line for the Sm-Nd isotopic system.

Figure 4.4 depicts the samples collected from the region in terms of their εNd (1450) versus Nd concentration, and shows the grouping defining the Mesoproterozoic (Quebecia) block ranging from +1 to +5, with a few samples plotting closer to 0 εNd units. Once again, a strong correlation can be seen between the newly collected samples, and those belonging to the Mauricie region. Samples defining Quebecia (Martin and Dickin, 2005) have a tighter clustering, and are indicative of the lack of magmatic reworking as Quebecia was juxtaposed to the Archean parautochthon in this region, instead of being intruded by large amounts of younger crustal material as seen in the current study area. The five samples with model ages greater than 1650 Ma plot near εNd = 0, with only SM 20 falling within the cluster of Mesoproterozoic samples. The overlap of Nd concentrations with the other suites suggests that these samples had a similar origin, but contained older sedimentary material in the crustal source.

Figure 4.5 plots the εNd values of the samples against their spatial location (northing) to illustrate the correlation to samples from Mauricie (Dickin et al., 2009). The samples collected from western Quebecia (1450 – 1650 Ma) show an εNd range that falls between the Mauricie region that has suffered some amount of crustal reworking. The narrowing of the εNd range is significant as it depicts the diminishment of influence by juvenile melt components to the north, where Quebecia is thrust against an isotopically distinct Archean crust. This scenario differs when the Quebecian crust is in contact with other Mesoproterozoic terranes, shown by the addition of samples with Nd model ages < 1450 Ma, where a strikingly similar range in εNd to the Mauricie region is observed.

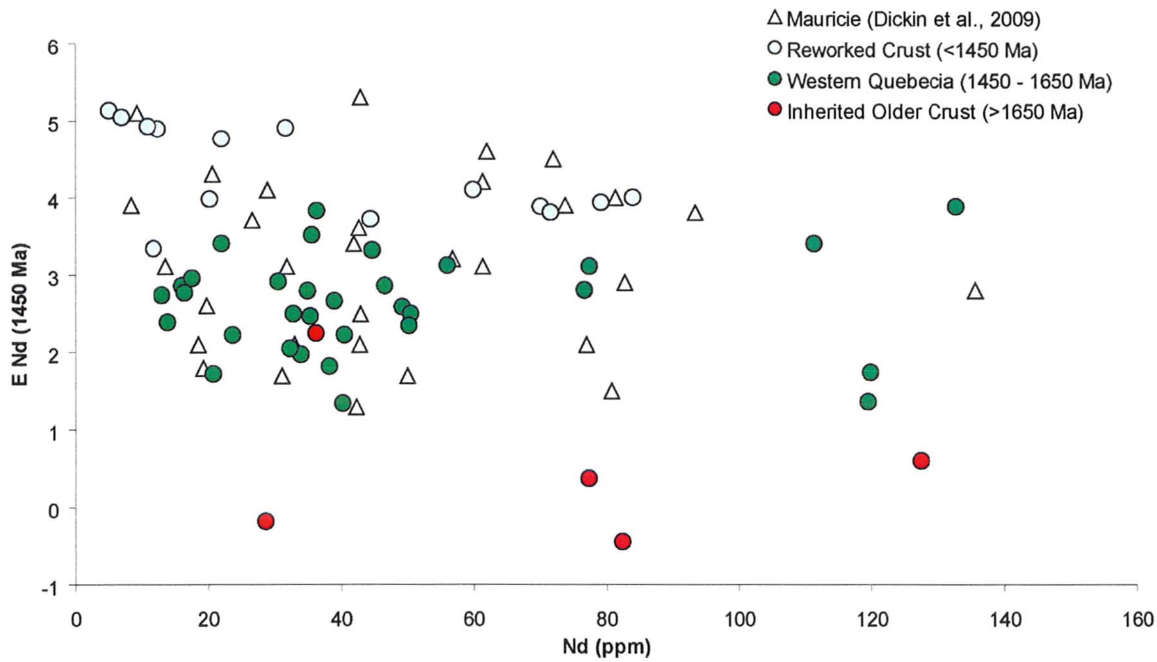

Figure 4.4 – Plot of Nd concentration (ppm) versus εNd (1450). Newly collected samples defining Western Quebecia are compared with samples from the Mauricie region (Dickin et al., 2009).

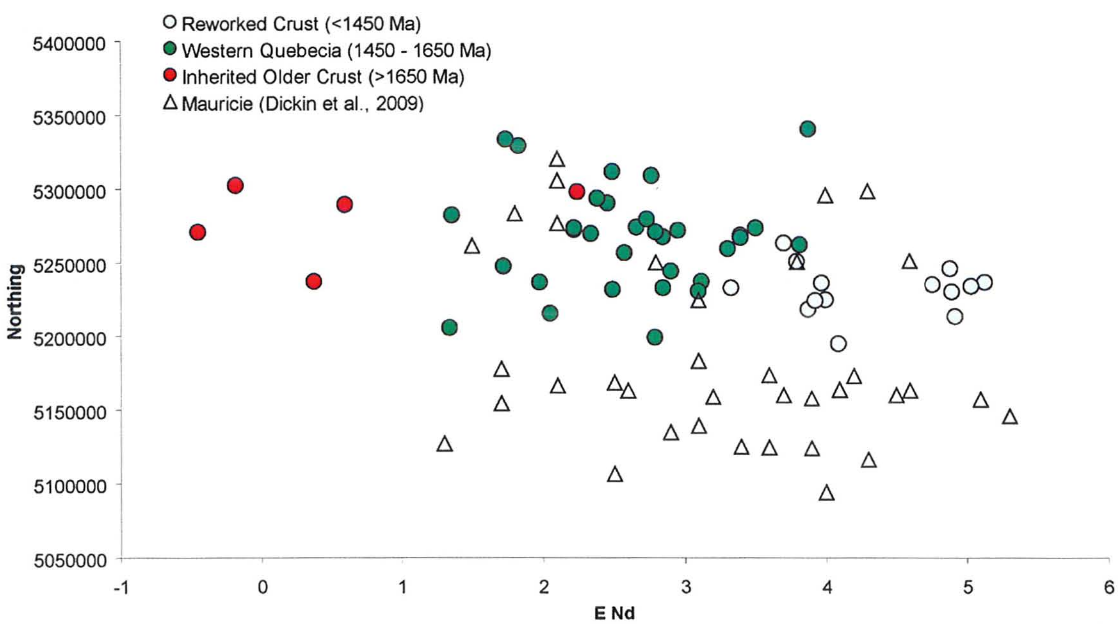

Figure 4.5 – Plot of εNd values versus sampling location (Northing - UTM), compared to the Mauricie region defined by Dickin et al. (2009).

4.3 Petrochemical Data

In order to establish a petrochemical relation to the surrounding region, major element analysis was preformed on samples throughout western Quebecia along the PT and LK series transects (Table 4.2). Samples were plotted on the quartz-plagioclase (Q-P) grid of Debon and LeFort (1983), which is intended to classify granitoid rocks following Steckeisen (1973), except based on whole-rock chemical data. Petrochemical analyses of samples collected from within western Quebecia are plotted in Figure 4.6, along with data from the 'Juvenile 1.5 Ga' eastern block (Quebecia) of Martin and Dickin (2005) and the Quebecia suite from Dickin et al. (2009).

Martin and Dickin (2005) found that Quebecia rocks northwest of the Lac St. Jean region had a strong concentration within the tonalite field, but also extended into more primitive monzodioritic and more evolved granodiorite and adamellite/monzogranite compositions. This range in composition is similar to that seen in Mesoproterozoic crust to the southeast (Dickin and Higgins, 1992) and combined with a strong 1.5 Ga Nd model age abundance, was inferred to be an extension of the Quebecia crust.

Dickin et al. (2009) mainly focused on the definition of the juvenile rift zone in the CMB but had also analyzed a suite of samples including those from Quebecia and the Mont-Laurier terranes when delineating the rift zone flanks. Unfortunately, no petrological analysis was conducted on samples from within the Mauricie terrane, but several samples from the present study area will be used to fill in this gap. The samples from within Quebecia plotted in good agreement to those seen in Martin and Dickin (2005) and expressed a petrologic signature that was concentrated within the tonalite field, with more evolved compositions of granodiorite and adamellite/monzogranite.

Mont Laurier on the other hand (not shown in figure 4.6) had a bimodial distribution with silica-rich and silica-poor trends, and was shown to have a significant amount of mantle-derived material (Marcantonio et al., 1990).

27 new major element analyses characterizing western Quebecia in figure 4.6 show a similar distribution to the published suites. Samples with Nd model ages within the 1.45 – 1.65 Ga range for Quebecia have a distribution that largely overlaps the other Quebecia examples, with the majority of the samples plotting from tonalite through to more evolved granodiorite and monzodiorite, which is attributed to the emplacement of these magmas into thin oceanic (ensialic) crust.

Samples from western Quebecia that fell into the < 1.45 Ga age range displayed a wide range of lithologies overlapping Quebecia but also similar to the Mont-Laurier terrane, except with slightly higher quartz values. The majority of these samples with younger ages reflect the magmatic reworking of Quebecia in the ensialic arc, which is argued to have led to a more alkaline geochemical signature. Collectively, these samples define a region that is similar in elemental composition to Quebecia, but has become more reworked along the very diffuse northern boundary of the ensialic arc that was established on the Laurentian continental margin.

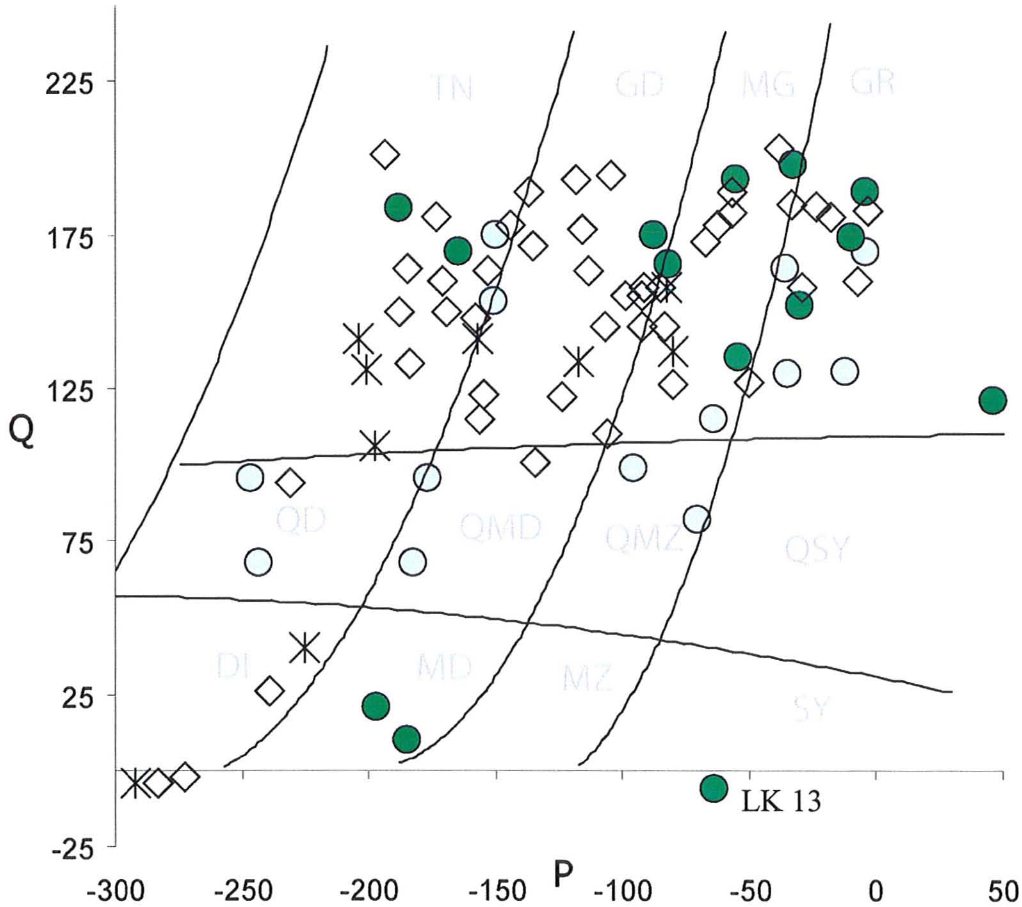

Figure 4.6 – Q-P petrochemical grid after Streckeisen (1973) for newly collected samples defining Western Quebecia. Light green circles – Western Quebecia (<1450 Ma); Green circles – Western Quebecia (1450 – 1650 Ma); stars – Quebecia (Eastern Block) from Martin and Dickin (2005); open diamonds – Quebecia from Dickin et al. (2009). TN – tonalite; GD – granodiorite; MG – monzogranite; GR – granite; QD – quartz diorite; QMD – quartz monzodiorite; QMZ – quartz monzonite; QSY – quartz syenite; DI – diorite; MD – monzodiorite; MZ – monzonite; SY – syenite.

Table 4.2 - Major element analysis for western Quebecia.

SAMPLE	SiO2	Al2O3	Fe2O3(T)	MnO	MgO	CaO	Na2O	K2O	TiO2	P2O5	LOI	Total	Si	K	Na	Ca	Q	P
Western Quebecia: T_{dm} ages <1650 Ma																		
PT01	62.1	15.38	4.94	0.078	2.63	4	3.32	5.09	0.633	0.33	0.56	99.06	1035.00	108.30	107.10	71.43	82	-70
PT04	73.72	13.57	1.65	0.029	0.2	1.18	3.25	5.49	0.186	0.05	1.01	100.4	1228.67	116.81	104.84	21.07	174	-9
PT06	64.21	18.46	3.24	0.069	1.02	4.64	5.73	1	0.281	0.15	0.58	99.36	1070.17	21.28	184.84	82.86	95	-246
PT08	69.46	15.07	3.08	0.04	0.64	1.72	3.35	5.97	0.408	0.16	0.55	100.4	1157.67	127.02	108.06	30.71	130	-12
PT09	68.54	14.64	2.98	0.037	0.69	1.63	3.67	5.33	0.5	0.15	0.46	98.63	1142.33	113.40	118.39	29.11	130	-34
PT10	70.99	15.42	2.86	0.068	0.66	3.34	4.49	1.89	0.293	0.12	0.35	100.5	1183.17	40.21	144.84	59.64	170	-164
PT12	52.05	18.4	9.75	0.187	4.21	4.26	5.22	2.82	0.966	0.22	0.54	98.63	867.50	60.00	168.39	76.07	10	-184
PT13	72.36	14.13	2.23	0.042	0.86	1.44	3.57	4.96	0.373	0.07	0.43	100.5	1206.00	105.53	115.16	25.71	164	-35
PT14	72.26	12.69	4.42	0.062	0.37	1.84	3.23	3.88	0.542	0.12	0.21	99.61	1204.33	82.55	104.19	32.86	193	-54
LK01	68.72	14.36	3.75	0.08	0.83	2.18	3.66	4.84	0.807	0.22	0.94	100.4	1145.33	102.98	118.06	38.93	135	-54
LK02	62.22	15.22	7.17	0.129	1.78	3.74	3.58	4.08	1.374	0.64	0.51	100.4	1037.00	86.81	115.48	66.79	99	-95
LK03	73.05	14.07	2.07	0.054	0.47	1.1	3.21	5.62	0.334	0.13	0.51	100.6	1217.50	119.57	103.55	19.64	170	-4
LK07	68.68	13.77	4.85	0.079	1.66	5.52	3.43	1.01	0.654	0.12	0.76	100.5	1144.67	21.49	110.65	98.57	184	-188
LK08	71.65	16.29	1.43	0.017	0.37	2.68	4.89	2.59	0.158	0.07	0.35	100.5	1194.17	55.11	157.74	47.86	153	-150
LK09	68.93	14.88	3.16	0.06	0.75	1.78	4.33	5.05	0.486	0.2	0.59	100.2	1148.83	107.45	139.68	31.79	115	-64
LK10	69.8	13.48	5.41	0.053	0.52	2.12	3.68	3.25	0.821	0.21	0.85	100.2	1163.33	69.15	118.71	37.86	175	-87
LK11	71.59	12.98	4.46	0.12	0.53	1.95	3.96	3.82	0.618	0.16	0.23	100.4	1193.17	81.28	127.74	34.82	165	-81
LK13	54.91	16.03	8.95	0.173	1.93	3.28	4.3	6.26	1.72	0.97	1.03	99.56	915.17	133.19	138.71	58.57	-6	-64
LK15	75.5	13.08	1.83	0.04	0.29	1.29	3.35	4.64	0.218	0.06	0.25	100.5	1258.33	98.72	108.06	23.04	197	-32
LK17	73.64	12.5	2.59	0.041	0.19	1.1	2.96	5.26	0.392	0.08	0.34	99.11	1227.33	111.91	95.48	19.64	189	-3
LK20	62.11	18.87	2.84	0.044	2.83	5.7	5.44	1.61	0.286	0.07	0.68	100.5	1035.17	34.26	175.48	101.79	67	-243
LK21	60.03	17.34	6.62	0.121	2.1	5.04	4.62	2.66	1.012	0.31	0.51	100.4	1000.50	56.60	149.03	90.00	68	-182
LK22	63.2	16.22	5.37	0.072	2.5	4.42	4.66	2.47	0.685	0.19	0.56	100.4	1053.33	52.55	150.32	78.93	96	-177
LK24	71.02	13.87	3.88	0.075	0.82	2.15	4.74	1.94	0.673	0.19	0.31	99.68	1183.67	41.28	152.90	38.39	175	-150
LK25	69.68	13.9	4.44	0.069	0.52	2.45	2.97	5.17	0.733	0.24	0.62	100.8	1161.33	110.00	95.81	43.75	152	-30
LK26	51.81	17.55	10.17	0.143	3.64	6.9	4.01	2.6	1.434	0.64	0.46	99.35	863.50	55.32	129.35	123.21	21	-197
LK27	68.03	15.75	2.79	0.037	0.59	1.14	2.74	7.29	0.498	0.31	0.55	99.72	1133.83	155.11	88.39	20.36	121	46

4.4 Discussion

Nd analysis of samples defining western Quebecia crust showed a close correlation to published data from the surrounding region, and had an analytical distribution that suggest a ~1.55 Ga Mesoproterozoic arc terrane protolith. Multiple samples had Nd model ages <1.45 Ga, but all were located generally near the known northern limit of younger Mesoproterozoic crust. This suggests that these resulted from the addition of juvenile melt components during Elzevirian orogenesis, which is also consistent with the observed major element analysis trends. The abundance distribution of the samples also suggests a bimodial range, in which a peak in Nd model ages around 1.55 Ga correlates well with Quebecia aged crust, while a smaller peak around 1.4 Ga provides evidence of crustal working that is also seen within the Mont-Laurier and Mauricie terranes.

This evidence supports the argument that all Mesoproterozoic crustal terranes within the study region should be incorporated into the broader concept of Quebecia, and that juvenile ages within this region are due to younger magmatic reworking, a notion that is also supported by their spatial distribution. Although more detailed sampling would be necessary to investigate a potential boundary marking the northern limit of the Elzevirian arc, the gradually diminishing contamination of Quebecia by juvenile components to the south suggests that this 'boundary' should be interpreted as a plutonic front, rather than a distinct suture zone. The southwestern portion of the study area also conclusively defined the limit to the CMB near the town of Mont-Laurier, since PT 04 (#20) returned a Nd model age (1643 Ma) significantly older than shown by any other analyses within the CMB.

CHAPTER 5
RESULTS: ABT AND ENSIALIC ARC

5.1 Geologic Context

The central section of the regional study area is situated around the remote logging town of Parent, Quebec, and is significant as it represents a region of the Grenville that has not yet been analyzed in regards to crustal formation (Figure 5.1). This area is situated in a region of Quebec where outcrop exposure and accessibility are very limited. However, recent upgrading of forest access roads has resulted in limited blasting of road-cuts, which provide new sampling targets.

The northern section of the study area is characterized by Archean aged charnockite gneisses, along with unspecified migmatites and gneisses. The limit of these Archean aged rocks is defined by the ABT, which trends northeast from a point just south of Clova and crosses the southeastern tip of Reservoir Gouin. There are notably some occurrences of Mesoproterozoic gneissic and granitoid plutons north of the ABT which occur proximal to Archean mafic gneisses and amphibolite packages.

South of the ABT lies a band of early Mesoproterozoic to late Paleoproterozoic mafic gneisses and amphibolites with a few identified granite intrusions generally occurring along regional fault structures. The eastern portion of the study area is dominated by a wide range of lithologies including, mixed, mafic and undifferentiated gneisses. Some AMCG suite complexes also trend along regional fault structures to the east (Davidson, 1998b). The exact location of the ABT in this region is relatively unknown, and has only been preliminarily delineated by changes in the aeromagnetic signature intensity trending through the region.

Due to its remote location and the lack of mapping efforts in the region, very little is understood about the geological history of the region, leading this area to be defined as undifferentiated polycyclic allochthonous crust by Rivers et al. (1989). Samples were collected to determine the location of the ABT east of Clova, with attempts made along the edge of Reservoir Gouin, to further refine this boundary. Also, sampling was focused on investigating the zone and limit of crustal mixing identified as an ensialic arc by Martin and Dickin (2005) that occurs as a 50 km zone of reworked Archean crust subparallel to the ABT directly to the northeast (refer to Figure 3.4).

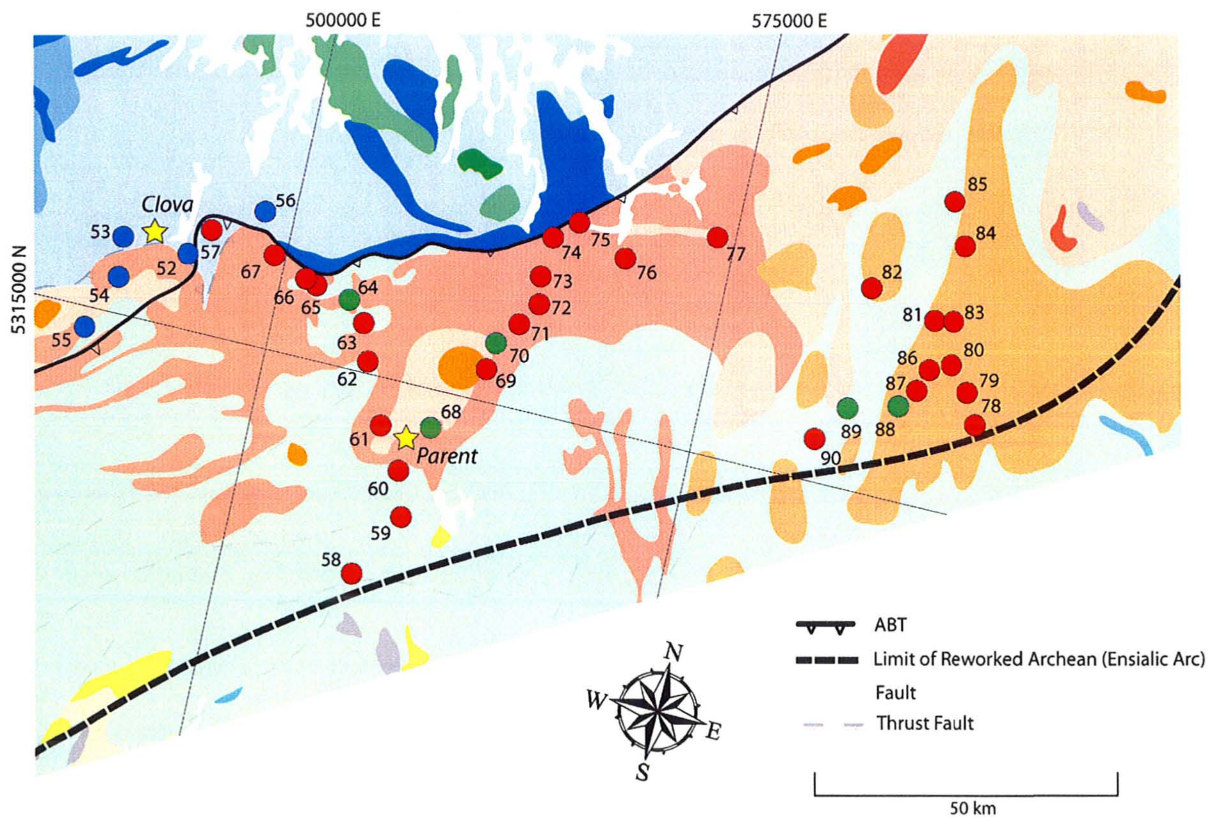

Figure 5.1 - Geology and sampling locations within the section of the study area defining the ABT and Ensialic Arc, near the Parent-Clova region, Quebec. • – Mesoproterozoic allochthon, • – Ensialic Arc (Reworked Parautochthon) • – Archean Parautochthon. Refer to Appendix B for lithologic key.

5.2 Nd Model Age Mapping

This region represents one of the last remaining gaps in the first-order crustal formation map of the Grenville, with only a few unpublished reconnaissance samples subjected to Nd isotopic study (Martin, unpublished). Thirty-two new Nd analyses were determined, and used to calculate Nd-model ages using the depleted mantle model of DePaolo (1981). Sampling was restricted to orthogneisses, and charnockite gneisses, with mafic and younger plutonic rocks avoided. The aim of sampling in the northern portion of the study area was to determine the position of the ABT between Parent and Clova, as well as to characterize the reworked crust in contact with the Laurentian margin. Figure 5.1 shows the geographical distribution of sampling across the region, with corresponding isotopic data presented in Table 5.1.

Table 5.1 - Sm-Nd isotopic data for the Archean, ABT and ensialic arc in the Parent-Clova region of south central Quebec.

Sample	Northing	Easting	Nd ppm	Sm ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	error	εNd 1450	T_{dm} (Ma)
Archean Parautochthon: T_{dm} ages >2300 Ma									
52 - CV 1	5328100	484300	21.09	3.67	0.1051	0.511082	0.012	-14.2	2774
53 - CV 5	5327800	472800	12.71	2.13	0.1013	0.510999	0.014	-15.1	2792
54 - CV 6	5322500	472900	5.33	0.62	0.0701	0.510707	0.016	-15.4	2490
55 - CV 12	5312260	468916	15.60	3.13	0.1212	0.511327	0.012	-12.6	2857
56 - PT 31	5340319	498776	29.20	2.62	0.0541	0.510235	0.015	-22.3	2696
Ensialic Arc (Reworked Paleoproterozoic): T_{dm} ages 1650 – 2300 Ma									
57 - CV 2	5334850	485700	38.64	6.95	0.1087	0.511641	0.016	-3.8	2036
58 - PT 17	5285204	526494	45.94	6.64	0.0874	0.511636	0.008	-0.7	1696
59 - PT 19	5293840	527596	15.77	3.24	0.1241	0.512051	0.011	1.1	1685
60 - PT 21	5302873	527397	67.59	13.33	0.1192	0.511945	0.010	-0.1	1769
61 - PT 22	5310109	522006	43.82	8.05	0.1110	0.511701	0.009	-3.5	1992
62 - PT 24	5319037	516678	41.24	7.36	0.1079	0.511704	0.011	-2.9	1928
63 - PT 25	5324533	515720	42.73	7.74	0.1095	0.511713	0.012	-3.0	1944
65 - PT 28	5329580	507438	32.10	5.46	0.1027	0.511576	0.013	-4.5	2016
66 - PT 29	5329575	505950	33.35	5.87	0.1063	0.511592	0.013	-4.8	2059
67 - PT 30	5332089	503285	23.07	3.99	0.1045	0.511412	0.016	-8.0	2283
69 - PT 34	5322886	537890	40.83	9.91	0.1467	0.512188	0.012	-0.2	1945
71 - PT 38	5331126	540795	68.47	13.85	0.1223	0.511942	0.012	-0.7	1834
72 - PT 39	5334297	544032	29.18	4.23	0.0877	0.511538	0.013	-2.6	1819

73 - PT 40	5338783	542855	43.15	6.85	0.0960	0.511567	0.016	-3.5	1910
74 - PT 42	5345715	542126	45.11	9.08	0.1217	0.511751	0.015	-4.4	2144
75 - PT 45	5349420	546184	23.69	4.58	0.1169	0.511751	0.013	-3.5	2036
76 - PT 46	5346301	556317	58.93	9.45	0.0969	0.511632	0.015	-2.4	1841
77 - PT 49	5352843	571388	5.11	0.57	0.0677	0.511450	0.012	-0.9	1662
78 - SM 27	5337071	620546	61.10	12.75	0.1261	0.511990	0.011	-0.5	1831
79 - SM 29	5339349	618111	61.43	10.84	0.1066	0.511793	0.010	-0.9	1776
80 - SM 30	5342182	614305	58.38	10.35	0.1072	0.511726	0.011	-2.3	1883
81 - SM 31	5348566	608753	58.01	9.54	0.0994	0.511621	0.011	-3.0	1896
82 - SM 33	5350767	597347	43.79	7.81	0.1077	0.511708	0.012	-2.8	1920
83 - SM 53	5349001	611235	40.26	8.40	0.1261	0.511986	0.016	0.4	1836
84 - SM 57	5360057	610729	34.62	5.63	0.0984	0.511656	0.017	-0.1	1832
85 - SM 59	5367482	608905	40.74	7.93	0.6051	0.511990	0.014	2.0	1669
86 - SM 61	5340195	608862	48.77	10.09	0.1250	0.511986	0.013	0.6	1813
87 - SM 62	5339908	608634	45.09	8.64	0.1159	0.511967	0.021	1.9	1674
90 - SM 66	5324318	590040	105.13	17.81	0.1024	0.511814	0.011	1.4	1680

Ensialic Arc (Juvenile): T_{dm} ages < 1650 Ma

64 - PT 27	5328314	512225	48.79	8.35	0.1035	0.512051	0.011	4.7	1370
68 - PT 32	5310663	530916	20.99	3.70	0.1067	0.511982	0.013	2.8	1507
70 - PT 36	5328510	538460	29.72	6.33	0.1288	0.512170	0.016	2.6	1563
88 - SM 63	5337877	606147	27.80	6.18	0.1345	0.512193	0.023	2.9	1631
89 - SM 65	5332003	598295	18.04	4.19	0.1404	0.512362	0.019	5.1	1412

An isochron diagram depicting $^{143}Nd/^{144}Nd$ versus $^{147}Sm/^{144}Nd$ for samples from the Parent-Clova region is shown in Figure 5.2, along with published data from Martin and Dickin (2005) which define the Archean block and ensialic arc observed in the Lac St. Jean region directly to the northeast.

Five newly collected samples which define the Archean parautochthon in the region are in good agreement with those of Martin and Dickin (2005), and plot accordingly along a 2.7 Ga reference line. However, the majority of the newly collected samples within this region plot in a wide array between the 1.51 and 2.7 Ga reference lines, and show a strong overlap with samples from Martin and Dickin (2005) that define the ensialic arc to the northeast. This scatter is expected in an ensialic arc environment, as crustal material from the Archean parautochthon was variably contaminated by younger mantle-derived magmas.

Five samples located within the zone defined as the ensialic arc returned Nd model ages < 1.65 Ga, and most likely represent younger intrusions with large mantle-derived components. These samples plot away from the ensialic array, clustering near the 1.51 Ga reference line.

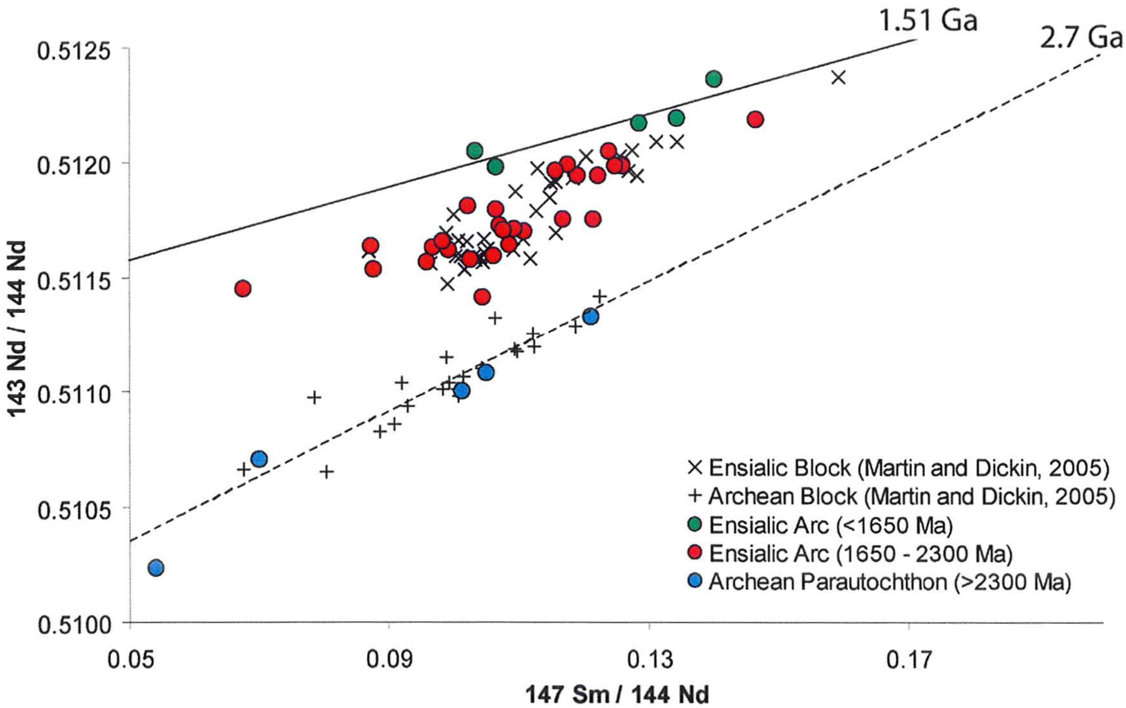

Figure 5.2 - Isochron diagram of $^{143}Nd/^{144}Nd$ versus $^{147}Sm/^{144}Nd$ for samples characterizing the Ensialic Arc identified in the Parent-Clova region, Quebec. The solid line represents a 1.51 Ga reference and the dashed line represents a 2.7 Ga reference.

Figure 5.3 is a graphical representation of the newly collected samples, along with those from Martin and Dickin (2005), based on their Nd concentration (ppm) versus εNd (1450). Again, there is a distinct clustering of samples from the region with strong correlation to the samples from northwest of Lac St. Jean. The five Archean samples plot with distinctly low Nd concentration and within the Archean cluster of Martin and Dickin (2005), with one sample plotting significantly lower (-22.3 εNd), but undoubtedly Archean in provenance.

The ensialic arc samples plot in a similar array to those of Martin and Dickin (2005), ranging between +2.0 to -4.8 with a wider range in Nd concentration. Only sample PT30 closely approaches the Archean cluster, with an εNd (1450 Ma) value of -8.0. This is however consistent with the Nd model age of 2.28 Ga calculated for the sample, which defines the southern most limit for the ABT near Clova. The 5 younger samples again plot away from the two main clusters and show the highest εNd values, which is indicative of their juvenile derived mantle composition.

Figure 5.4 looks at the effect of εNd variation in the region relative to geographical distribution of the samples using the northing location as the fixed variable, as the ABT and proposed limit of ensialic reworking generally trend east-west. The five newly collected samples from the Archean parautochthon plot in a similar range to those defining the Archean block of Martin and Dickin (2005), with a single outlier (PT 31) showing a strong Archean εNd value which helps to refine the location of the ABT east of Clova.

The ensialic arc sample suite shows a good correlation in εNd range similar to that of Martin and Dickin (2005) and convincingly argues that this is in fact a continuation of the same ensialic arc terrane. Although the five younger samples plot in a wide distribution throughout the zone of ensialic mixing, their juvenile provenance can be distinguished by their clustering towards higher εNd values, in a range not observed in the ensialic arc of Martin and Dickin (2005). This reflects the greater intensity of younger magmatic reworking seen in the Parent-Clova region, as opposed to the Lac St. Jean area, as discussed in Chapter 4.

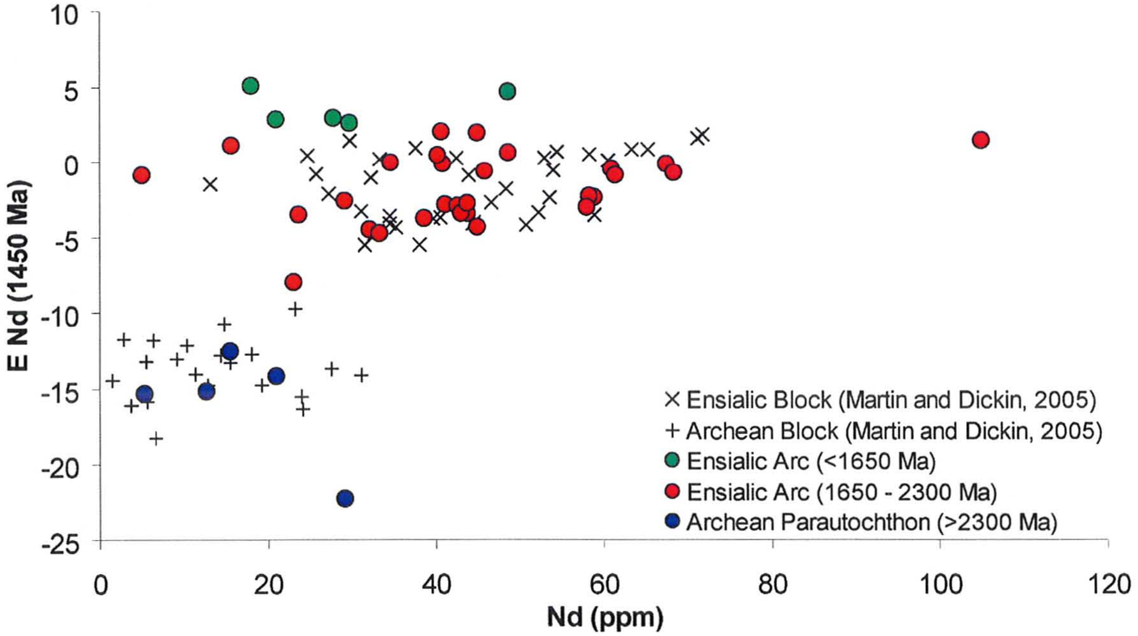

Figure 5.3 - Plot of Nd concentration (ppm) versus εNd (1450). Newly collected samples defining the Ensialic Arc of the Parent-Clova region are plotted against Archean (Western Block) and Ensialic Arc (Central Block) samples from Martin and Dickin (2005).

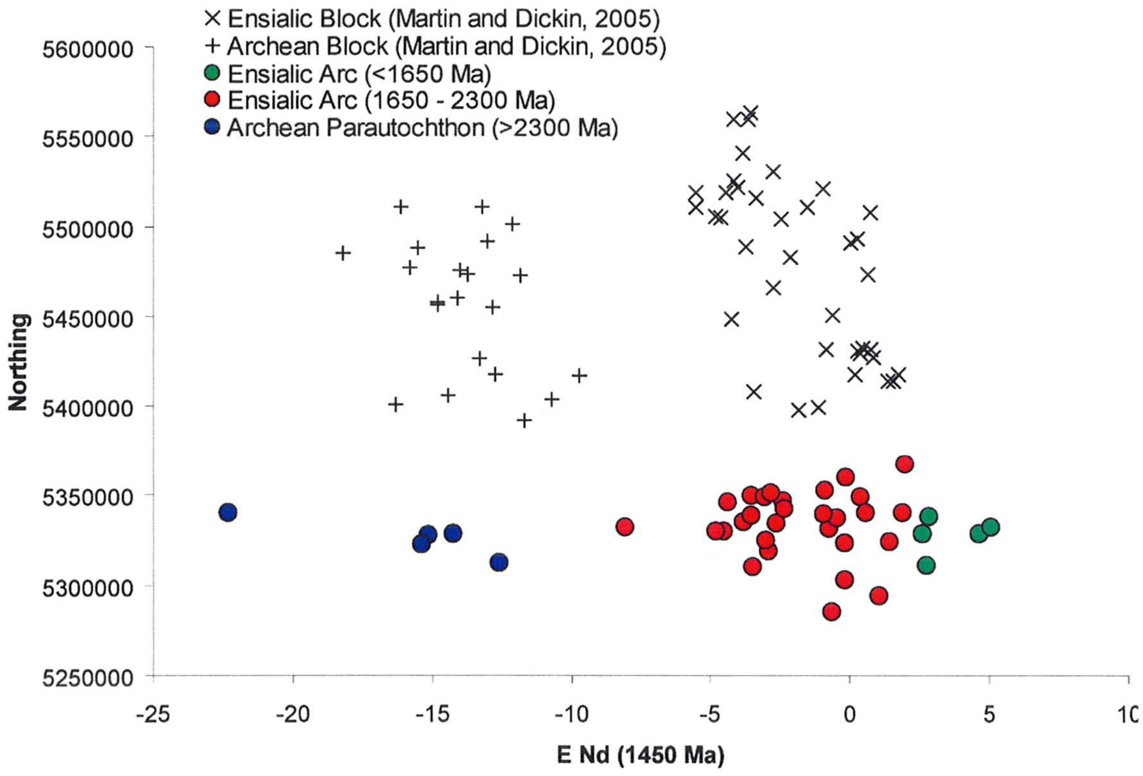

Figure 5.4 - Plot of εNd values versus sampling location (Northing), compared to the Archean and Ensialic Arc sample suite of Martin and Dickin (2005).

5.3 Petrochemical Data

Martin and Dickin (2005) demonstrated the importance of using complimentary petrochemical data when delineating an ensialic arc expression via Nd isotope analysis in the Grenville Province, as a wide range of lithologies can be attributed to variable mixing processes in an ensialic arc system.

Major element analyses (Table 5.2) for the newly collected sample suite from the Parent-Clova region are presented in Figure 5.5, along with samples from the central and Archean blocks of Martin and Dickin (2005). Similar to the ensialic expression to the northeast, the data extend across the diagram from the diorite field through quartz monzodiorite to granodiorite and adamellite, with a single point plotting in the tonalite field. One notable difference to the data from Martin and Dickin (2005) is the stronger concentration of samples within the granite field, suggesting that samples from the Parent-Clova region may be of a more evolved composition. Four samples with juvenile melt components within the ensialic mixing zone are plotted, and although it is difficult to generalize trends from such a small sample set, it can be noted that they plot within quartz monzodiorite to adamellite fields in a similar range to those samples that had Nd model ages >1.65 Ga, suggesting that they have derived melt components from rocks associated with the ensialic mixing process.

The new data thus show close petrochemical correlations with the proposed ensialic arc to the northeast, which is analogous to a modern ensialic arc example of the Blano Batholith in Peru (Martin and Dickin, 2005). Ensialic reworking, which causes magma differentiation during the slow diapiric rise through a thickened crust, may alter magma chemistry from the tonalite-granite suite towards a more alkaline monzonite and quartz-monzonite composition. Modal mineral analysis of the Peruvian plutonic suite revealed a similar diagonal distribution on the Q-P (quartz - plagioclase) diagram showing a large range in lithologies, which was attributed to the variable mixing of the subduction related magmas within the existing Mesoproterozoic continental crust (Atherton et al., 1979).

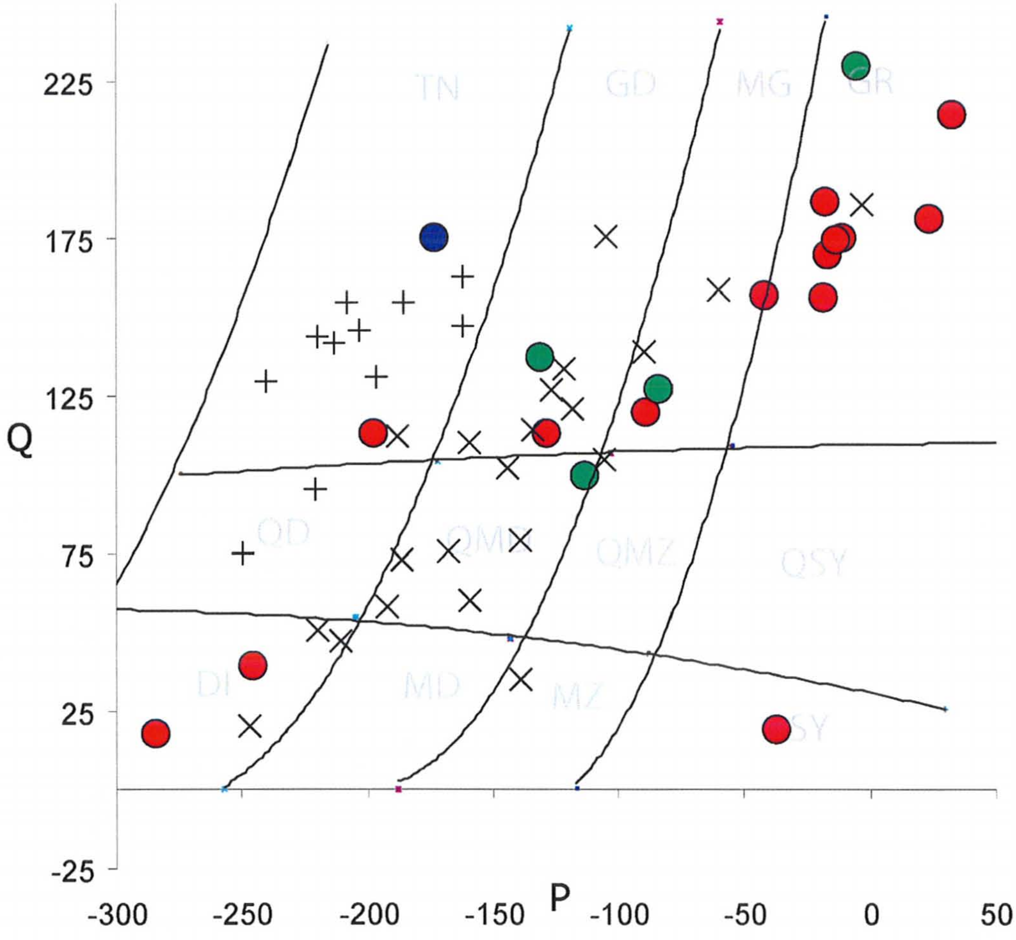

Figure 5.5 --Q-P petrochemical grid after Streckeisen (1973) for newly collected samples defining the Ensialic Arc, along with one Archean sample. ● – Ensialic Arc (2300 – 1650 Ma); ● – Juvenile samples (<1650 Ma) within the Ensialic Arc; ● – Archean Parautochthon; × – Ensialic Arc (Central Block) and + – Archean (Western Block) from Martin and Dickin (2005), respectively. TN – tonalite; GD – granodiorite; MG – monzogranite; GR – granite; QD – quartz diorite; QMD – quartz monzodiorite; QMZ – quartz monzonite; QSY – quartz syenite; DI – diorite; MD – monzodiorite; MZ – monzonite; SY – syenite.

Table 5.2 - Major element analysis for the Archean, ABT and ensialic arc in the Parent-Clova region of south central Quebec.

SAMPLE	SiO2	Al2O3	Fe2O3(T)	MnO	MgO	CaO	Na2O	K2O	TiO2	P2O5	LOI	Total	Si	K	Na	Ca	Q	P
<u>Archean Parautochthon</u>: T_{dm} ages >2300 Ma																		
PT31	71.16	15.6	1.98	0.02	1.09	3.1	4.66	1.55	0.303	0.13	0.47	100.1	1186.00	32.98	150.32	55.36	175	-173
<u>Ensialic Arc</u>: T_{dm} ages 1650 – 2300 Ma																		
PT17	71.29	13.83	2.9	0.04	0.6	2.04	2.64	5.24	0.431	0.14	1.17	100.3	1188.17	111.49	85.16	36.43	175	-10
PT19	53.31	25.12	3.49	0.056	1.1	9.84	4.71	0.86	0.697	0.1	0.73	100	888.50	18.30	151.94	175.71	9	-309
PT21	68.12	13.19	6.35	0.131	0.31	1.93	2.83	5.09	0.731	0.12	0.14	98.95	1135.33	108.30	91.29	34.46	156	-17
PT22	70.78	14.21	2.83	0.041	0.69	1.98	3.39	4.86	0.534	0.17	0.47	99.96	1179.67	103.40	109.35	35.36	157	-41
PT24	65.42	16.13	4.18	0.08	1.22	3.51	3.53	4.13	0.832	0.25	0.38	99.66	1090.33	87.87	113.87	62.68	120	-89
PT25	73.4	13.28	2.4	0.047	0.64	1.57	2.97	5.03	0.476	0.15	0.33	100.3	1223.33	107.02	95.81	28.04	186	-17
PT29	64.93	16.15	4.86	0.111	1.71	4.05	3.96	3.37	0.593	0.21	0.49	100.4	1082.17	71.70	127.74	72.32	113	-128
PT30	64.76	16.7	4.3	0.07	1.88	4.19	4.94	1.76	0.525	0.22	0.64	99.98	1079.33	37.45	159.35	74.82	113	-197
PT34	58.55	17.92	4.93	0.081	1.54	3.1	3.89	6.76	0.708	0.54	1	99.01	975.83	143.83	125.48	55.36	19	-37
PT38	70.63	12.48	5.02	0.096	0.31	1.93	2.8	5.14	0.608	0.12	0.09	99.23	1177.17	109.36	90.32	34.46	170	-15
PT39	72.36	13.42	2.12	0.04	0.58	1.58	2.99	5.27	0.446	0.11	0.4	99.3	1206.00	112.13	96.45	28.21	175	-13
PT40	73.09	13	1.57	0.015	0.35	1.16	2.57	6.02	0.374	0.07	0.52	98.73	1218.17	128.09	82.90	20.71	181	24
PT42	55.32	18.57	7.51	0.172	2.46	5.97	5.2	1.39	1.094	0.44	0.47	98.58	922.00	29.57	167.74	106.61	39	-245
PT45	54.27	19.84	6.75	0.119	3.14	8.17	5.04	1.14	0.902	0.34	0.76	100.5	904.50	24.26	162.58	145.89	17	-284
PT46	74.32	12.69	3.14	0.06	0.61	1.38	1.92	5.65	0.533	0.07	0.21	100.6	1238.67	120.21	61.94	24.64	214	34
<u>Ensialic Arc</u>: T_{dm} ages < 1650 Ma																		
PT27	67.42	16.3	3.07	0.104	0.77	1.97	5.1	4.09	0.568	0.17	0.35	99.91	1123.67	87.02	164.52	35.18	100	-113
PT32	65.13	14.99	5.6	0.084	1.71	2.68	3.7	3.94	0.722	0.15	0.63	99.34	1085.50	83.83	119.35	47.86	127	-83
PT36	67.41	14.46	4.87	0.096	0.95	3.17	4.24	2.94	0.601	0.18	0.32	99.23	1123.50	62.55	136.77	56.61	137	-131
PT49	77.81	11.88	0.63	0.017	0.16	1.31	2.6	4.86	0.179	0.03	0.51	99.97	1296.83	103.40	83.87	23.39	229	-4

5.4 Discussion

The samples collected from the Parent-Clova region of south-central Quebec help to fill in a major gap in the crustal formation age map of the Grenville Province, as they define a ~50 km wide zone of crustal mixing adjacent to the Archean parautochthon, separated to the north by the ABT. This zone of mixed crust is a result of ensialic arc formation, in which Mesoproterozoic magmas were contaminated by partial melts of the Archean lower crust, resulting in a mixed isotopic signature that displays broad trends between the two crustal components. The ensialic signature shows strong isotopic correlation to the ensialic arc terrane (central block) proposed by Martin and Dickin (2005) and can be considered to be a continuation of that same structure.

Although five samples within the region returned Nd model ages that were abnormally young relative to the rest of the ensialic arc, it was shown that they are most likely part of the same arc system, but with a larger mantle derived component. The vast majority of the samples collected within the region define a typical range of isotopic heterogeneity that results from crustal mixing processes and provides sufficient evidence for classification as an ensialic arc. Nd isotope analysis of the region also allowed for the refinement of the ABT near Clova, where newly acquired samples help to better delineate the ABT in a region where its position was largely unknown. Unfortunately, poor exposure and limited accessibility hindered efforts to map the ABT north of Parent and along the southeastern edge of Reservoir Gouin. Improved resolution of the ABT in this area would require sampling by boat.

CHAPTER 6
RESULTS: CABONGA TERRANE

6.1 Geologic Context

The Cabonga terrane (Figure 6.1) is a region identified as a 4km thick allochthonous thrust sheet (Ludden and Hynes, 2000) based on Lithoprobe studies, and is part of the CMB, thus included in the AMB defined by Rivers et al. 1989. This monocyclic allochthonous package overlies Archean aged migmatites of the Parautochthonous Belt (PB) that underwent high-grade metamorphism at least 200 million years prior to deformation and metamorphism associated with the Grenville orogeny. Bounded to the west by the Cabonga Thrust, a shear zone comprising straight gneisses and discrete bands of anastomosing mylonites, this terrane has been deformed by large-wavelength, northeast-trending buckle folds which are associated with its emplacement over PB crust (Martignole, 2000). Much of the terrane is comprised of Grenvillian Supergroup mid-Mesoproterozoic paragneisses, bounded to the north by the Bouchette anorthosite complex. Multiple deformed units of gabbro and norite have been intruded along much of the boundary between the AMB and older gneisses of the APB.

This terrane can therefore be identified as a crustal slice that has been thrust to the northwest over the PB during the Shawinigan pulse of the Grenville orogeny (Martignole et al., 2000). Terminal uplift, post-collisional extension and subsequent erosion has left this slice of monocyclic crust further northwest than the rest of the AMB, but Nd isotope mapping will help to constrain its geological history.

A sharp contrast in crustal extraction ages between Archean and Mesoproterozoic aged rocks should clarify the regional position of the ABT, particularly near Clova, Quebec where the exact location of the ABT is still largely unknown. In addition, a large area of poorly understood late Paleoproterozoic to early Mesoproterozoic granitoid orthogneisses and mixed charnockite gneisses will be sampled to probe any connection to the ensialic isotopic signatures observed to the northeast.

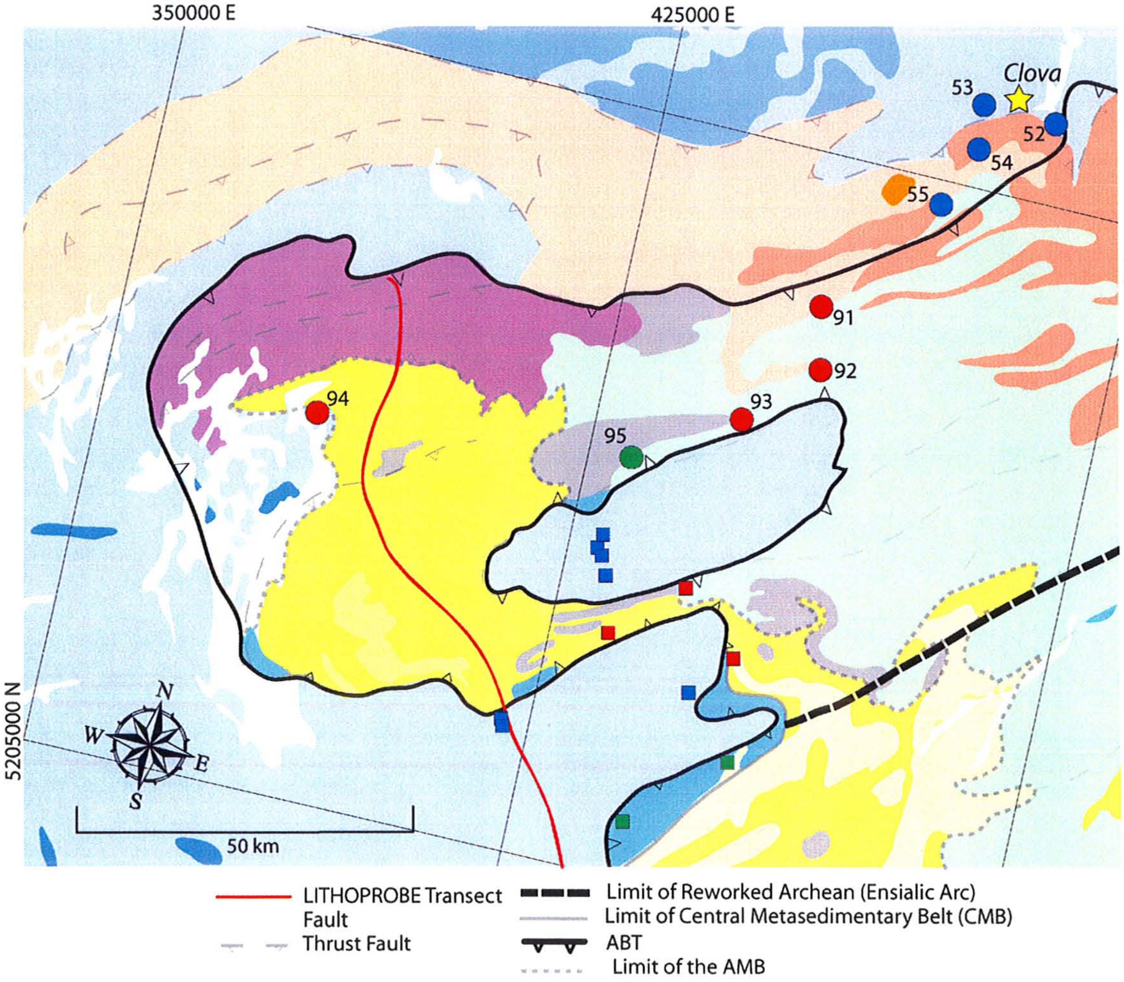

Figure 6.1 – Geology and sample distribution within the Cabonga Terrane, with a portion of the LITHOPROBE transect 52 (red line). Refer to Appendix B for geologic legend and Figure 6.2 for interpreted seismic profile. Sample distribution throughout the Cabonga Terrane illustrating the presence of an erosional window of Archean aged rocks within reworked crust, and the revised location of the ABT. ● – Mesoproterozoic allochthon, ● Paleoproterozoic-aged ensialic arc ● – Archean Parautotochthon. After Guo and Dickin (1996), ■ – Mesoproterozoic allochthon, ■ - Ensialic arc, ■ –Reworked Archean crust.

6.2 Structural Setting

Seismic reflection data collected by the LITHOPROBE program in 1993 has allowed for a better understanding of Grenvillian structure. Although many transects were used to characterize the crustal architecture of Canada, only one of these transects passed through the current study area, namely transect 52 which passes through the Reservoir Cabonga Terrane and travels through Mont-Laurier along Highway 117.

The Reservoir Cabonga transect reveals a crustal depth of ~36km in the region (Martignole et al., 2000) with several strong seismic reflectors indicating some of the major crustal divisions (Figure 6.2). Deep beneath the Cabonga Terrane, the LITHOPROBE study identified the southeastern extent of the Grenville Front, where the hanging wall of the Grenville Province is in direct contact with the footwall of the Superior Province. This zone indicates the southeast dipping structural trend widely associated with the Grenville orogeny, but also shows a zone of thinned crust relative to the rest of the transect. This thinning of crust beneath the Cabonga terrane and the resultant sharp MOHO boundary has been attributed to post-accretionary extension (Martignole et al., 2000), and also may be related to the variations in strength of the relatively cold lithosphere in this area, as revealed by low heat flow in the region (Mareschal et al., 2000).

Seismic profiling of the region complements the geological interpretation that the Reservoir Cabonga terrane is a thin slab of metasedimentary and metaigneous rocks, producing a synformal shape that formed through thrusting over rocks of Archean provenance and preserved through emplacement in an extensional setting during orogenesis.

The Bouchette anorthosite, which bounds the metasedimentary slab to the northwest, also preserves evidence of northwest transport through shear zones within the complex hosting rotated porphyroclasts and C-S fabrics (Indares and Martignole, 1990). This transect also shows the possibility of the presence of an Archean window outcropping through the thinned synformal Proterozoic-aged crustal slice, which Guo and Dickin (1996) delineated from four Archean-aged gneissic samples.

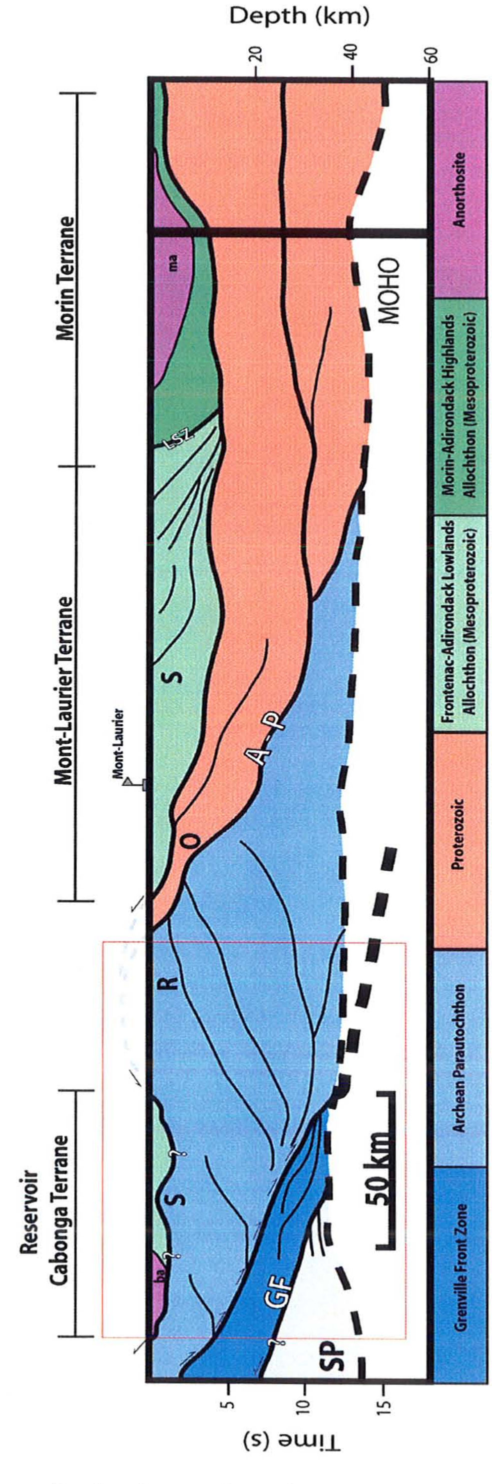

Figure 6.2 – Interpretation of seismic sections from the LITHOPROBE study (line 52) from Ludden and Hynes (2000). Age of metamorphism in each crustal unit indicated by S (Shawinigan), O (Ottawan) and R (Rigolet). Red outline corresponds to the extents of LITHOPROBE coverage documented in Figures 4.1. ba – Bouchette anorthosite, ma – Morin anorthosite, SP – Superior Province, GF - Grenville Front.

6.3 Nd Model Age Mapping

Five new Nd-model ages were calculated on orthogenesis from the Cabonga Terrane using the depleted mantle model of DePaolo (1981) and combined with several ages from Guo and Dickin (1996) from various locations across the Cabonga terrane. The objective of sample collection was to clarify the location of the ABT and test for the presence of reworked ensialic Paleoproterozoic aged crust. Sampling was also used to confirm the presence of the Archean crust (Guo and Dickin, 1996), allowing for the plausibility of an erosional window to be investigated within the Cabonga terrane.

Sample distribution throughout the region is illustrated in Figure 6.1, which primarily focused on sampling of locations hosting early-Mesoproterozoic and late-Paleoproterozoic mixed, charnockite and unspecified gneisses. The northeastern section of the study area displayed some mafic gneisses and amphibolites, while the northwestern section hosted the Bouchette anorthosite complex, both of which were avoided because of difficulty associated with analyzing mafic samples. The samples correspond to isotopic data listed in Table 6.1.

Table 6.1 - Sm-Nd Isotopic Data for the Cabonga Terrane. New data presented below in conjunction with published data from Guo and Dickin (1996).

Sample	Northing	Easting	Nd ppm	Sm ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	error	εNd 1450	T_{dm} (Ma)
Ensialic Arc (Reworked Paleoproterozoic): T_{dm} ages 1650 – 2300 Ma									
91 - CV 13	5295342	456384	3.80	1.18	0.1880	0.512727	0.017	3.23	1863
92 - CV 15	5286604	460404	18.92	3.14	0.1004	0.511586	0.011	-3.89	1960
93 - CV 16	5277250	451218	36.32	5.04	0.0839	0.511602	0.018	-0.71	1690
94 - RC 03	5260720	388259	20.49	2.97	0.0875	0.511348	0.012	-6.31	2048
Juvenile Crust: T_{dm} ages <1650 Ma									
95 - CV 10	5268399	435241	11.23	2.55	0.1377	0.512364	0.020	4.85	1359

Figure 6.3 is an isochron diagram showing data for the newly collected samples in the region, along with 12 samples from Guo and Dickin (1996). The solid line in the figure represents a reference line for 1.51 Ga allochthonous units, whereas the dashed line is used as a reference for 2.7 Ga pristine Archean crust. Most Archean aged samples plot near the 2.7 Ga reference line, in good agreement with the presence of Archean crust north of Clova, and constrain the northern limit for the repositioning of the ABT.

Sample CV10 (#95) which was collected north of the Archean window, returned a Mesoproterozoic age and represents either the addition of young mantle-derived components or may be evidence of the eastward continuation of the Cabonga nappe terrane, since it plots tightly with CMB samples of Dickin et al. (2009), nearly 50km away across Archean and Proterozoic crust.

The remainder of the samples scatter between the two reference lines, in good agreement with the biotite gniesses analysed by Guo and Dickin (1996) south of the Archean window, which at the time were regarded as representing a Paleoproterozoic arc terrane. Newly collected samples defining the ensialic arc in the region (along with the ensialic signatures surrounding the Parent region), in combination with Guo and Dickin's (1996) Paleoproterozoic arc samples, define the extent of the ensialic arc signature in the region and show that the ensialic arc signature is contiguous from northwest of the Lac St. Jean region (Martin and Dickin, 2005) southwest to the Cabonga Thrust.

Figure 6.4 depicts the newly collected samples graphed by their respective εNd (1450) versus Nd concentration (ppm). The Archean ages plotted expectedly in the negative field, with of εNd values clustering around -15 to -12. The Mesoproterozoic sample, CV 10, is believed to be a relict crustal slice similar to that north of the Mont-

Laurier terrane, plots in the positive (+4.85) and marks the youngest age in the Cabonga dataset and limit of the AMB in the region. The reworked Archean samples which characterized the northeastern extent of the Cabonga terrane plotted with a wide array of εNd values (+3.23 to -6.31), and had associated variation in Nd concentrations that are typically expressed in reworked material that inherits older crustal material.

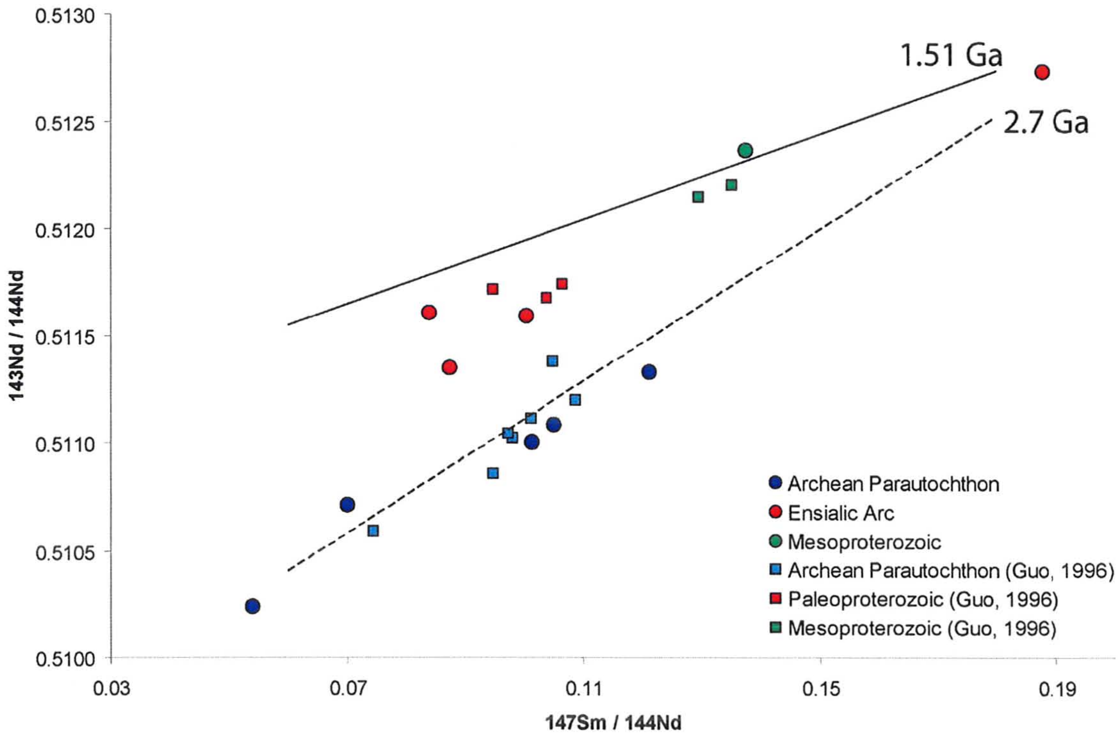

Figure 6.3 - Isochron diagram of $^{143}Nd/^{144}Nd$ versus $^{147}Sm/^{144}Nd$ for newly collected samples along with published samples from Guo and Dickin (1996) characterizing the Cabonga terrane. Solid line indicates 1.51 Ga reference, dashed line indicates 2.7 Ga reference.

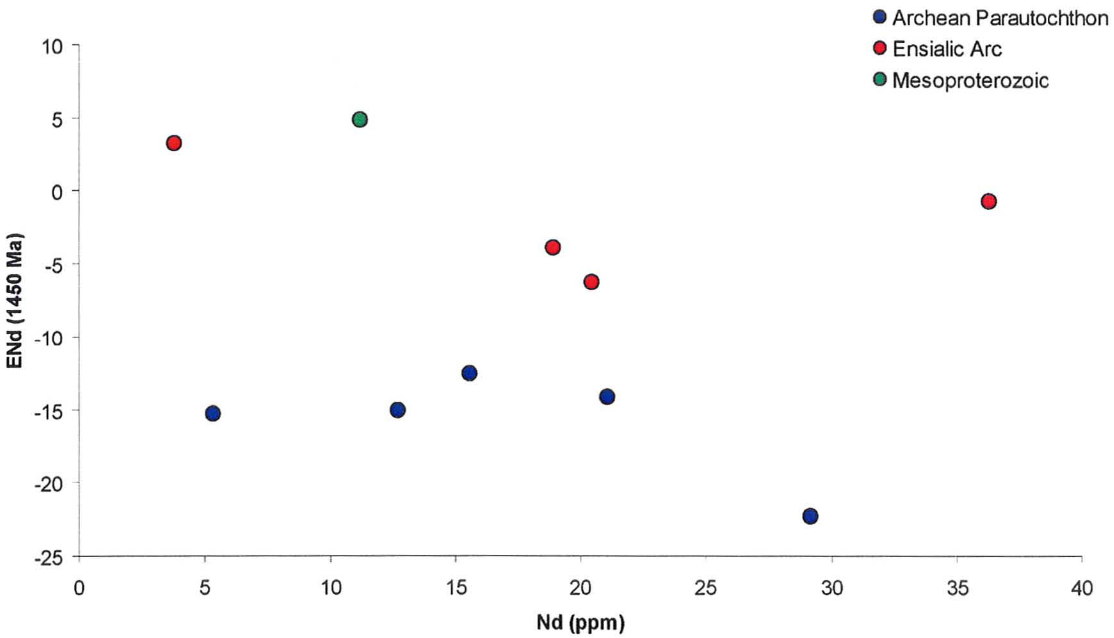

Figure 6.4 - Plot of Nd concentration (ppm) versus εNd (1450) for newly collected samples from the Cabonga terrane.

6.4 Discussion

Collectively, these samples define a region that has suffered from the exhumation and overthrusting of Mesoproterozoic crust during the Shawinigan metamorphic episode (Martignole, 2000), resulting in a displaced thin-skinned allochthon regarded as the Cabonga terrane.

Newly collected data points show a strong isotopic correlation to published data of Guo and Dickin (1996), when defining the extent of the Archean parautochthon and are complimentary to the evolutionary history of Mesoproterozoic crustal terranes in the region. The newly analyzed sample suite, with mixed isotopic signatures of Paleoproterozoic age, shows evidence of crustal contamination, consistent with crustal mixing in an ensialic arc system.

The collected data points also help to refine the position of the ABT in the northeastern section of the Cabonga study area, since it runs between CV 12 (#55) and CV 13 (#91), where a significant Nd model age break occurs, in addition to complimentary geologic and trending fault structures.

Sample RC 03 showed a Paleoproterozoic signature in the western section of the Cabonga terrane. However this is a preliminary determination, and further sampling is required to better characterize the position of the ABT in the western portion of the Cabonga terrane.

CHAPTER 7
REGIONAL INTERPRETATION

7.1 Regional Interpretation

Reconnaissance sampling of a 50,000 km^2 area including the Parent-Clova region of south central Quebec, has allowed for the near completion of Province–wide Nd model age mapping across the entire Grenville (Figure 7.1). Distinct crustal terranes and associated boundaries identified within the current study area help to define a region of the Grenville Province that has largely been ignored due to inaccessibility and lack of mineral resources.

Several Archean aged samples that were collected near Clova have resulted in the redefinition of the ABT in the region, as they show strong isotopic and Nd model age correlation to the PB. This new delineation shows that current boundary definition is still ambiguous in the region and several areas would benefit from more detailed sampling (western Cabonga Terrane and near the southeastern portion of Reservoir Gouin).

Most notably was the continuation of the ensialic arc investigated by Martin and Dickin (2005) northwest of Lac St. Jean, which has been extended to the southwest nearly 500 km along strike, where it has been traced into the Cabonga Terrane and may in fact reappear further southwest into Ontario. This mixed isotopic signature is attributed to ensialic arc formation, resulting from a subduction flip which occurred shortly after the docking of Quebecia onto Laurentia, resulting in a wide range on Nd model ages (1.7 – 2.2 Ga) occurring within a ~50 km wide belt reworked crust. The limit of crustal reworking was also able to be delineated, and represents a relatively abrupt diminishment in the ensialic arc influence on the pristine Mesoproterozoic aged Quebecia crust to the south

The extent of homogeneous Quebecia crust was also addressed by sampling efforts within the region and showed that Nd model ages reflective of Quebecia crust can be found west of the TSZ. However, no distinct boundary could be delineated between Quebecia and younger crustal units of the APB as the contact of these terranes better reflect a plutonic front (i.e. stitching plutons found throughout the region) rather than a discrete crustal boundary. In addition, isotopic and seismic evidence make a convincing case for a cryptic Archean-Proterozoic suture beneath (at least) the western portion of the APB in the region. More detailed sampling and mapping may better reveal the interactions of these more closely related Mesoproterozoic terranes, as well as any influence that the cryptic suture may have on current crustal isotopic compositions.

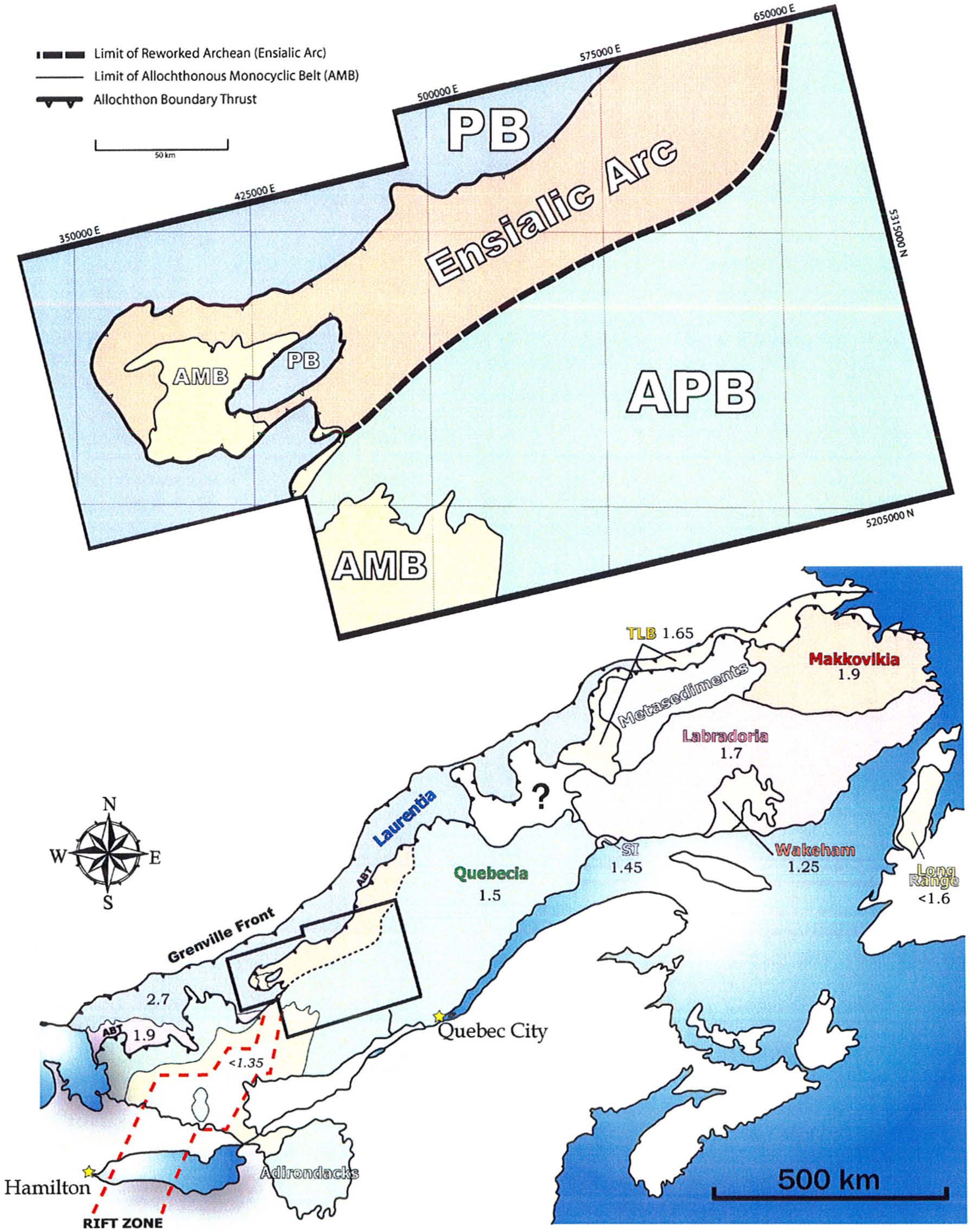

Figure 7.1 - Proposed limit of first-order crustal terranes based on Nd model ages within the study area, relative to the Grenville Province.

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APPENDIX A
ANALYTICAL PROCEDURE

A.1 Introduction

Using the Sm-Nd isotopic system for geochronological analysis requires multi-component analytical procedures to be stringently followed, as analysis via TIMS mass spectrometry follows precise methodology. The procedure can be divided into the following categories, of which will be explained in order of operation. The procedures are: 1) Sample collection, 2) Rock crushing, 3) Chemical dissolution and column chromatorgraphy, and 4) Mass spectrometry.

A.2 Sampling Collection

Rock samples were collected through various sections of the study area defined in Figures 4.1, 5.1 and 6.1. The collection of samples throughout such a vast area required for samples to be extracted from road outcrops, logging roads and river shores, as there was limited accessibility throughout much of the region. Since the samples were taken from a region that had undergone intense metamorphism, attention was paid to collecting representative homogenous fresh-rock samples, which are optimal for mass spectrometry analysis. Actual extraction of the samples was done by use of a 12 lbs. sledgehammer and rock hammer. Approximately 5 – 10 kg of rock was extracted at each location, with care given in selected 'fresh' rock that had not undergone any intensive chemical weathering. Sample locations were attained by using a handheld GPS unit, which determined localities based on the GPS array, and were catalogued before moving on.

A.3 Rock Crushing

The primary objective in this step of the procedure is to acquire a small amount of uncontaminated sample that is representative of the rock in the field. Samples, which had undergone initial weathering removal in the field, were taken to the rock crushing laboratory where a heavy wire brush was initially uses to remove any earth dust and/or loose fragments that may have been transferred to the sample during transportation from the field. Once initial cleaning was completed, a hydraulic jaw splitter was used to 'break' the sample into small cubes (maximum 1 in^3) of fresh material, free from any signs of chemical weathering. Any pieces that had weathering were discarded. Similarly, if any of the samples showed to have secondary veining within, these veins were avoided as they are not representative of the original rock chemistry.

Once a sufficient amount of sample was collected from the splitting process, the sample was run through a jaw crusher to convert the cubed material to gravel sized pieces. To help prevent contamination from previous samples, a small lot of sample was initially introduced to the jaw crusher and promptly discarded. Along with thorough cleaning between each sample, this procedure ensured that potential contamination between samples was minimized. The crushed sample was then split several times on a table-top splitter under a small amount of randomized material was left to be powdered, the remainder of the gravel was bagged and labeled, to be kept in storage in case repeats were necessary. The small gravel sample lot was then placed inside a tungsten carbide disc mill on a shatterbox, which was used to pulverize the material into a fine grain, suitable for acid digestion. The material was removed from the disc mill and placed into a labeled glass jar and taken to the clean lab for weighing and acid digestion.

It should be noted that this crushing procedure generated a significant amount of dust and rock debris, such that additional precautions were taken into consideration to help prevent contamination. During any point at which the rock sample underwent mechanically induced breakage, which typically generated rock dust, an air filtration system was used to remove any airborne particles. In addition, after each piece of equipment was used, a thorough cleaning followed that included vacuuming and wiping with dustless tissues.

A.4 Chemical Dissolution and Column Chromatography

The objective of this procedural stage is to determine the correct sample amount necessary of Sm-Nd analysis and to dissolve all of the organic and silicate compounds from the sample. The column chromatography stage is then used to separate the Nd and Sm of the sample, for analytical purposes.

A.4.1 Weighing

Individual solid FEP Teflon (Sarillex) digestion vessels were assigned to each sample, so that measurements can be made with precision and accuracy. Each bomb is carefully de-staticed to remove any mass associated with a static build-up. The empty bomb was then weighed on an analytical balance, then removed and rechecked. Discrepancies greater than 0.0002 g resulted in the de-statification of the bomb again. The powered sample is then carefully administered to the empty bomb using a clean spatula, with approximately 100 mg as the optimal sample weight. Once weighed, if the sample weight falls within the acceptable range (70-100 mg), the mass is recorded and the sample progresses onward.

A.4.2 Dissolution

At this stage, the bombs are tapped gently to release powder stuck on the sides. Because of the use of hazardous chemicals, all proper lab techniques and WHMIS procedures are followed strictly. After lid removal, 1 mL of concentrated HNO_3 and then 12 mL of concentrated HF is added to the bomb, and then the lid is replaced. After wrench tightening, the bombs are placed in a protective plastic jacket and placed in a 125°C oven for 4 days. The bombs are then removed from the oven and taken out of their plastic jacket to cool. The bomb lids are then removed and the bombs are transferred to a hot plate on which evaporation occurs. Approximately 5 mL of concentrated HNO_3 is added, and then the bomb is returned to the hot plate to further evaporate. Finally, 5 mL of 6M HCL is added to the bomb and then placed in the oven overnight.

A.4.3 Splitting

The samples are the diluted with 10 mL of MilliQ (de-ionized H_2O) and shaken. The bomb, lid and sample are then weighed on the balance, having the values recorded. Approximately 1/3 of the solution is then poured into a 15 mL beaker. The bomb, lid and solution is then re-weighed and re-recorded.

A.4.4 Spiking

Homogenization of the spiking solution is achieved by rolling the bottle, and placing three drops onto a tissue aids in reducing contamination on the nipple. The spike solution is enriched with Sm and Nd. The spike bottle is then massed without the lid. The balance is then tared and 5 drops (approximately 200 mg) is added to the beaker. The spike is then re-massed and the value is re-recorded. This sequence is repeated for each sample, and then the spike is carefully rewrapped and shelved accordingly. The spiked (ID) and unspiked (IR) beakers are then placed on a hot plate to evaporate the solution.

A.4.5 Column Chemistry

The column chemistry used in Nd-isotopic analysis has two parts. First REEs are collected by means of cation exchange. Secondly, the REEs are put through and anion column to collect Sm and Nd separetly. These processes are further explained below:

<u>Cation Exchange</u>

2 mL of 2.5 M HCl is added to the samples, which then are placed in a centrifuge for 10 minutes. 1 mL is then loaded into the cation columns, which is eluted with 2 mL of 2.5 HCl. Another 36 mL of 2.5 HCl is added along with 12 mL of 2M HNO_3, which removes Na, Ca and other major elements. 7.5 M HNO_3 is then added, which collects the REEs. This is evaporated under heat lamps and 1 mL of 0.3 M HCl is added in order to load the sample on the next set of columns.

<u>REE Chromatography</u>

1 mL of 0.3 M HCl solution is loaded into the REE columns, which is then washed in with 2 mL of 0.3 M HCl. Another 24 mL of 0.3 M HCl is added, followed by 12 mL of 0.3 M HCl, responsible for collecting the Nd. Subsequently, 2.5 mL of 1 M HCl is added after which, 12 mL of 1 M HCl is used to collect the Sm. The resulting solutions are evaporated under a heat lamp. One drop of 0.0003 M H_3PO_4 is then added to the residue, and evaporated down until a minute amount of liquid is left at the bottom.

A.5 Mass Spectrometry

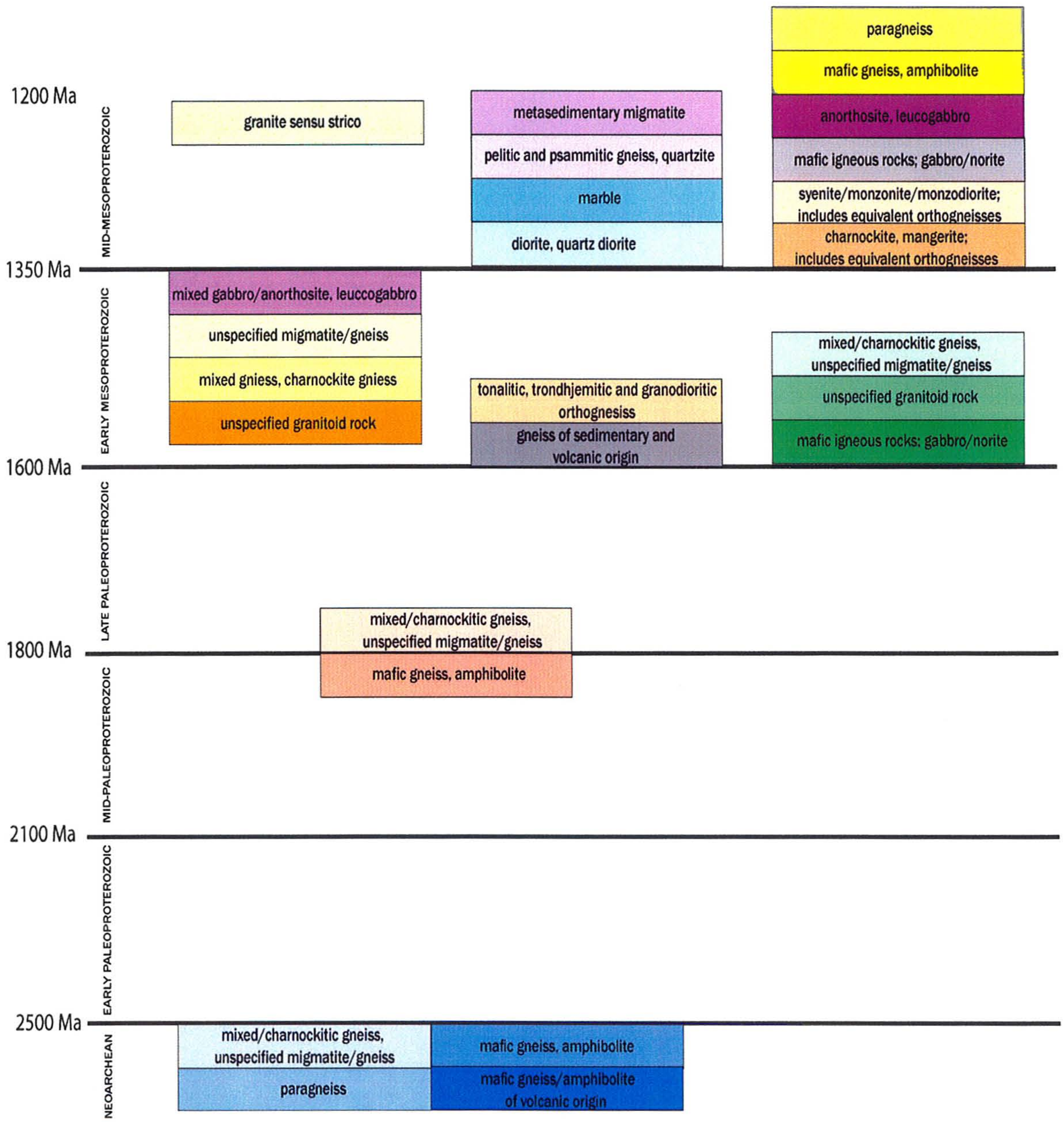
0.4 microlitres of 0.2 M H_3PO_4 is then added to the sample. This solution is then carefully loaded onto an outgassed bead, to be run in the mass spectrometer. The bead consists of a central Rhenium filament flanked on one side by a Tantalum side filament, on which the sample is loaded. Approximately a 2.0 amps current is then passed through the sample to dry it. The bead is now ready for mass spectrometer analysis. The mass spectrometer used in this isotopic analysis was a VG ISOMASS 354 mass spectrometer. The La Jolla standard was used in this study (Appendix A).

Table A.1: La Jolla Standard Analysis ($^{143}Nd/^{144}Nd$, June 2006 – April 2009)

	^{143}Nd / ^{144}Nd	Standard Error (/mil)		^{143}Nd / ^{144}Nd	Standard Error (/mil)
1	0.511873	0.009	35	0.511887	0.013
2	0.511872	0.009	36	0.511868	0.011
3	0.511855	0.010	37	0.511860	0.012
4	0.511852	0.009	38	0.511857	0.010
5	0.511853	0.009	39	0.511879	0.010
6	0.512010	0.008	40	0.511849	0.011
7	0.511909	0.010	41	0.511822	0.011
8	0.512004	0.012	42	0.511815	0.011
9	0.511915	0.009	43	0.511865	0.022
10	0.511903	0.012	44	0.511864	0.011
11	0.511869	0.010	45	0.511867	0.010
12	0.511857	0.013	46	0.511885	0.011
13	0.511869	0.010	47	0.511866	0.011
14	0.511874	0.009	48	0.511873	0.012
15	0.511875	0.010	49	0.511876	0.010
16	0.511848	0.010	50	0.511878	0.011
17	0.511853	0.011	51	0.511855	0.012
18	0.511880	0.010	52	0.511869	0.010
19	0.511878	0.009	53	0.511867	0.011
20	0.511860	0.011	54	0.511825	0.011
21	0.511878	0.010	55	0.511834	0.013
22	0.511862	0.010	56	0.511838	0.011
23	0.511849	0.010	57	0.511854	0.012
24	0.511857	0.011	58	0.511835	0.013
25	0.511854	0.010	59	0.511840	0.010
26	0.511854	0.008	60	0.511837	0.010
27	0.511857	0.010	61	0.511836	0.012
28	0.511844	0.009	62	0.511821	0.012
29	0.511859	0.011	63	0.511845	0.012
30	0.511855	0.010	64	0.511845	0.010
31	0.511867	0.012	65	0.511843	0.012
32	0.511883	0.011	66	0.511833	0.012
33	0.511841	0.011	67	0.511862	0.010
34	0.511868	0.013	68	0.511857	0.012

Average value of all 68 $143^{Nd}/144^{Nd}$ ratios derived from the La Jolla standard is:
0.511864 $\pm$ 0.000011 (2σ, population)

APPENDIX B
LITHOLOGY



APPENDIX C
ADDITIONAL DATA TABLES

C.1 Western Quebecia

Published Data after Dickin et al. (2009)

Mauricie: T_{dm} ages 1350 - 1700 Ma

Sample	Northing	Easting	Nd ppm	Sm ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	εNd 1450	T_{dm} (Ma)
JO 2	5138900	599600	61.40	13.37	0.1316	0.512224	3.1	1520
JO 3	5145600	593300	50.00	9.60	0.1166	0.512017	1.7	1610
JO 4	5124700	611400	42.70	9.28	0.1313	0.512247	3.6	1470
JO 5	5145600	598300	43.00	9.12	0.1280	0.512301	5.3	1320
JO 6	5173000	580000	61.40	12.85	0.1266	0.512233	4.2	1410
JO 7	5182900	579100	31.80	6.11	0.1160	0.512084	3.1	1490
LT 8	5276400	670300	32.90	7.00	0.1289	0.512150	2.1	1600
LT 1*	5250700	667300	93.50	16.20	0.1046	0.512022	3.8	1430
LT 14	5320200	700300	42.80	9.34	0.1320	0.512173	2.1	1620
LT 15	5320200	700300	77.00	12.61	0.0990	0.511886	2.1	1530
LT 16	5295700	688400	81.40	17.03	0.1265	0.512223	4.0	1430
LT 17*	5283300	689000	19.20	4.34	0.1372	0.512208	1.8	1660
LT 18*	5251200	668800	62.10	10.72	0.1043	0.512059	4.6	1370
LT 19	5261200	672200	80.80	16.37	0.1224	0.512058	1.5	1640
LT 2	5298500	688800			0.0904	0.511918	4.3	1390
LT 20	5250000	667500	135.80	25.93	0.1154	0.512065	2.8	1510
LT 22	5224200	660700	13.60	2.33	0.1038	0.511977	3.1	1470
MK 1	5168600	653700	42.90	8.80	0.1239	0.512124	2.5	1560
MK 2	5127300	643500	42.30	8.95	0.1228	0.512096	1.3	1680
MK 3	5134900	651500	82.90	17.25	0.1258	0.512161	2.9	1530
MK 5	5160000	640100	72.10	13.12	0.1099	0.512101	4.5	1380
MK 6	5163700	636900	28.90	5.44	0.1136	0.512114	4.1	1410
MK 7	5166400	634000	18.50	3.36	0.1099	0.511982	2.1	1550
MK 8	5157700	640800	73.90	14.47	0.1184	0.512147	3.9	1430
MK 9	5157000	642800	9.20	1.60	0.1054	0.512094	5.1	1330
MK 10	5125200	627200	41.90	8.94	0.1292	0.512218	3.4	1480
MK 11	5123800	628100	8.40	1.68	0.1203	0.512164	3.9	1430
MK 12	5116300	630000	20.70	3.99	0.1166	0.512151	4.3	1400
SH 3	5177800	684900	31.10	5.89	0.1143	0.512000	1.7	1590
SH 6	5173500	673300			0.1146	0.512100	3.6	1450
SH 7	5159600	672300	26.60	5.170	0.1177	0.512130	3.7	1450
SH 9	5158700	670400	56.90	11.50	0.1222	0.512144	3.2	1490
SH 10	5163300	675500			0.1172	0.512174	4.6	1370
SH 11	5163300	659400	19.70	4.27	0.1309	0.512189	2.6	1570
SH 12	5158400	671400	25.80	4.77	0.1119	0.512080		1440
VO 343	5106400	535900			0.1338	0.512212	2.5	1580
VO 381	5093900	561200			0.1219	0.512182	4.0	1430

* - averaged from two duplicates

C.2 ABT and Ensialic Arc

Published Data after Martin and Dickin (2005)

Central Block: T_{dm} ages 1700 – 2300 Ma

Sample	Northing	Easting	Nd ppm	Sm ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	εNd 1450	T_{dm} (Ma)
DO 5	5408100	607300	52.32	8.70	0.1151	0.511914	-3.4	1950
DO 6	5399400	605400	32.34	5.30	0.1346	0.512094	-1.1	1790
DO 9	5397600	590000	48.50	9.05	0.1046	0.511569	-1.8	1890
GA 4	5515500	672300	31.17	4.98	0.1008	0.511661	-3.3	1920
GA 5	5521700	676400	44.65	7.75	0.1049	0.511605	-4	2020
GA 6	5525200	678200	34.52	5.95	0.1041	0.511591	-4.1	2020
GA 7	5530400	679200	46.61	8.08	0.1257	0.512030	-2.7	1920
GA 8	5541000	678800	39.65	6.77	0.1092	0.511620	-3.8	2000
GA 9	5560000	684000	34.56	6.02	0.1118	0.511586	-3.6	1990
GL 4	5473500	668200	54.54	11.97	0.1270	0.511967	0.7	1750
GL 7	5490800	659800	60.63	11.88	0.1276	0.512054	0.1	1770
GL 8	5493300	660300	42.48	8.09	0.1205	0.512027	0.3	1740
GL 12	5503900	668800	53.65	9.06	0.0992	0.511473	-2.4	1890
GL 16	5559600	687700	44.51	8.53	0.1283	0.511942	-4.1	2100
GV 04	5563700	607000	58.92	9.87	0.1021	0.511658	-3.5	1960
GV 05	5519000	659000	31.54	5.84	0.1148	0.511850	-5.5	2180
GV 06	5519000	657000	35.26	6.37	0.1158	0.511694	-4.4	2080
LS 32	5413800	656500	71.30	14.21	0.0990	0.511695	1.6	1660
LS 36	5413700	649800	29.74	7.84	0.1107	0.511668	1.4	1880
LSJ 6	5417400	647600	33.40	5.53	0.1005	0.511592	0.2	1700
LSJ 8	5418000	636700	71.82	13.43	0.1128	0.511788	1.8	1620
LSJ 9	5431100	622700	53.02	10.16	0.1034	0.511579	0.3	1750
LSJ 10	5432500	620200	58.34	10.58	0.1130	0.511973	0.5	1710
LSJ 13	5448200	597200	50.86	8.70	0.0965	0.511563	-4.2	2020
LSJ 26	5482600	652300	27.29	4.55	0.1048	0.511667	-2.1	1860
ND 8	5504700	628400	33.03	5.72	0.1032	0.511596	-4.6	2060
ND 9	5505600	628700	32.76	5.52	0.1053	0.511627	-4.8	2060
ND 10	5510400	632900	38.07	6.25	0.1187	0.511971	-5.5	2090
PB 2	5450500	619300	54.09	7.79	0.1001	0.511776	-0.6	1720
RT 1	5507500	696500	65.36	12.84	0.1595	0.512372	0.8	1720
RT 2	5510700	697800	13.16	2.79	0.1012	0.511595	-1.5	1960
RT 3	5520800	699400	44.06	8.37	0.0870	0.511614	-0.9	1840
TD 3	5431500	652400	25.82	5.43	0.1018	0.511535	-0.8	1890
TD 10	5465700	620800	46.61	8.08	0.1185	0.511933	-2.7	1930
TD 11	5488600	621200	40.61	7.45	0.1048	0.511670	-3.7	2040
TD 29	5427300	663100	37.66	8.18	0.1158	0.511920	0.9	1750
TD 31	5429500	656700	24.69	5.50	0.1313	0.512093	0.4	1830
TD 32	5431500	653500	63.34	13.37	0.1096	0.511876	0.8	1750

Published Data after Martin and Dickin (2005)

Western Block: T_{dm} ages 1700 – 2300 Ma

DO 11	575200	5391800	2.77	0.36	0.0785	0.510972	-11.7	2340
DO 12	568300	5400700	24.21	3.55	0.0887	0.510828	-16.3	2720
DO 13	567300	5403700	14.88	3.02	0.1226	0.511418	-10.7	2740
DO 14	566400	5405600	1.41	0.23	0.0984	0.511011	-14.4	2700
DO 16	550000	5417100	23.23	4.09	0.1065	0.511325	-9.7	2450

DO 17	549500	5417500	18.1	3.56	0.1189	0.511286	-12.7	2850
DO 18	543300	5426800	15.54	2.89	0.1124	0.511197	-13.3	2800
LSJ 15	594600	5454900	14.41	2.19	0.0920	0.511039	-12.8	2520
LSJ 16	594300	5456400	12.89	1.98	0.0929	0.510940	-14.8	2670
LSJ 17	591800	5458200	19.22	3.20	0.1006	0.511010	-14.8	2760
LSJ 19	584600	5460100	31.14	5.12	0.0993	0.511037	-14.1	2690
LSJ 24	570000	5473000	27.55	4.75	0.1043	0.511101	-13.7	2730
PB 7	590500	5475200	11.39	1.92	0.1016	0.511062	-14	2710
PB 3	611500	5472300	6.41	1.05	0.0989	0.511149	-11.8	2530
TD 21	611900	5477200	5.59	0.63	0.0676	0.510661	-15.8	2470
TD 19	611300	5484900	6.61	0.89	0.0803	0.510653	-18.2	2750
TD 15	610300	5488300	23.97	4.00	0.1009	0.510980	-15.5	2810
TD 16	608500	5491500	9.18	1.66	0.1095	0.511186	-13	2740
TD 18	610500	5501500	10.42	1.93	0.1122	0.511255	-12.1	2710
ND 6	621900	5510800	5.44	0.96	0.1098	0.511177	-13.2	2760
ND 4	624100	5510800	3.66	0.55	0.0908	0.510859	-16.1	2730

C.3 Cabonga Terrane

Published Data after Guo and Dickin (1996)

Pristine Archean: T_{dm} ages >2300 Ma

Sample	Northing	Easting	Nd ppm	Sm ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	T_{dm} (Ma)
RB 13	VH 263	267	13.18	2.14	0.0980	0.511021	2680
RB 15A	VH 330	490	14.28	2.24	0.0947	0.510852	2830
RB 16	VH 322	513	10.75	1.80	0.1011	0.511113	2630
RB 17	VH 318	519	16.72	3.01	0.1088	0.511198	2700
RB 18	VH 319	526	8.09	1.30	0.0973	0.511038	2640
RB 20	VH 263	258	75.74	13.13	0.1048	0.511377	2340
ZP 05	VH 465	330	34.29	4.23	0.0745	0.510589	2700

Ensialic Arc: T_{dm} ages 1700 – 2300 Ma

ZP 09	VH 154	733	34.53	6.11	0.1065	0.511740	1850
ZP 12	VH 116	814	30.40	5.21	0.1038	0.511674	1890
ZP 14	VH 519	430	61.74	9.67	0.0946	0.511715	1700

Juvenile Crust: T_{dm} ages <1700 Ma

RB 24	VH 431	180	38.34	0.59	0.1354	0.512203	1630
ZP 02	VH 522	252	29.53	8.34	0.1297	0.512145	1630