WHOLE-ROCK PB ISOTOPE DELINEATION OF ARCHEAN AND PALEOPROTEROZOIC CRUSTAL TERRANES IN THE GRENVILLE PROVINCE AND ADJACENT MAKKOVIK PROVINCE: EVIDENCE FOR JUVENILE CRUSTAL GROWTH DURING THE PALEOPROTEROZOIC

By

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Abstract

The Grenville Province and adjacent Makkovik Province represent two long-lived ancient orogenic belts that contain remnants of Paleoproterozoic crust accreted to the southeastern Laurentian margin during the Great Proterozoic Accretionary Orogen (GPAO). However, the addition of juvenile Paleoproterozoic crust to the Archean craton during this period was followed by a span of intermittent ensialic arc magmatism and high-grade metamorphism that overprinted much of the early- to mid- Proterozoic geologic history of the region. As a result, these ancient orogenic belts contain cryptic terrane boundaries that require extensive geochronologic mapping in order to reconstruct the accretionary and collisional growth of the southeastern Canadian Shield.

Accreted Proterozoic terranes in the Grenville and Makkovik Provinces have been previously mapped using Nd isotopes in order to determine their crustal formation ages and the boundaries between them. Since the U-Pb isotope system has completely different chemical behaviour to the Sm-Nd system, whole-rock Pb isotope analysis provides an independent method to test the results of Nd isotope analysis. Likewise, Pb isotope mapping acts as a useful tool for determining the exhumation of highly metamorphosed crust, as uranium is preferentially transported from lower crustal levels into the upper crust during regional metamorphism. Therefore, whole-rock Pb isotope analysis was performed on over 200 Archean and Proterozoic gneisses from the SW Grenville Province and Makkovik Province in order to 1) differentiate areas of accreted Paleoproterozoic crust from the reworked Archean margin, 2) test the location of the Archean-Proterozoic suture previously mapped in both regions by Nd model ages, and 3) investigate the variable degrees of crustal

burial-uplift within the Archean foreland of the SW Grenville Province that was exhumed during the Grenville orogeny.

In the Makkovik Province, whole-rock Pb isotope data from the Cape Harrison domain are comparable with published Pb data from the central Ketilidian mobile belt of southern Greenland. The similarity in Pb signatures between the two belts points to a crustal component in the Cape Harrison domain that was derived from a Proterozoic mantle-derived source with minimal input from older Archean crust. This is largely different from published Pb signatures for the Aillik domain in southeastern Labrador and border zone in southern Greenland that suggests a crustal component comprised of reworked Archean crust analogous to the pre-Makkovikian Laurentian foreland. Comparison of new and published Pb data from the Makkovik Province and southern Greenland in turn helps to constrain a revised single arc accretionary model for the Makkovik Province.

Previous Nd isotope mapping in the SW Grenville Province revels a break in model ages inferred by authors as a cryptic collisional suture between the reworked Archean foreland and an accreted Paleoproterozoic arc. However, some workers have suggested that this terrane actually consists of Archean crust that was magmatically reworked in the Mesoproterozoic. Whole-rock Pb isotope data presented in this study points to a crustal component south of the proposed suture in Ontario that was derived from a Paleoproterozoic mantle source and subsequently reworked by ensialic arc magmatism during the Mesoproterozoic. North of the suture, Pb data reveals an Archean crustal component analogous to reworked Superior basement that was exhumed from different crustal levels during the Grenville orogeny. Here, regions of anomalously radiogenic and unradiogenic Pb signatures differentiate the Archean-Proterozoic suture in Ontario from a tectonic duplex in western Quebec.

Acknowledgements

I would like to begin by thanking my supervisor Dr. Alan Dickin, as your guidance and support have made completing this thesis possible. I look back at the first time I had you as a professor for mineralogy and am truly grateful for all the opportunities you have provided me since then. Alan, I am very grateful for not only having you as my supervisor, but also a friend, and look forward to collaborating with you on many projects in the future!

Next, I would like to thank Dr. Robert McNutt and Dr. Maureen Padden for taking the time to review my thesis and sit on my defense committee. I would also like to acknowledge Dr. Charlie Gower for his comments on my research in the Makkovik Province, and Dr. Rebecca Moumblow for her advice, whether it was during my time as an undergraduate or graduate student.

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Finally, I would like to thank my family and friends for their support during my time at McMaster and for listening to me talk about the Grenville Province (even though you didn't understand or care in the slightest). I am grateful for the friendships I have made at McMaster, which in turn have made my time in Hamilton one I will always remember.

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Preface

This thesis contains three chapters (2, 3, and 4) that have been organized in publication format. The candidate carried out the research presented in this dissertation under the supervision of Dr. Alan P. Dickin in partial fulfillment of a M.Sc. degree. The following information identifies the co-authors involved in each chapter and their overall contribution.

Whole-rock Pb data presented in chapter 2 from the Makkovik Province was combined with Nd isotope data by Moumblow (2014) and submitted for publication:

Title: Nd and Pb Isotope Mapping of Crustal Domains within the Makkovik Province, Labrador

Authors: Moumblow, R.M., Arcuri, G.A., Dickin, A.P., and Gower, C.F.

Journal: Precambrian Research (submitted)

The candidate preformed all whole-rock Pb isotope analysis, while Dr. Rebecca M. Moumblow performed Nd isotope analysis. All authors suggested comments and revisions.

Whole-rock isotope analysis, data interpretation, and writing for chapters 3 and 4 were carried out by the candidate, which represent manuscripts for peer-reviewed publication. Dr. Alan P. Dickin was closely involved in the laboratory analysis, data interpretation, and revision of each chapter.

Chapter 1: Introduction

1.1. U-Pb Isotope System

1.1.1. Introduction

Of the four naturally occurring isotopes of lead, ^{206}Pb, ^{207}Pb and ^{208}Pb are the final decay products generated from the three complex decay chains of ^{238}U, ^{235}U and ^{232}Th respectively. All intermediate members of each series are minor when considering time scales of a million years or greater as they are relatively short lived and can generally be ignored. However, the half-lives of the ^{238}U and ^{232}Th parents are relatively long, comparable to the age of the Earth and age of the universe respectively. The half-life of ^{235}U is relatively short in comparison to that of ^{238}U and ^{232}Th with nearly all of the Earth's primordial ^{235}U having decayed to ^{207}Pb.

The U-Pb system has served as a unique method for modeling the evolution of the Earth's mantle and terrestrial reservoirs, in that the generation of ^{206}Pb and ^{207}Pb are from isotopes of the same parent element but with varying half-lives. Since the half-life of ^{235}U is much shorter than ^{238}U, the decay of ^{235}U will occur more rapidly and generate a Pb isotopic evolution curve over time. The trajectory of this curve is determined by the U/Pb ratio or 'μ' value of the system of interest, and Pb isotope analysis can therefore be used to determine the crystallization age of a sample and the timing of subsequent open-system behavior (Wetherill, 1956).

1.1.2. U-Pb Age Calculation

When considering a geologic event of age *t*, each parent-daughter pair can be written following the law of radioactive decay to obtain the following equations

$$^{206}Pb_P = {}^{206}Pb_I + {}^{238}U(e^{\lambda 238t} - 1) \qquad [1.1]$$

$$^{207}Pb_P = {}^{207}Pb_I + {}^{235}U(e^{\lambda 235t} - 1) \qquad [1.2]$$

$$^{208}Pb_P = {}^{208}Pb_I + {}^{232}Th(e^{\lambda 232t} - 1) \qquad [1.3]$$

where P and I represent the present and initial abundances respectively. For the U-Pb method, each of the uranium decay schemes above is divided by ^{204}Pb in order to convert each absolute abundance into an isotopic ratio, giving the equations

$$\left(\frac{^{206}Pb}{^{204}Pb}\right)_P = \left(\frac{^{206}Pb}{^{204}Pb}\right)_I + \frac{^{238}U}{^{204}Pb}(e^{\lambda 238t} - 1) \qquad [1.4]$$

$$\left(\frac{^{207}Pb}{^{204}Pb}\right)_P = \left(\frac{^{207}Pb}{^{204}Pb}\right)_I + \frac{^{235}U}{^{204}Pb}(e^{\lambda 235t} - 1) \qquad [1.5]$$

The abundances above are normalized by ^{204}Pb, as it is the only non-radiogenic isotope of lead and therefore has remained constant since the formation of the Earth. Theoretically, the decay equations [1.4] and [1.5] can be used to construct U-Pb isochron diagrams, and thus date the age of crystallization of a closed-system. However, the mobility of U and Pb in silicate rocks during conditions of low-grade metamorphism and weathering disrupts this closed-system by allowing various amounts of uranium and lead to be lost.

This greatly limits the application of U-Pb isochron dating to whole-rock systems but it can still be applied to some minerals such as zircon that are resistant to uranium mobility.

1.1.3. U-Pb 'Zircon' Dating

By removing the initial ^{206}Pb and ^{207}Pb terms from the U-Pb age calculation, equation [1.1] and [1.2] can be simplified to yield

$$^{206}Pb^* = {}^{238}U(e^{\lambda 238t} - 1) \qquad [1.6]$$

$$^{207}Pb^* = {}^{235}U(e^{\lambda 235t} - 1) \qquad [1.7]$$

where Pb* represents radiogenic lead only. Rearranging equations [1.6] and [1.7] by bringing the ^{238}U term to the left hand side produces

$$\frac{^{206}Pb^*}{^{238}U} = (e^{\lambda 238t} - 1) \qquad [1.8]$$

$$\frac{^{207}Pb^*}{^{235}U} = (e^{\lambda 235t} - 1) \qquad [1.9]$$

which can be used to solve for *t* when dating U-rich minerals, such as zircon.

Zircon is a widely distributed mineral found in most felsic rocks that strongly incorporates uranium into its crystal structure while rejecting initial lead. When these minerals have remained in a closed-system for U and Pb, their isotopic compositions can be plugged into the left hand side of equations [1.8] and [1.9] to produce a series of concordant values for *t*. When plotted on a U-Pb isochron diagram, the concordant ages will define a curved line referred to as the concordia (Wetherill, 1956; Fig. 1.1). However, most samples do not remain closed to U and Pb and therefore experience Pb loss or U gain. The zircon displaced from the concordia curve lie along a discordia line, where the upper and lower intercept with the concordia represents the crystallization age and timing of open system behavior respectively (Wetherill, 1956; Fig. 1.1).

1.1.4. Whole-Rock Pb-Pb Dating

An alternate approach to U-Pb dating that is commonly used for the dating of meteorites and the age of the earth in which no zircons (high U-Pb phases) are available is the whole-rock Pb-Pb dating technique. This method is based on the rearrangement of the U-Pb decay equations [1.4] and [1.5] to bring the lead ratios to the left hand side. By dividing equation [1.5] by equation [1.4]

$$\frac{\left(\frac{^{207}Pb}{^{204}Pb}\right)_P - \left(\frac{^{207}Pb}{^{204}Pb}\right)_I}{\left(\frac{^{206}Pb}{^{204}Pb}\right)_P - \left(\frac{^{206}Pb}{^{204}Pb}\right)_I} = \frac{^{235}U\,(e^{\lambda 235t} - 1)}{^{238}U\,(e^{\lambda 238t} - 1)} = \frac{1}{137.88}\,\frac{(e^{\lambda 235t} - 1)}{(e^{\lambda 238t} - 1)} \quad [1.10]$$

the ^{204}Pb terms on the right hand side of the equation cancel out, giving the term $^{235}U/^{238}U$, which has a constant value throughout the solar system of 1/137.8 (Brennecka et al., 2010). By combining these equations the isotopic ratios of $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ can be expressed for a suit of whole-rocks that contain a similar age and initial isotopic composition. Based on the U/Pb ratios of the system (e.g., $^{238}U/^{204}Pb$ for equation [1.4] and $^{235}U/^{204}Pb$ for equation [1.5]), each suite will develop a different radiogenic Pb composition at the present day. If the system has remained closed over time, the present day composition of radiogenic Pb should generate a linear array when plotted. The slope of the array, referred to as an isochron, is dependent on time '*t*' and therefore provides an igneous crystallization age for the system (e.g., Stacy and Kramers, 1975; Fig. 1.2). As a result, Pb-Pb isochron ages are reliable for determining the timing of Pb loss (or U gain) for an isotopically homogeneous crustal reservoir during periods of extensive igneous activity and high-grade metamorphism.

1.1.5. Terrestrial Pb Evolution

Independent studies by Holmes (1946) and Houtermans (1946) were the first to conceive a single-stage Pb evolution of the earth using a series of analyzed galena ores. The Holmes-Houtermans model follows the assumption that there is no U decay in a galena ore after it is separated from its source rock, as galena is a common Pb mineral that contains no U at the time of crystallization. In this case, it can be assumed that the source rock from which the galena was isolated represents a closed-system with a single-stage Pb isotope history. Therefore, the Holmes-Houtermans model was believed to measure the age of the source rock from the formation of the earth (primordial Pb) up until the isolation of the galena (Fig. 1.3). However, an increase in the number of galena ores analyzed resulted in a greater degree of scatter on the Pb-Pb isochrons, thus indicating that some galena sources were unlikely to be a closed-system since the formation of the Earth.

Subsequent work by Stanton and Russell (1959) examined nine galena deposits of various ages that were associated with sediments and volcanics from greenstone belts and island arcs. The source rock for these galena ores were believed to have been isolated directly from the upper mantle. Since all samples accurately fell on an upper mantle growth curve (Fig. 1.4), Stanton and Russell (1959) concluded that the galena originated from a homogenous mantle reservoir with a specific μ value ($^{238}U/^{204}Pb$). These ores were referred to as 'conformable leads'.

Re-examination of the conformable lead model in the 1970's using new measurements for the uranium decay constants showed that the closed-system model for Pb evolution in the mantle no longer fit (Oversby, 1974; Cummings and Richards, 1975). However, attempts to adjust the model tended to under-estimate the age of the Earth in comparison to the Pb-Pb meteorite isochron determined by Patterson (1956). Therefore, Stacy and Kramers (1975) proposed a two-stage (open-system) model with terrestrial Pb evolving in two stages containing different μ values (μ_1 and μ_2). Stacy and Kramers (1975) attributed the change in the μ value to be the result of a hypothetical worldwide differentiation event with the galena source rock evolving along a higher μ growth curve for the last 3.8 Byr (Fig. 1.5).

Doe and Zartman (1979) developed a much more generalized open-system Pb evolution model, arguing that the change in the mantle μ value could be accounted for by recycling of Pb between the upper crust, lower crust and mantle. This model was termed 'plumbotectonics' and was based on the idea that frequent orogenies (at 400 Myr intervals) mixed mantle and crustal sources yielding differentiated crustal blocks (Fig. 1.6). U, Th and Pb are extracted from the upper crust, lower crust and mantle during each orogeny, mixed and re-distributed back into their respected reservoirs. This would generate an upper mantle μ value similar to that of the total crust, as well as increase the μ value in the mantle over time as more radiogenic crust is recycled back into the mantle source.

The Pb isotope systematics discussed above show how a two-stage Pb isotope evolution model for the Earth is more plausible than a single-stage model, as the latter was shown to be an oversimplification. However, Pb-Pb isotope studies of early-Archean crustal evolution have shown the effectiveness of using a single-stage Pb evolution model as a 'yardstick' for resolving Archean rocks from latter metamorphic disturbances (e.g., Moorbath and Taylor, 1989). Therefore, it is reasonable to apply a single-stage Pb isotope evolution model to Archean and Paleoproterozoic crustal reservoirs exhibiting complex mixing relations in order delineate Pb signatures on a Pb-Pb isochron diagram. In this case, Pb model ages can be paired with an independent isotope proxy, such as Nd model ages, in order to yield important age information and estimate the timing of magma extraction from the mantle.

1.2. Study Area and Research Objectives

The Great Proterozoic Accretionary Orogen (GPAO) represents a long-lived period of crustal growth that began during the amalgamation of supercontinent Nuna (ca. 2.0-1.9 Ga), and endured for at least 900 Myr until the formation of supercontinent

Rodinia at 1.2-1.0 Ga (Condie, 2013). The Grenville Province defines a long-lived ancient orogenic belt along the southeastern Laurentian margin that comprises a mosaic of Paleoproterozoic to Mesoproterozoic aged crust amalgamated to the Archean craton during the GPAO (e.g., Dickin, 2000; Fig. 1.7). Likewise, the Makkovik Province is situated adjacent to the Grenville Province and defines a segment of Paleoproterozoic crustal growth and subsequent ensialic arc magmatism that developed along the southeastern Laurentian margin during the 1.9-1.7 Ga Makkovikian orogeny (e.g., Ketchum et al., 2002; Fig. 1.7). However, in both geologic provinces, the crustal boundary between the Archean margin and accreted Paleoproterozoic crust is cryptic due to subsequent ensialic arc magmatism that overprinted the earlier collisional zone. During the assembly of Rodinia, the terminal Grenville orogeny halted subduction along this active continental margin causing considerable crustal stacking in the Grenville Province. This again overprinted many pre-Grenvillian crustal boundaries. Therefore, the focus of this study is to constrain the Paleoproterozoic history of the southeastern Laurentian margin in the SW Grenville Province and adjacent Makkovik Province (Fig. 1.7). The research objectives of this thesis are subdivided into three main chapters.

Chapter 2: Pb isotope mapping of crustal domains in the Makkovik Province

1) Constrain the boundary between the Archean craton and accreted juvenile Makkovikian crust
2) Compare the timing of Paleoproterozoic crustal growth in the Makkovik Province with the adjacent Ketilidian mobile belt of southern Greenland.

3) Enhance our understanding of the tectonic evolution of the Makkovikian-Ketilidian orogeny during the GPAO.

Chapter 3: Paleoproterozoic evolution of the SW Grenville Province: evidence from whole-rock Pb isotope analysis

1) Differentiate areas of accreted Paleoproterozoic crust from the reworked Archean craton to the northwest.
2) Test the location of the Archean-Proterozoic suture previously mapped by Nd model ages
3) Compare the timing of Paleoproterozoic crustal growth with the adjacent Makkovikian-Ketilidian orogeny, thus enhancing our understanding of the tectonic evolution of the SW Grenville Province during the GPAO.

Chapter 4: Assessing the crustal burial and exhumation of the Archean parautochthon in the SW Grenville Province using whole-rock Pb isotope analysis

1) Investigate the burial-uplift history of the Archean foreland
2) Determine the origin of the Archean-Proterozoic boundary in Ontario and western Quebec
3) Enhance our understanding of the crustal structure of the SW Grenville Province following the transport of the Mesoproterozoic crust over the Archean margin during the Grenville orogeny.

A brief conclusion in Chapter 5 will integrate the results from each study. The whole-rock Pb data will be used to construct a crustal cross-section based on the inferred terrane boundaries in each region. This will assist in understanding the crustal structure of the southeastern Canadian Shield in the Grenville Province and adjacent Makkovik Province.

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1.4. Figures

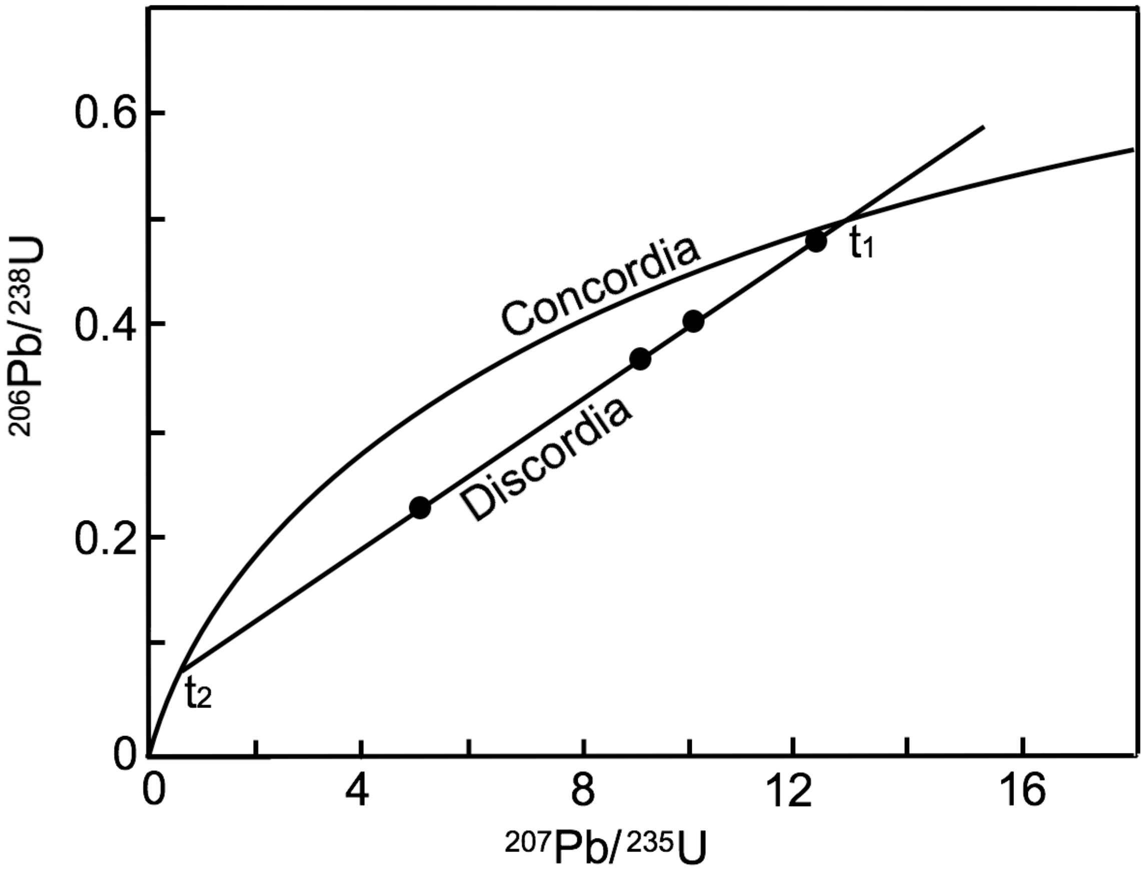

Fig. 1.1. U-Pb concordia diagram showing discordant points relative to the concordia line: t_1 = age of crystallization; t_2 = age of open system behavior. After Wetherill (1956). Modified from Dickin (2005).

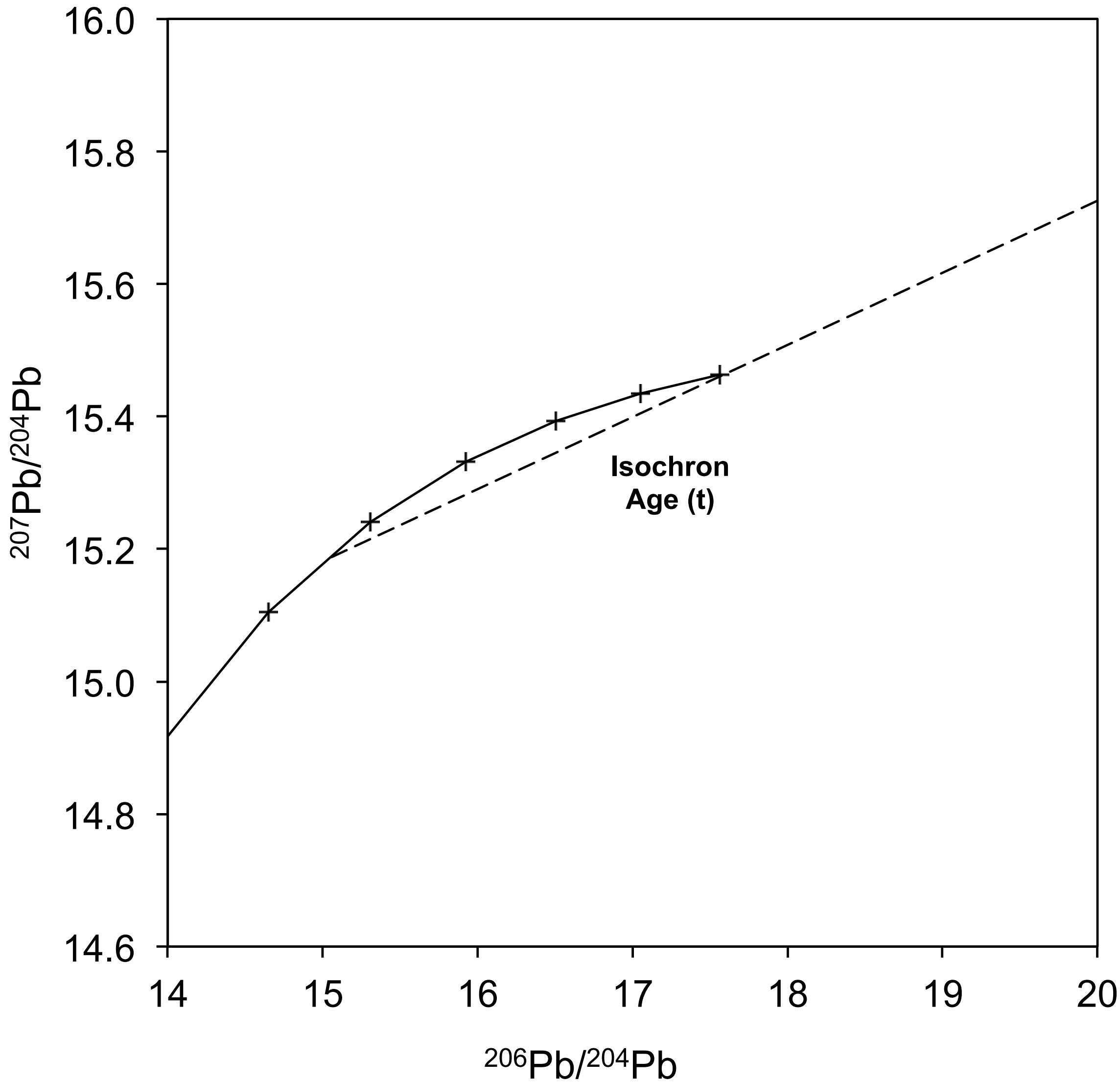

Fig. 1.2. The slope of a Pb-Pb isochron representing the $^{207}Pb/^{206}Pb$ isochron age 't' of a system (growth curve = 400 Myr intervals).

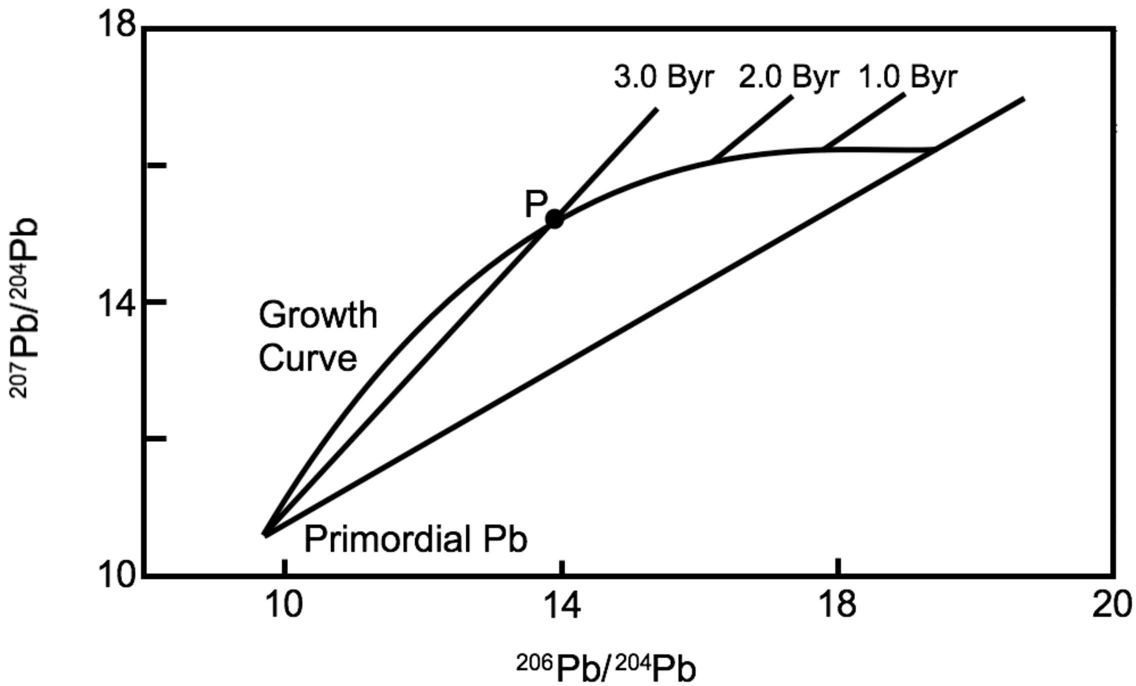

Fig. 1.3. Pb-Pb isochron diagram showing the present day Pb composition of galena (P) extracted from a primordial reservoir 3 Byr ago. After Russell and Farquhar (1960). Modified from Dickin (2005).

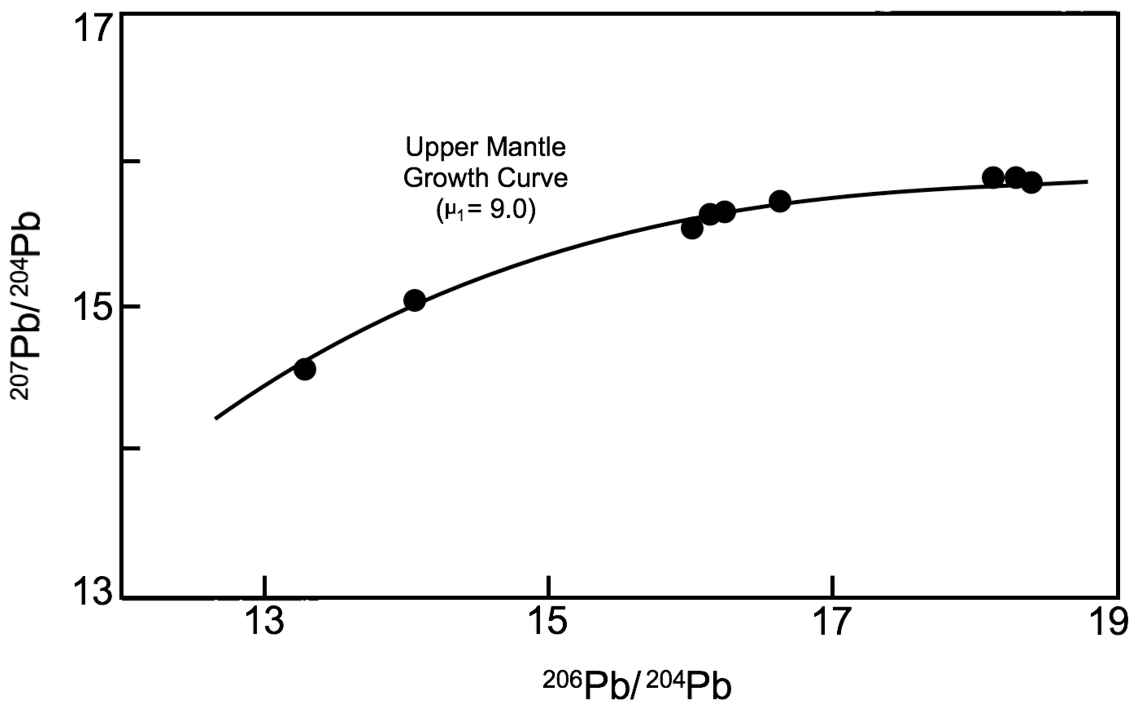

Fig. 1.4. Pb-Pb isochron of galena ores (black circles) that represent samples of 'conformable Pb'. After Stanton and Russell (1959). Modified from Dickin (2005).

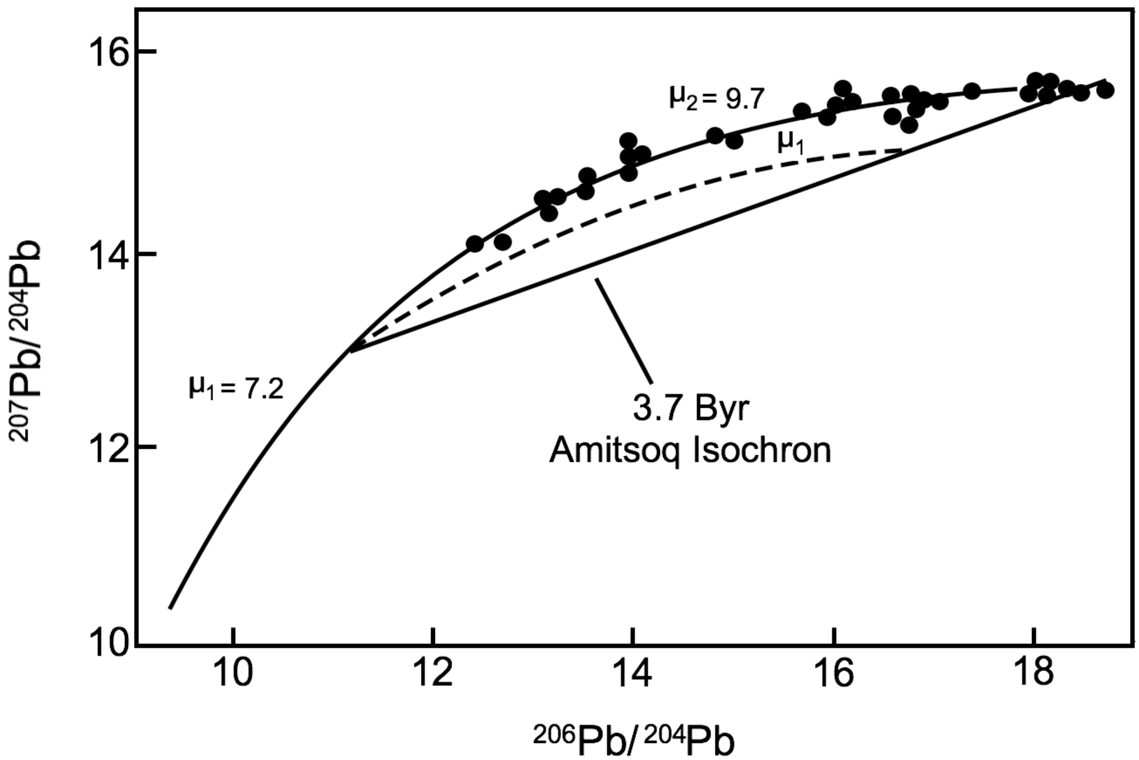

Fig. 1.5. Pb-Pb isochron diagram showing a two-stage Pb evolution model for a series of galena ore. After Stacey and Kramers (1975). Modified from Dickin (2005).

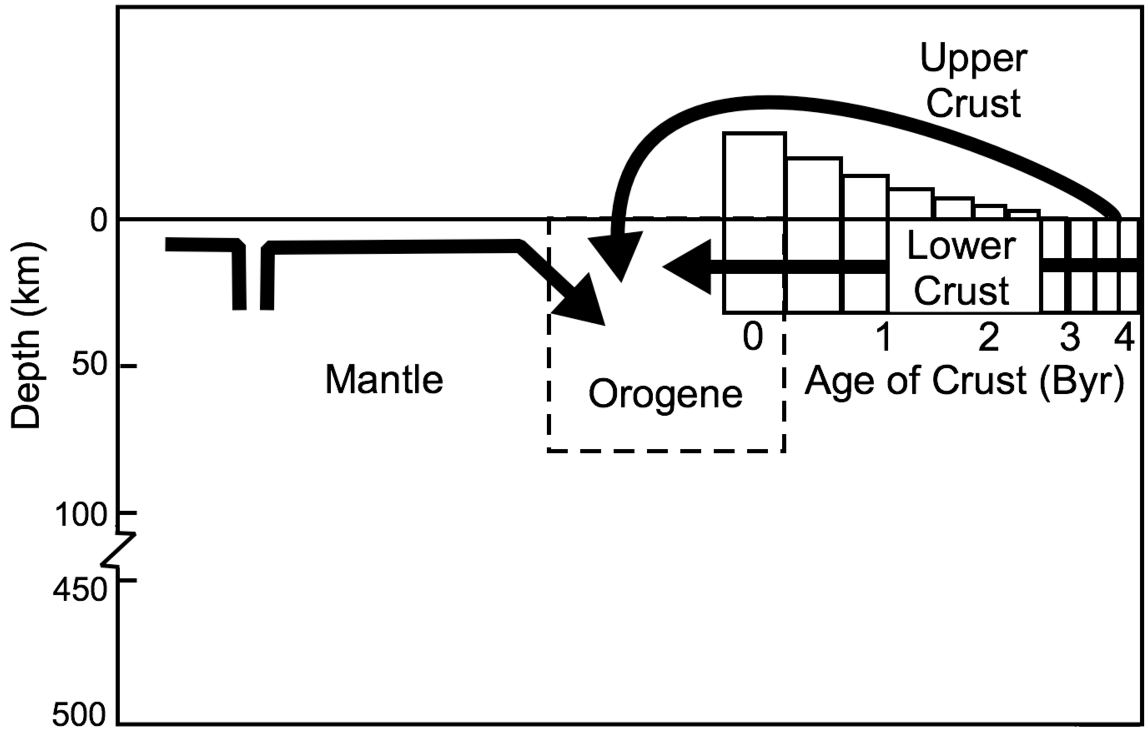

Fig. 1.6. Illustration of the plumbotectonics model demonstrating mixing of crustal and mantle reservoirs. After Doe and Zartman (1979). Modified from Dickin (2005).

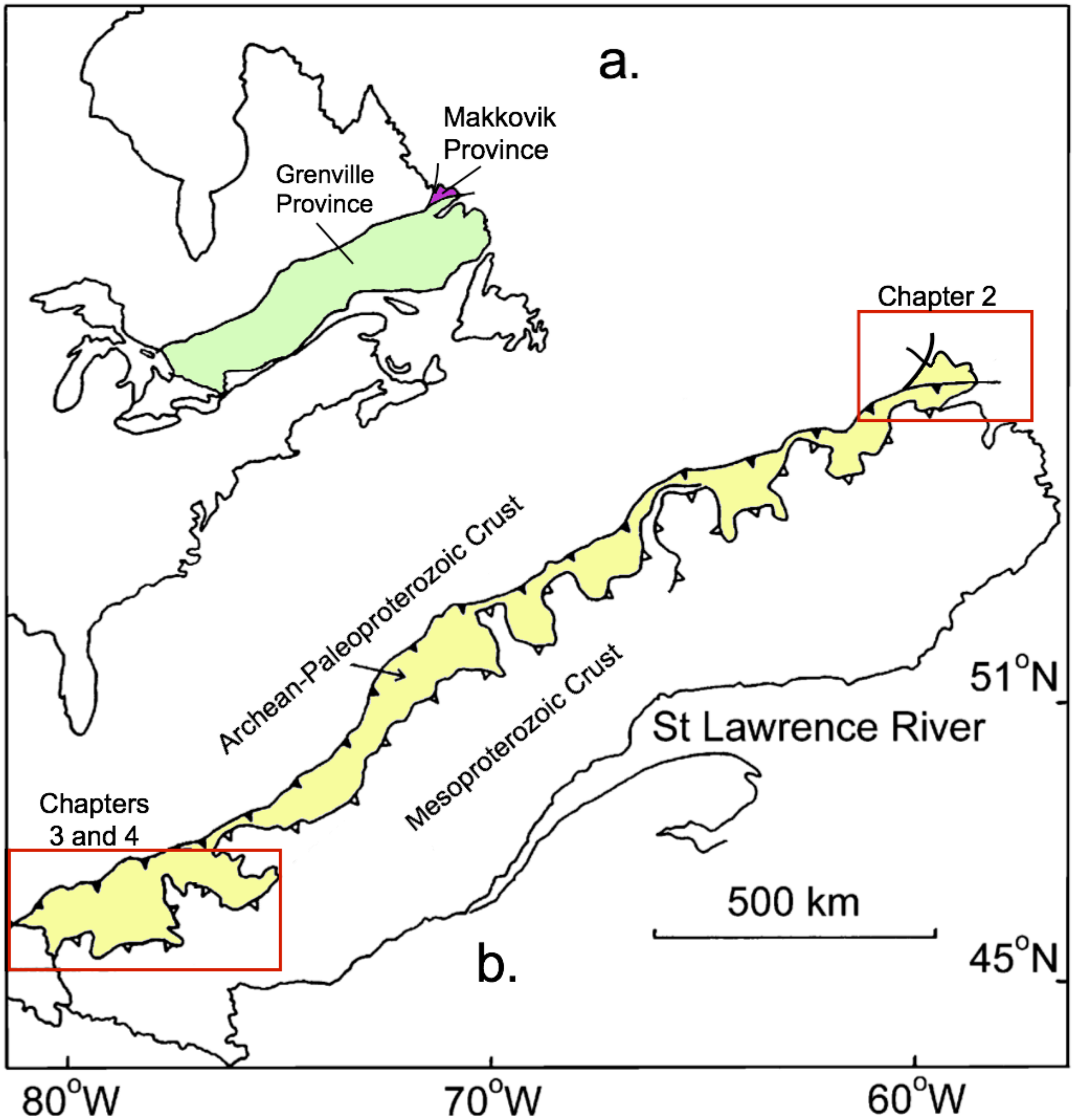

Fig. 1.7. View of the southeast Canadian Shield showing (a) the location of the Grenville Province (green shading) and adjacent Makkovik Province (purple shading); and (b) the location of each study area in Chapters 2, 3 and 4 indicated by red boxes. After Dickin et al. (2008).

Chapter 2:
Pb Isotope Mapping of Crustal Domains within the Makkovik Province, Labrador

2.1. Introduction

The Makkovik Province of eastern Labrador is a structural province of the Canadian Shield that contains remnants of Paleoproterozoic crust accreted to the southeastern margin of the Laurentian craton during the 1.9 to 1.7 Ga Makkovikian orogeny (e.g., Ketchum et al., 2002). The Makkovik Province is situated between the Archean Nain Province to the northwest and the Mesoproterozoic Grenville Province to the southeast (Fig. 2.1). On a broader scale, the Makkovik Province is believed to correlate with the Ketilidian mobile belt of south Greenland, with the Makkovikian and Ketilidian Orogens representing adjacent parts of a single orogenic belt (e.g., Gower and Ryan, 1986; Kerr et al., 1997; Ketchum et al., 2002).

The Makkovik Province is subdivided based on its lithology and tectonic history into the Kaipokok domain, Aillik domain and Cape Harrison domain (e.g., Gower and Ryan, 1986; Ketchum et al., 2002; Fig. 2.1). In Greenland, the Ketilidian mobile belt is subdivided into the border zone, the Julianehåb Batholith, the psammite zone and the pelite zone (Chadwick and Garde, 1996; Fig. 2.1). While there are significant geologic differences between the Makkovik Province and Ketilidian mobile belt, several major similarities in lithology can be correlated across the orogen (e.g., Ketchum et al, 2002). The Kaipokok domain and border zone both comprise a reworked margin of the Archean foreland, overlain by Paleoproterozoic metavolcanic and metasedimentary units. In contrast, the Cape Harrison domain and Julianehåb Batholith are comprised almost solely of Paleoproterozoic plutonic and supracrustal rocks.

Similar to the Cape Harrison domain, the Aillik domain contains plutonic and supracrustal rocks of Paleoproterozoic origin. However, it also contains remnants of Archean basement preserved at the surface in a fault-bounded block (Culshaw et al., 2000). The psammite zone and the pelite zone in Greenland are comprised of Paleoproterozoic metasediments; however, no onshore equivalents in the Makkovik Province have been identified (Kerr et al., 1997). Extensive psammitic and pelitic gneisses are present in the Grenville Province, with deposition ages (ca. 1805-1770 Ma) that are similar to the time of supracrustal deposition in the Ketilidian Orogen (e.g, Gower and Krogh, 2003; Gower et al., 2008), likely representing the along-strike continuation of the psammite and pelite zones (Ketchum et al., 2002).

Overall, the tectonic setting of the Makkovikian-Ketilidian Orogen has been interpreted as an active continental margin that underwent juvenile arc accretion and extensive post-accretionary reworking (e.g., Kerr et al., 1997; Culshaw et al., 2000; Ketchum et al., 2002). However, younger reworking of the continental margin has resulted in some ambiguity regarding the origin and location of several tectonic boundaries in the Makkovik Province, such as the southern and eastern extent of the Archean foreland. Hence, different tectonic evolutionary models have been suggested, involving a double arc accretionary event (e.g., Culshaw et al., 2000; Ketchum et al., 2002) versus a single arc accretionary event (Moumblow, 2014).

In Greenland, whole rock Pb-Pb data were determined for granites from the Ketilidian mobile belt by Kalsbeek and Taylor (1985) in order to distinguish Proterozoic mantle-derived crust in relation to Proterozoic reworking of Archean crust. Granites from the central Ketilidian mobile belt (blue diamonds, Fig. 2.1) show Pb signatures derived from a more radiogenic source characteristic of Proterozoic crust ($^{238}U/^{204}Pb$ or 'μ' value of 7.9-8). Only in the border zone (blue crosses, Fig. 2.1) were Kalsbeek and Taylor (1985) able to detect the involvement of Archean crust in the petrogenesis of the Paleoproterozoic granites. Since Pb isotope signatures can provide information regarding the initial source reservoir of the crust, the whole-rock Pb-Pb method can be used to differentiate areas of reworked Archean crust from younger Proterozoic crust formed from a juvenile mantle-derived source. Hence, the aim of this study is to contribute whole-rock Pb isotope data for Paleoproterozoic crust from across the Makkovik Province and use it to better define the Proterozoic history of the region.

2.2. Geologic Context

The northern limit of Makkovikian orogenesis in eastern Labrador is marked by the Kanairiktok Bay Shear Zone (KNSZ, Fig. 2.2), identified as a deformational front that separates the Nain Province to the north from the Kaipokok domain of the Makkovik Province to the south. The Kaipokok domain represents a southern continuation of the Archean basement that was reworked during the Makkovikian orogeny up to amphibolite facies (Culshaw et al., 2000). Paleoproterozoic metavolcanic and metasedimentary units of the Post Hill Group (Fig. 2.2) overlie the Archean basement in the Kaipokok domain and are interpreted as part of a Paleoproterozoic passive margin that developed on the Archean craton prior to the Makkovikian orogeny (e.g., Culshaw et al, 2000; Ketchum et al., 2002). The Island Harbour Bay plutonic suite (IHBPS) invaded large areas of the northwest Kaipokok domain and is believed to represent part of a calc-alkaline magmatic arc that formed on the continental margin ca. 1.89 - 1.87 Ga (Barr et al, 2001; Fig. 2.2).

The Kaipokok Bay Shear Zone (KBSZ, Fig. 2.2) separates the Kaipokok domain to the northwest from the Aillik domain to the southeast. It was suggested by Kerr et al. (1997) that the KBSZ represents the southeast limit of reworked Archean crust at the surface, terminating as an east-thinning wedge below the Aillik domain. However, it was later established that the Aillik domain contains a large block of Archean basement (e.g., Culshaw et al., 2000; Ketchum et al., 2002), suggesting that the KBSZ does not represent a fundamental suture between Archean foreland and accreted Paleoproterozoic crust.

Nd isotope data from the Aillik domain (Kerr and Fryer, 1994) display several Nd T_{DM} model ages (> 2.5 Ga) that fall within the same range as the Kaipokok domain (Fig. 2.2). Since the Kaipokok domain is known to represent a reworked equivalent of the Archean craton (e.g., Ketchum, 2002), similar T_{DM} ages found in the Aillik domain suggest that the basement is dominantly Archean in age. This implies that the KBSZ likely represents a surface expression of a major structure separating the relatively intact Archean crust of the Kaipokok domain from the largely reworked Archean crust in the Aillik domain.

The Aillik domain contains Paleoproterozoic metavolcanic and metasedimentary rocks that lie in thrust contact with the underlying basement. These rocks are referred to as the Aillik Group (Fig. 2.2), and are exposed in two major locations; the Makkovik zone situated along the coast, and the Michelin zone further inland (Wilton and Wardle, 1987). The lithology and geochemical properties of the Aillik group suggest deposition in a shallow marine environment within a back arc or rifted arc setting (e.g., Sinclair et al., 2002). This is in contrast to portions of the Aillik Group located within the Cape Harrison domain that exhibit chemical signatures more characteristics of a volcanic arc setting (Sinclair et al., 1999; Ketchum et al., 2002).

Crustal formation Hf–isotope T_{DM} model ages for magmatic zircons from felsic volcanic rocks in the Aillik Group (LaFlamme et al., 2013; Fig. 2.2) indicate that a substantial component of the crust's parent magma contained melt derived from an older crustal component (ca. 2.2-2.9 Ga). LaFlamme et al. (2013) suggested that subduction-related magmatism in the Aillik Group (ca. 1.89-1.85 Ga) involved a significant amount of crustal reworking rather than a period of juvenile crustal growth.

Similarly, whole-rock Pb-Pb data for galena separates collected from galena-bearing veins in the Makkovik zone and Michelin zone of the Aillik Group (Wilton, 1991; Fig. 2.2) demonstrate Pb signatures that are characteristic of older Archean crust. These signatures extend to the SE edge of the Aillik domain and show that the metavolcanic and metasedimentary units in the Aillik Group received Pb that was remobilized from an Archean source. This would require a significant amount of Archean basement present in the subsurface, emphasizing that the Archean foreland extends eastward of the KBSZ.

The Cape Harrison domain lies to the southeast of the Aillik domain and is comprised dominantly of Paleoproterozoic plutonic and supracrustal rocks. The plutonic suites were emplaced during late Makkovikian-Labradorian magmatism, dated at ca. 1.8 Ga, 1.72 Ga and 1.65 Ga (e.g., Gower and Ryan, 1986; Kerr and Fryer, 1994). Unlike in the Aillik domain, the Cape Harrison domain contains no recognized blocks of Archean basement, but instead, possible remnants of a Paleoproterozoic arc basement referred to as the Cape Harrison Metamorphic Suite (CHMS; Kerr and Fryer, 1994). The oldest identified rocks of the CHMS have an average ca. 2.05 Ga Nd T_{DM} model age (Kerr and Fryer, 1994).

When compared with the published Pb-Pb data from the Aillik domain (Wilton, 1991; Fig. 2.2) and Ketilidian mobile belt (Kalsbeek and Taylor, 1985; Fig. 2.1), the new whole-rock Pb-Pb data in this study for the Cape Harrison domain can assist in better understanding the tectonic evolution of the Makkovik Province. If the Cape Harrison domain represents a single outboard arc that formed just prior to the Makkovikian orogeny, then the Pb signatures should reflect derivation from a solely Proterozoic mantle source.

2.3. Sample Selection

Whole-rock Pb isotope analysis were determined for thirty-eight granitoid samples from the Cape Harrison domain and are displayed in Table 2.1. The Geologic Survey of Newfoundland and Labrador provided all igneous whole-rock powders (collected by C. F. Gower) with sample localities indicated in Fig. 2.2. Samples are subdivided into the groups Cape Harrison north (solid red circles) and Cape Harrison south (solid grey circles) based on their geographic location within the Makkovik Province and Grenville Province respectively. The Nd T_{DM} model ages for samples within the two Cape Harrison suites lie between ca. 1.85 Ga to 2.14 Ga (Moumblow, 2014). This implies that a majority of the crust in the Cape Harrison domain formed just prior to the Makkovikian orogeny. Samples with slightly older T_{DM} ages (ca. > 2.15) were also included in this study, however, are plotted in Fig. 2.2 as the groups north old (open red circles) and south old (open grey circles) based on their location in the Makkovik and Grenville Provinces respectively (Fig. 2.2).

The Grenville Front marks the boundary between the Makkovik and Grenville Provinces and represents the northward extent of Grenville metamorphism. This boundary also coincides with the Trans-Labrador Batholith (Kerr and Krogh, 1990), which marks the northern border of the Labradorian Orogen. Thus, samples from the Cape Harrison south suite were not only affected by late Makkovik magmatism but also Grenvillian and Labradorian orogenesis. The separation of the Cape Harrison domain into north and south suites provides a way to test the effects of younger Labradorian and Grenville metamorphism on the Pb signatures developed during the Makkovikian orogeny.

2.4. Analytical Techniques

All Pb isotope analysis followed the previous procedures of Dickin (1998b). After dissolution in HF, HNO_3 and HCl, Pb extraction followed standard techniques, using Savillex 'bomb' dissolution and anion exchange in HBr. Samples were loaded with silica gel and phosphoric acid onto single Re filaments and analyzed on a VG 354 mass spectrometer at McMaster University. Average within-run precision on samples was .02%(1σ) with the reproducibility of $^{207}Pb/^{204}Pb$ estimated at 0.1% (2σ). All data were fractionation corrected (average 0.12% per amu) based on frequent analysis of NBS 981.

2.5. Pb-Pb Isochron

2.5.1. Cape Harrison Domain

Whole-rock Pb isotope data from the Cape Harrison domain were plotted on a Pb-Pb isochron diagram (Fig. 2.3), following the same symbology established in Fig. 2.2 (red circles - Cape Harrison north; grey circles – Cape Harrison south; open red circles – north old; open grey circles – south old). Published Pb isotope data from Loewy et al. (2003) for samples of Labradorian age (ca. 1.71-1.62 Ga) and Pinwarian (ca. 1.52-1.46 Ga) were plotted alongside samples from the Cape Harrison domain (blue and yellow triangles respectively, Fig. 2.3). A single-stage Pb mantle growth curve was fitt to the data following an average Proterozoic mantle μ value of 8.0. The regression line for the Labradorian array projected back to the growth curve yields a Pb model age of ca. 1.8 Ga. This is in agreement with U/Pb ages dated at ca. 1.8-1.77 Ga for reworked pre-Labradorian crust (Gower et al., 2008).

When compared to the Labradorian and Pinwarian data, most samples from the Cape Harrison north and south suites have much more radiogenic Pb isotope signatures. However, the regression lines project back to the growth curve with reasonable Pb model ages (ca. 1.8-2.1 Ga) that are characteristic of Proterozoic mantle-derived rocks. The slope ages of the Cape Harrison north and south arrays assuming a closed system Pb isotope evolution are ca. 1.83 Ga and 1.71 Ga respectively. The lower age for samples within the Grenville Province is likely attributed to younger reworking during Labradorian orogenesis, which would have caused the single stage model to yield a slightly younger slope age relative to the Cape Harrison north samples. The 1.83 Ga age for the Cape Harrison north array is consistent with the age of late Makkovikian plutonism. Most samples would not remain closed to U and Pb during Makkovikian metamorphism and therefore would experience enrichment in U (or loss in Pb). This probably explains the radiogenic Pb signatures in the Cape Harrison domain.

The Makkovik Pb data are compared in Fig. 2.4 with published whole-rock Pb data from the central Ketilidian mobile belt of southern Greenland (blue diamonds, Kalsbeek and Taylor, 1985). The similarity between the Pb arrays provides evidence for the juvenile character of the Cape Harrison suites, since the central Ketilidian mobile belt is interpreted as juvenile Paleoproterozoic crust (e.g., Kalsbeek and Taylor, 1985; Garde et al., 2002). This is in agreement with the average ε_{Nd} (T) at 1.85 Ga of ca. +3 for the Cape Harrison domain, which is characteristic of a depleted Proterozoic mantle (Moumblow, 2014). The Nd isotope data, together with Pb signatures, shows that granites in the Cape Harrison domain were derived from a juvenile Proterozoic mantle source with minimal input from older Archean basement.

Granites from the central Ketilidian mobile belt have μ values (7.9 - 8.0) that are characteristic of Proterozoic mantle derived magmas (Kalsbeek and Taylor, 1985). This is supported by Sr isotope data from van Breemen et al. (1974) that shows low initial $^{87}Sr/^{86}Sr$ ratios (0.7022-0.7032) for the same Ketilidian granites. Nd isotope data from Patchett and Bridgwater (1984) show that metatholeiites from the central Ketilidian mobile belt formed from a depleted mantle source with ε_{Nd} (T) at 1.8 Ga of +4. The evidence from the Pb, Sr and Nd systems suggest that a majority of the crust in the central Ketilidian mobile belt was derived from juvenile Proterozoic mantle sources. The similar isotopic composition for granites from the Cape Harrison domain can be linked to the central Ketilidian mobile belt, and thus, show that the origin of the Cape Harrison domain is dominantly Proterozoic.

2.5.2. Foreland Zone

Pb signatures from the uraniferous and nonuraniferous galena-bearing occurrences in the Aillik Group (Wilton, 1991; Fig. 2.2) show a steeper array relative to the Cape Harrison domain when plotted on a Pb-Pb isochron diagram (Fig. 2.5). The slope of this array assuming a closed system Pb isotope evolution is ca. 2.75 Ga. Likewise, the intersection of the regression line for the Aillik array with the single stage mantle growth curve (μ=8) yields a Pb model age of ca. 2.75 Ga. The projection of this array back to the Archean indicates that Pb signatures for the Aillik Group were derived from an Archean source. This is in agreement with the average Hf-isotope T_{DM} age of ca. 2.5 Ga for zircons in the Aillik Group, which indicates that felsic magmatism during the formation of the Aillik Group involved a substantial contribution from Archean melt (LaFlamme et al., 2013).

The 2.75 Ga Pb age for the Aillik array is consistent with the conclusion of Wilton (1991) that suggests that the supracrustal units of the Aillik Group received Pb that was remobilized from the Archean basement. Wilton (1991) argued that the presence of Archean derived Pb in the Aillik Group, as well as in the Moran Lake Group located further west, indicate a common isotopic source for the basement to the Aillik domain that resembles Archean gneisses of the Nain Province. The SE continuation of the Archean foreland up to the Aillik-Cape Harrison boundary (Fig. 2.1) would account for the Archean signatures in the Aillik data that are clearly absent in the Cape Harrison data.

The Storø, Quiartorfik and Kaerne granites from the border zone in Greenland (blue crosses, Fig. 2.1) were plotted on a Pb-Pb isochron diagram (blue crosses, Fig. 2.5) with Pb-Pb isochron ages of ca. 1.70 Ga, 1.56 Ga and 1.72 Ga respectively (Kalsbeek and Taylor, 1985); however, the regression lines project back to the growth curve with reasonable Archean Pb model ages (ca. 2.4-2.8 Ga). Kalsbeek and Taylor (1985) argued that the low μ signatures (7.2-7.6) and low ε_{Nd} (T) at 1.75 Ga (-5 to -7) of these granites suggest that crust was derived from the anatexis of older Archean materials. As a result, these authors concluded that the border zone in Greenland represents a reworked segment of the Archean foreland. The Storø granites have Pb signatures characteristic of a higher μ source than the Kaerne and Quiartorfik granites, however, are significantly lower than the granites from the central Ketilidian mobile belt and Cape Harrison domain (Fig. 2.5). This is likely due to various contributions of Proterozoic mantle-derived material relative to Archean melt (Kalsbeek and Taylor, 1985). A similar regression back to the Archean for the Aillik and border zone arrays shows a basement component in both regions that is dominantly Archean. This is completely different from the Proterozoic mantle-derived Pb signatures in the Cape Harrison domain.

On a plot of thorogenic versus uranogenic Pb (Fig. 2.6) granites from the Cape Harrison domain and Ketilidian mobile belt (central and border zones) show a wide distribution across thorogenic and uranogenic space with significant overlap. This is quite different for the Aillik Group galena (Wilton, 1991), which shows a significant depletion in thorogenic Pb. However, this is to be expected as the Aillik Group has been reported to be Th poor (Wilton, 1991). The scatter in the data implies a substantial decoupling of Th and U, likely during intense magmatism and deformation.

2.6. Petrochemical Data

Major- and trace element whole-rock analysis for the Cape Harrison domain were compared with published data from the IHBPS of the Kaipokok domain (Barr et al., 2001) and the Ketilidian mobile belt (Kalsbeek and Taylor, 1985) to produce a series of petrochemical diagrams shown in Figs. 2.7, 2.8 and 2.9.

Samples were characterized using the petrochemical Streckeisen grid of Debon and LeFort (1983), which aims to define the petrological nature of each sample using their Q (quartz) and P (plagioclase vs. K-feldspar) indices (Fig. 2.7). Samples from the IHBPS trend across the left of the diagram from the quartz diorite to granodiorite field. This is consistent with their emplacement in the Archean foreland during early stages of Makkovikian magmatism. The Cape Harrison domain (north and south suites) and Ketilidian mobile belt (central and border zones) show a more alkaline character and trend across the middle of the diagram. This is indicative of a continental margin arc setting and shows that the crust in both the Makkovik and Ketilidian belts were involved in extensive subduction related magmatism.

Samples were plotted on a TAS diagram (Le Bas et al., 1986) to compare the silica saturation of the crust across the Makkovik and Ketilidian belts (Fig. 2.8). The Cape Harrison suites span the silica saturated area, whereas, the IHBPS span tighter to the boundary between silica saturated and oversaturated with a majority of samples clustered in the rhyolite field. This demonstrates that the Cape Harrison domain is slightly more alkaline and less saturated with silica than the Kaipokok domain. This is in agreement with the data from the Ketilidian mobile belt (Kalsbeek and Taylor, 1985) where samples from the central Ketilidian mobile belt are generally less silica rich than the border zone.

Samples were additionally plotted on Y versus Nb and Y+Nb versus Rb discrimination diagrams, in order to subdivide the granitoid suites based on the tectonic setting in which they were formed. In both plots (Fig. 2.9a,b) samples from the Cape Harrison domain and IHBPS lie within the volcanic arc granite field with little distinction between them. This is consistent with a continental arc setting where the petrochemical signatures of samples in both domains were extensively affected by juvenile mantle-derived magma during subduction-related magmatism. Samples from the central Ketilidian mobile belt overlap with the Makkovik data, whereas, samples from the border zone plot along the boundary between the volcanic arc granites and within plate granites. This may just be a result of the granites from the border zone being more evolved relative to the more juvenile Proterozoic mantle source, as they also contain more silica in Figs. 2.7 and 2.8.

2.7. Discussion

New whole-rock Pb isotope data show a petrogenetic distinction between the Aillik domain and the Cape Harrison domain. The Pb signatures from the Cape Harrison domain point to a crustal component derived solely from a Paleoproterozoic mantle-derived source. Pb signatures for galena from the Aillik Group (Wilton, 1991) point to an Archean origin for the basement beneath the Aillik Group that is similar to the pre-Makkovikian Laurentian foreland.

Nd isotope signatures for most samples from the Cape Harrison domain (Moumblow, 2014) reveal an average ε_{Nd} (T) value of ca. 3 when calculated at the time of Makkovikian magmatism (T=1.85 Ga). This is characteristic of granites that were derived from a depleted Paleoproterozoic mantle source, which is in agreement with the slope age of 1.83 Ga for the Cape Harrison north array. The Cape Harrison samples from the north old and south old suites (Fig. 2.2) have Nd T_{DM} model ages > 2.15 Ga showing mixing between an older Archean crustal source and Makkovikian magmatism. However, the Pb signatures for these samples have a slope that is collinear to Cape Harrison north and south arrays (Fig. 2.3). This is largely different from the steeper slope of the Aillik array (Fig. 2.5) that projects back to the Archean. This suggests that samples from the north old and south old suites have evolved from small fragments of Archean crust (possibly sedimentary) whose Pb isotope signatures largely equilibrated with the surrounding crust. A dominantly Paleoproterozoic derived mantle source for the Cape Harrison granites indicate that the crust formed outboard the Archean foreland just prior to the Makkovikian orogeny.

U/Pb zircon ages (e.g., Hinchey and Rayner, 2008; LaFlamme et al., 2013) provide constraints to the timing of major felsic magmatism in the Aillik Group to ca. 1.86-1.85 Ga. The U/Pb and Hf-isotope data for magmatic zircons in the Aillik Group (LaFlamme et al, 2013) revealed that the parent magma source within the Aillik domain contain a large component of Archean melts. This would require a substantial Archean basement beneath the Aillik Group during Makkovikian orogenesis. These crustal signatures are in agreement with the Pb signatures for galena from the Aillik Group (Wilton, 1991), which show the remobilization of country rock Pb (low Archean μ source) into the upper crust (Aillik Group).

In Greenland, the Archean foreland north of the Ketilidian mobile belt is comprised of late Archean Nûk gneisses that yield Rb-Sr whole-rock ages and U-Pb zircon ages in the range ca. 3.0-2.75 Ga (e.g., Moorbath and Pankhurst, 1976; Taylor et al., 1984). These ages are consistent with the ca. 2.75 Ga Pb model age for the Aillik array (Fig. 2.5). The relationship in age suggests that the basement source for the Aillik Group is likely part of the Archean foreland zone (Fig. 2.1) with a stronger link to the border zone (e.g., reworked continental margin) rather than the central Ketilidian mobile belt and Cape Harrison domain (e.g., juvenile Paleoproterozoic crust). This would imply that the deposition of the Aillik Group supracrustal units were on the Archean continental margin rather than an accreted island arc complex.

In the tectonic model by Ketchum et al. (2002), it was suggested that the Aillik domain represent the first of two island arcs accreted to the continental margin (Fig. 2.10a). However, the Pb isotope data for the Aillik Group (Wilton, 1991) shows no correlation to those from the Cape Harrison domain. The evidence of a dominantly Archean basement below the Aillik domain makes it improbable that this narrow crustal segment (<30 km) represents an accreted island arc complex. The Proterozoic Pb signatures (Fig. 2.3) and wider crustal zone (>150 km) for the Cape Harrison domain represent a more probable candidate for an accreted island arc.

Moumblow (2014) proposed an alternate model involving a single arc accretionary event along the Archean continental margin (Fig. 2.10b). Early stages involve the southeast subduction of the continental margin beneath oceanic crust with an outboard arc approaching around ca. 2.0 Ga. The accretion of this arc (CHMS) at ca. 1.90-1.87 Ga would result in a subduction flip towards the northwest and the beginning of a long-lived ensialic margin, similar to that seen in the Ketilidian mobile belt (e.g., Chadwick and Garde, 1996; Garde et al, 2002). The timing of felsic magmatism in the Kaipokok domain (IHBPS) dated at ca. 1.9-1.87 Ga (Barr et al, 2001) can act as a constraint for the timing of this change to cratonward subduction.

Following the generic kinematic model by Beaumont et al. (1996), the attempt to subduct the foreland margin under the accreted arc can explain the preservation of older passive margin material (e.g., Post Hill group) in the foreland zone. Loading of the continental margin after arc accretion would contribute to depression in the back arc region of the foreland zone. This is consistent with the deposition of the Aillik Group supracrustals in a retro-arc foreland basin (e.g., Ketchum et al., 2002). The formation of a retro-arc basin on the continental margin would account for the input of country rock Pb (Archean basement) in the Aillik Group samples during subsequent syn- and post-Makkovikian orogenesis (e.g., Wilton, 1991; LaFlamme et al., 2013).

The Labradorian Orogen in south Labrador is defined as a deformational and metamorphic event at ca. 1.65 Ga (Gower et al., 1992). The much more radiogenic Pb signatures for the Cape Harrison domain relative to those of Labradorian age (Fig. 2.3) demonstrate that regional deformation and extensive granitoid plutonism during the late Makkovik event is likely due to intense magmatism along the continental margin. The central Ketilidian mobile belt shares a similar radiogenic Pb signature with the Cape Harrison domain (Fig. 2.4), which is in agreement with the model for a long-lived ensialic margin during much of the Makkovikian-Ketilidian orogeny.

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2.9. Figures

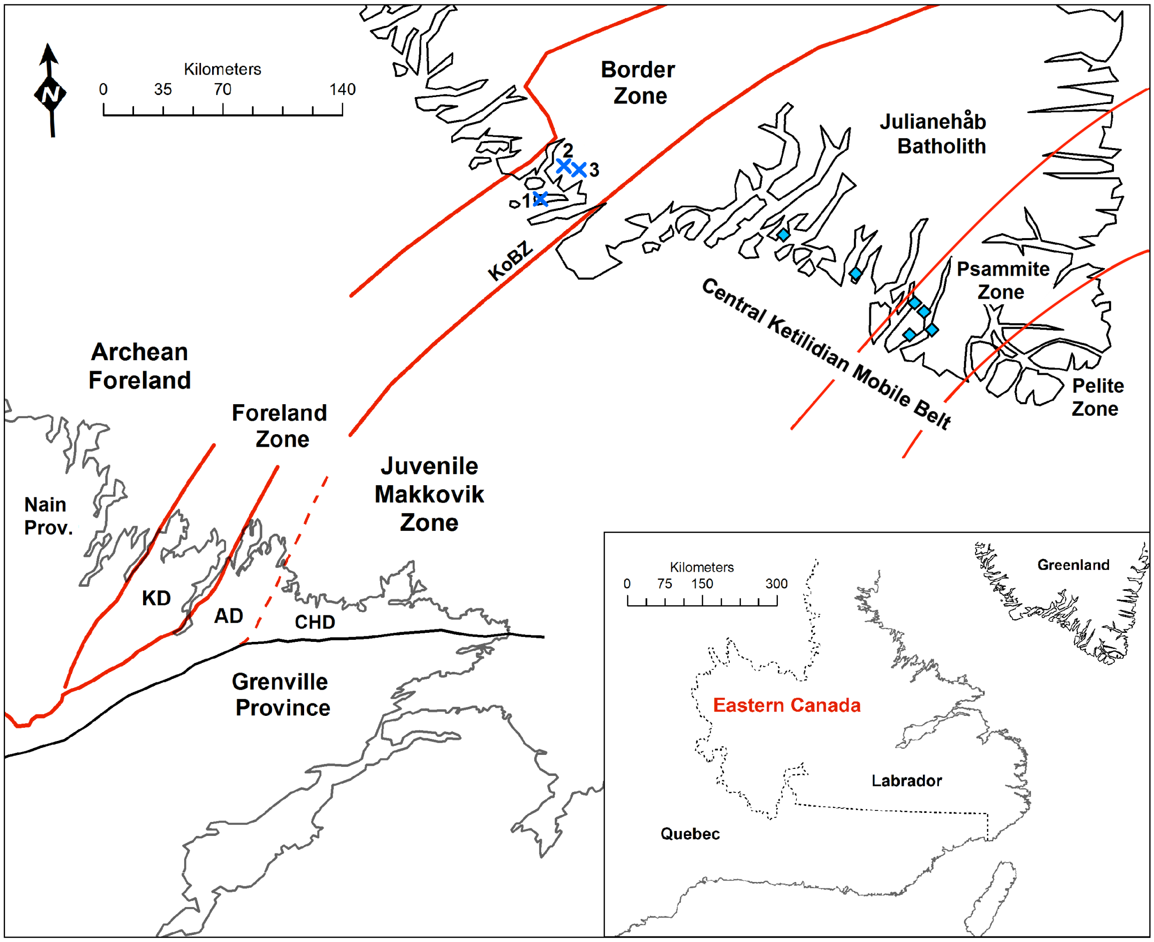

Fig. 2.1. Map of eastern Labrador and southern Greenland showing the reworked edge of the Archean continental margin restored to its pre-Mesozoic configuration. Dotted red line represents the Aillik-Cape Harrison boundary (assumed contact, Moumblow, 2014). Kaipokok domain (KD); Aillik domain (AD); Cape Harrison domain (CHD); Kobberminebugt Zone (KoBZ). Published sample localities by Kalsbeek and Taylor (1985) from the border zone (blue crosses: 1. Storø granite, 2. Quiartorfik granite, 3. Kaerne granite) and central Ketilidian mobile belt (blue diamonds). After Moumblow (2014).

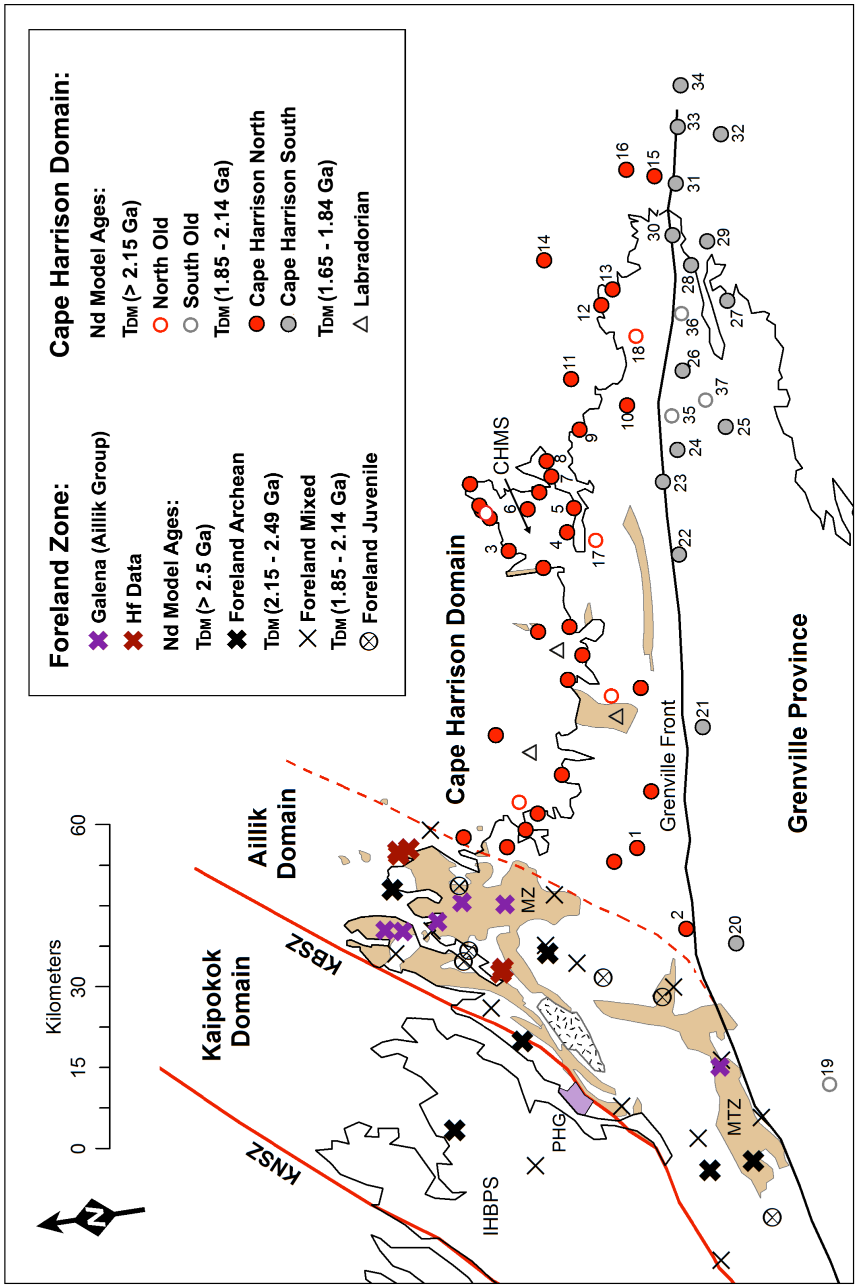

Fig. 2.2. Map of the Makkovik Province and northeast Grenville Province, illustrating the sample locations for published (un-numbered samples), and new Nd and Pb data (number samples). Published Nd data locations from Kerr and Fryer (1994), Dickin (2000), and Ketchum et al. (2002). Published Hf and Pb data locations from LaFlamme et al. (2013) and Wilton (1991) respectively. Boundaries: Kanairiktok Bay Shear Zone (KNSZ); Kaipokok Bay Shear Zone (KBSZ); Aillik-Cape Harrison boundary (dotted red line). Units: Archean block (stippled); Post Hill Group (PHG, purple shading); Aillik Group (brown shading): Makkovik zone (MZ); Michelin zone (MTZ); Island Harbour Bay plutonic suite (IHBPS); Cape Harrison Metamorphic Suite (CHMS). After Moumblow (2014).

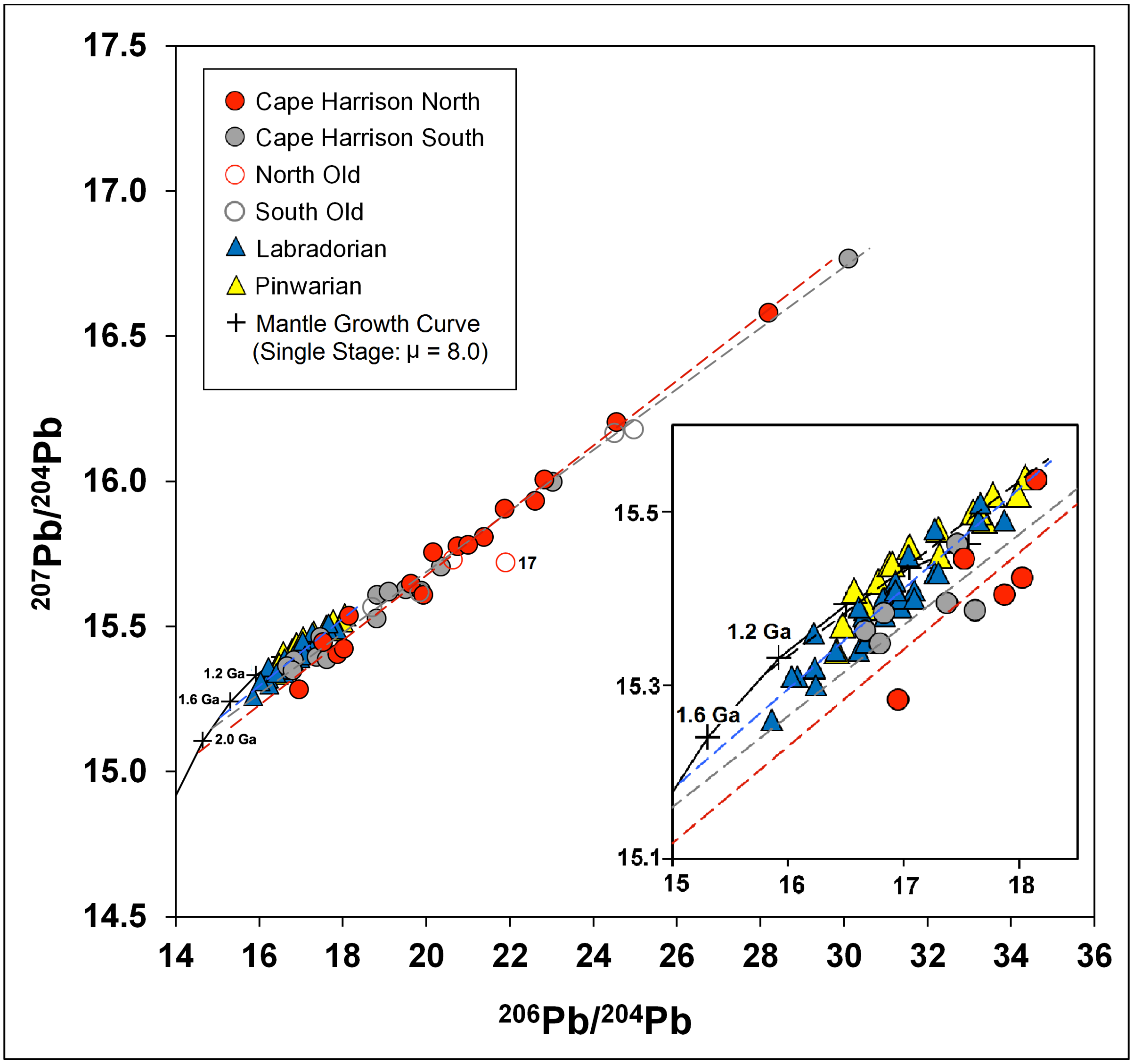

Fig. 2.3. Pb-Pb isochron diagram of samples from the Cape Harrison domain compared with published data of Labradorian (ca. 1.71-1.62 Ga) and Pinwarian age (ca. 1.52-1.46 Ga) (Lowey et al., 2003).

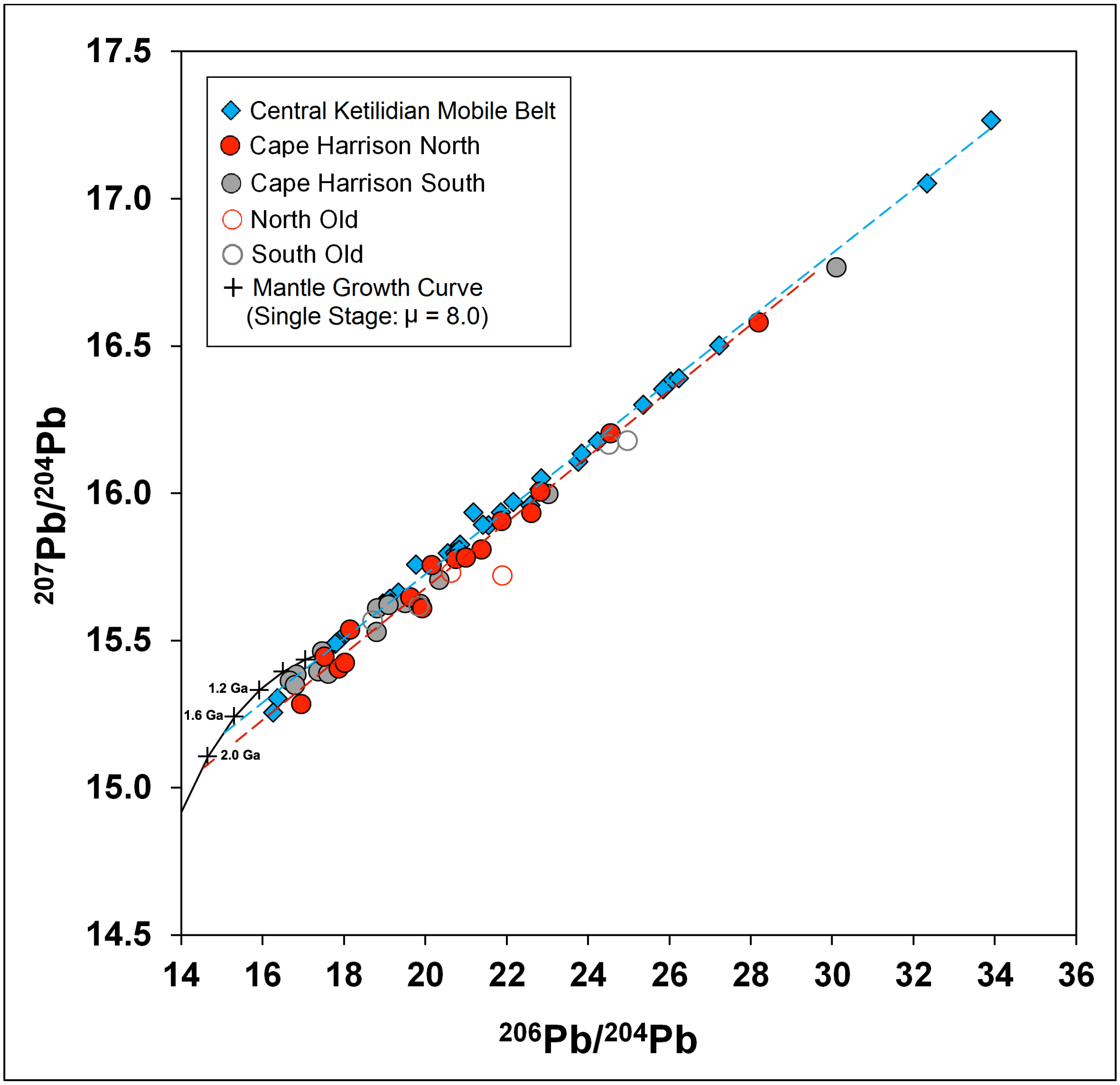

Fig. 2.4. Pb-Pb isochron diagram of samples from the Cape Harrison domain compared with published data from the central Ketilidian mobile belt of southern Greenland (Kalsbeek and Taylor, 1985).

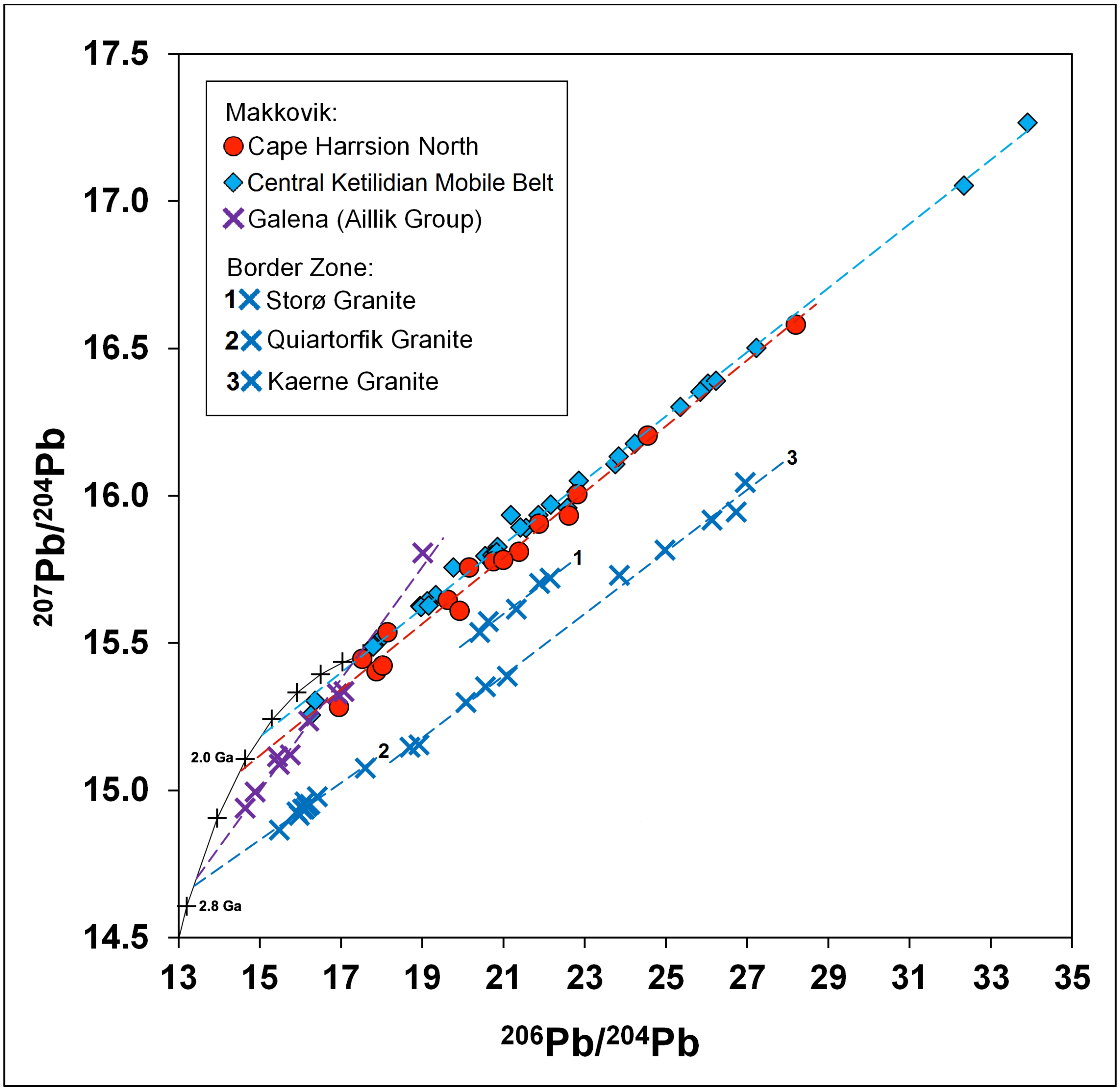

Fig. 2.5. Pb-Pb isochron diagram of published data from galena in the Aillik Group (Wilton, 1991) and granites from the border zone of southern Greenland (Kalsbeek and Taylor, 1985) demonstrating Pb arrays that project back to the Archean. All published data plotted against data from the Cape Harrison north suite and central Ketilidian mobile bet (Kalsbeek and Taylor, 1985) for reference. Horizontal axis ($^{206}Pb/^{204}Pb$) shifted down relative to Figs. 2.3 and 2.4.

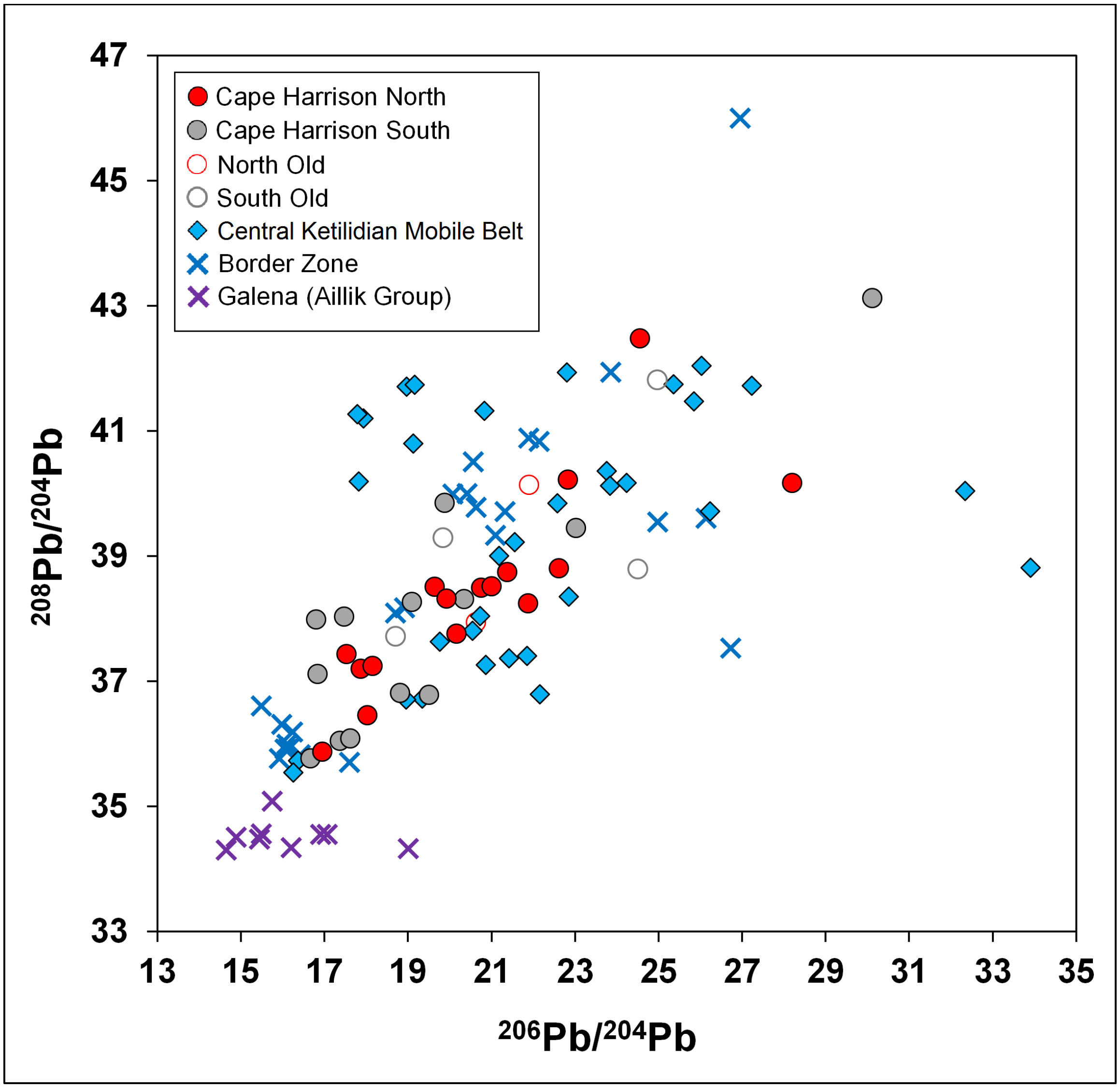

Fig. 2.6. Diagram of thorogenic versus uranogenic Pb for granites from the Cape Harrison domain compared with published data for granites from the central Ketilidian mobile belt and border zone of southern Greenland (Kalsbeek and Taylor, 1985) and galena from the Aillik Group (Wilton, 1991).

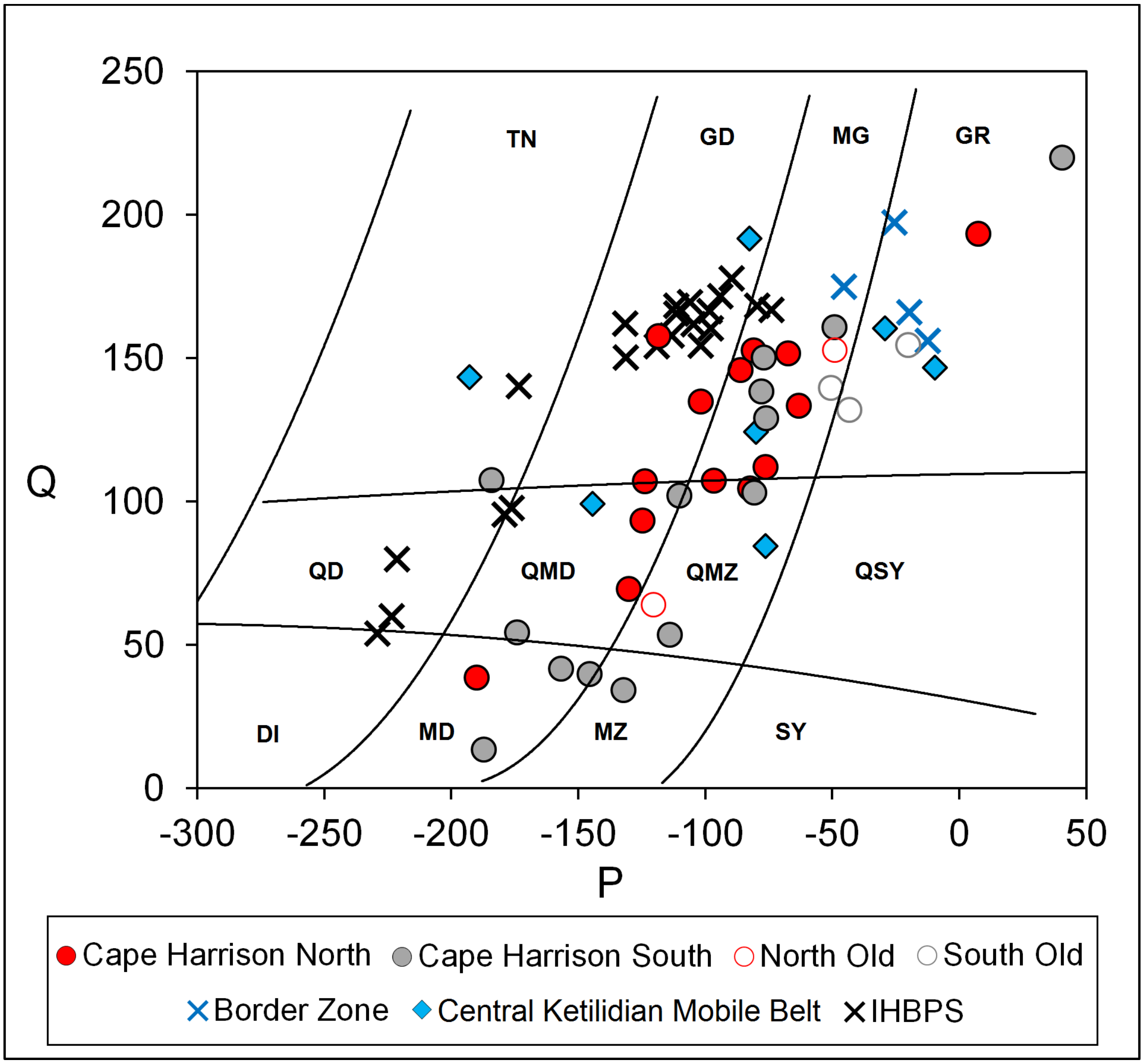

Fig. 2.7. Petrochemical grid of Debon and LeFort (1983) for the chemical Streckeisen classification of granitoid rocks. Q, 1/3 Si-(K+Na+2/3Ca); P, K-(Na+Ca). Tonalite (TN), granodiorite (GD), monzogranite (MG), granite (GR), quartz diorite (QD), quartz monzodiorite (QMD), quartz monzonite (QMZ), quartz syenite (QSY), diorite (DI), monzodiorite (MD), monzonite (MZ), syenite (SY). Published data from the central Ketilidian mobile belt (Kalsbeek and Taylor, 1985) and the Island Harbour Bay plutonic suite (Barr et al., 2001).

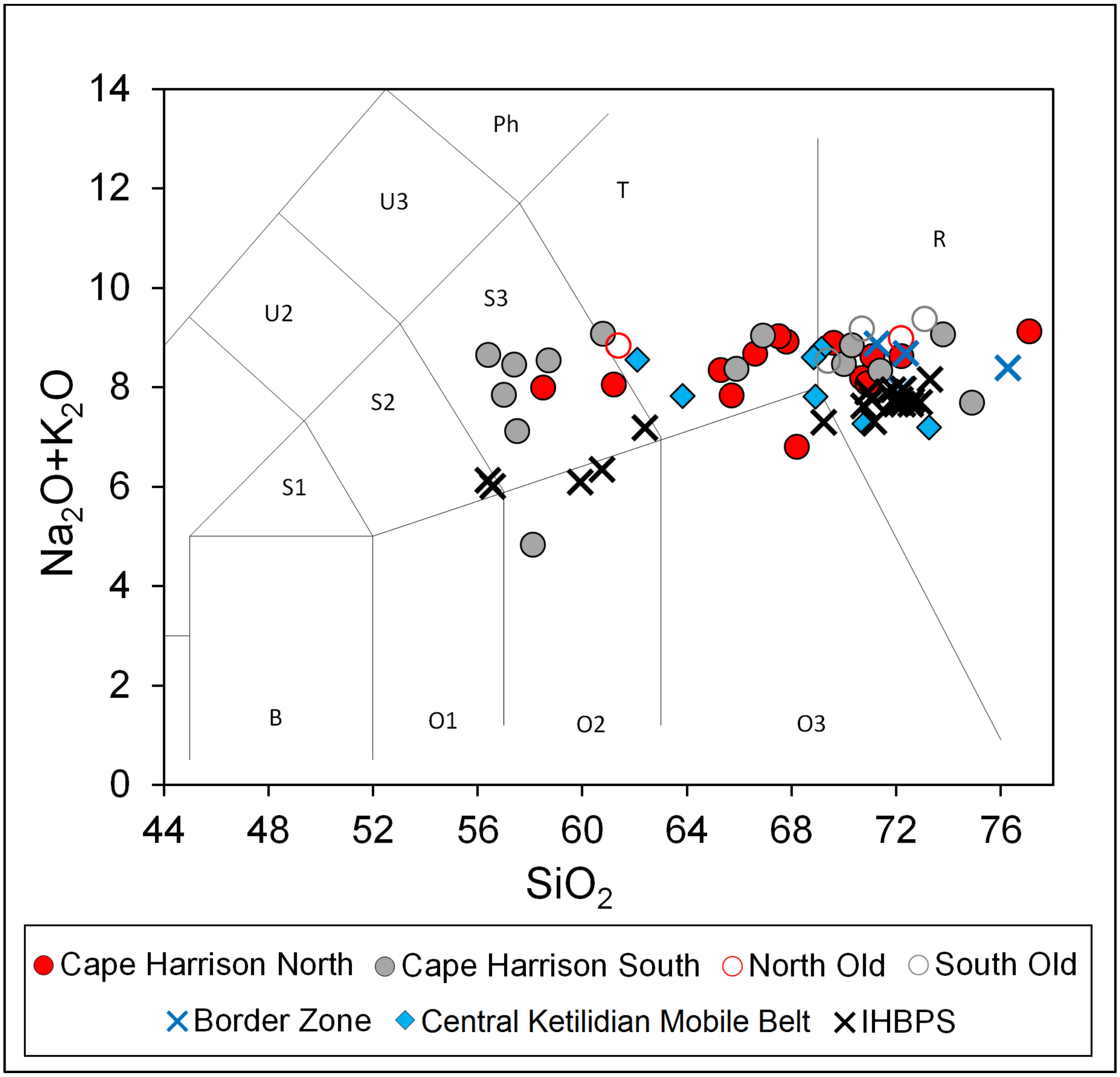

Fig. 2.8. TAS diagram after Le Bas et al. (1986) comparing total alkalis and SiO_2. Silica under saturated (U2, U3); Phonolite (Ph); Silica saturated (S1, S2, S3); Trachyte (T); Basalt (B); Silica over saturated (O1, O2, O3); Rhyolite (R). Published data from the central Ketilidian mobile belt (Kalsbeek and Taylor, 1985) and the Island Harbour Bay plutonic suite (Barr et al., 2001).

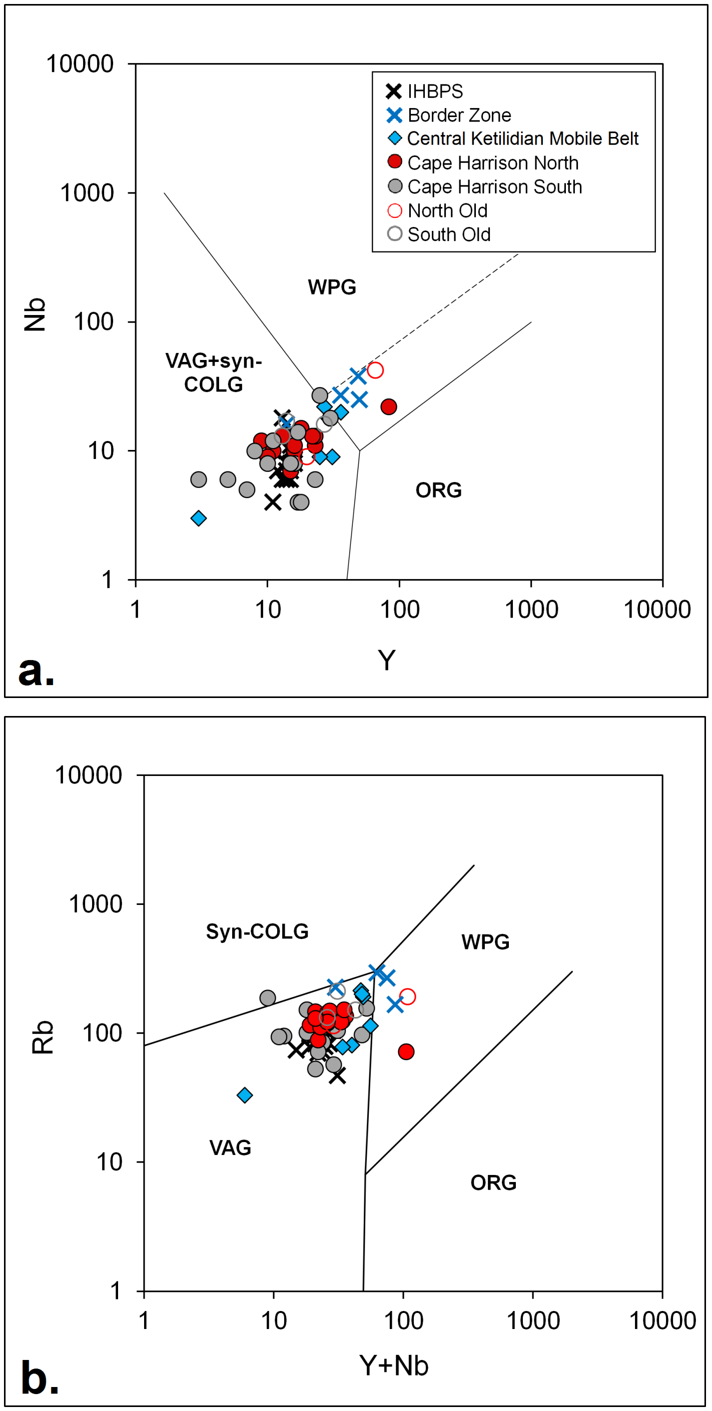

Fig. 2.9. Discrimination diagrams of (a) Y versus Nb and (b) Y+Nb versus Rb after Pearce et al. (1984). Volcanic arc granites (VAG); syn-collisional granites (syn-COLG); orogenic granites (ORG); within plate granites (WPG). Published data from the central Ketilidian mobile belt (Kalsbeek and Taylor, 1985) and the Island Harbour Bay plutonic suite (Barr et al., 2001).

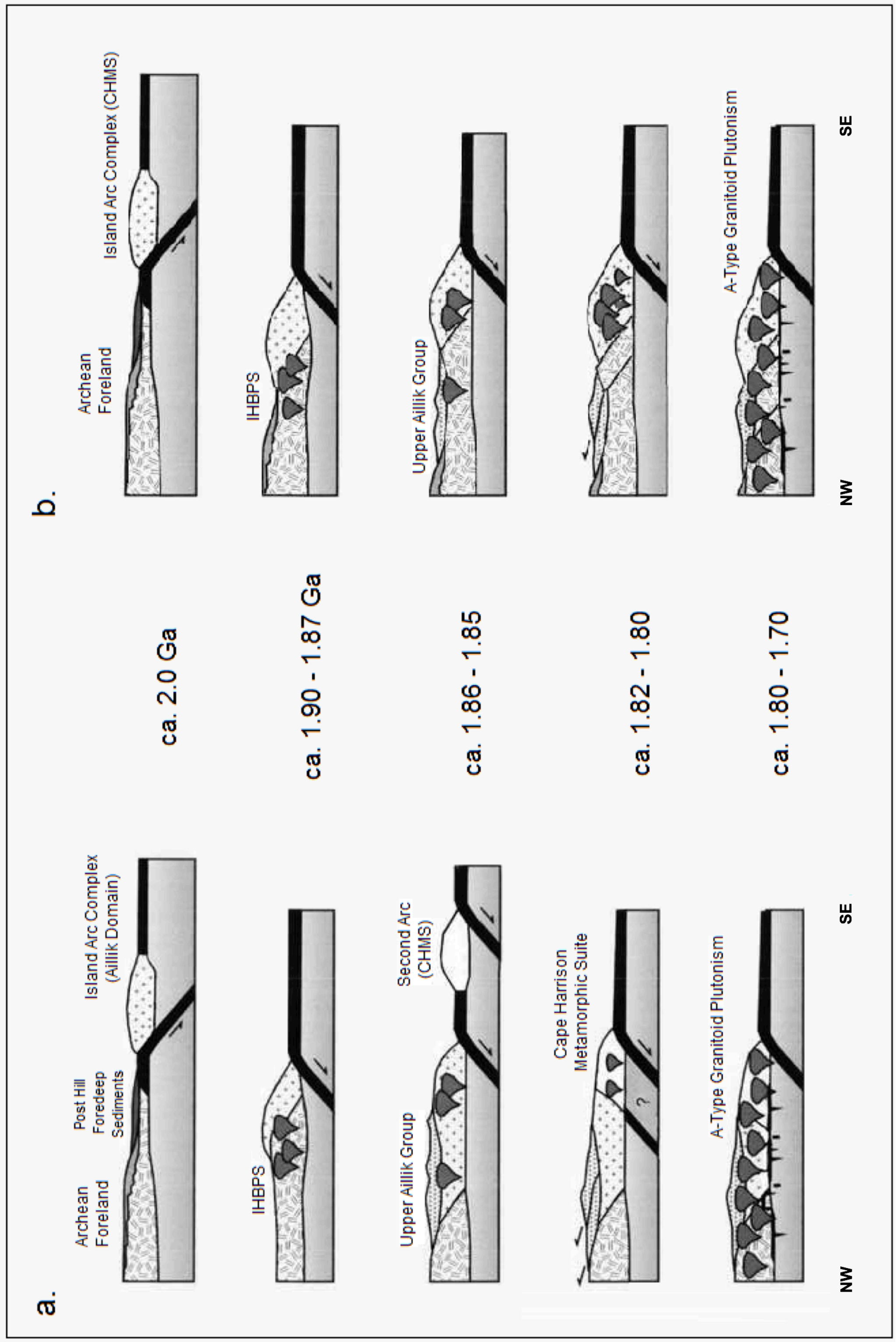

Fig. 2.10. Tectonic interpretations for the evolution of the Makkovik Province: (a) double arc accretionary model of Ketchum et al. (2002), and (b) single arc accretionary model of Moumblow (2014).

2.10. Tables

Table 2.1. Pb isotope data for samples from the Cape Harrison domain. Nd model ages based on the depleted mantle model of DePaolo (1981) from Moumblow (2014).

Map ID	Sample ID	UTM N NAD 83	UTM E NAD 83	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Age (TDM)
Cape Harrison North							
1	CG82-009	6067070	368042	16.949	15.284	35.873	1.96
2	CG83-627	6060630	351860	19.924	15.610	38.324	2.13
3	CG79-130	6081113	426109	28.197	16.581	40.170	2.11
4	CG79-493	6069921	427649	17.870	15.405	37.201	2.06
5	CG79-201	6067912	431835	18.025	15.424	36.459	2.07
6	CG79-500	6076392	433075	24.554	16.204	42.478	2.06
7	CG79-198A	6071034	438274	20.750	15.777	38.492	2.01
8	CG79-196	6071431	441216	21.379	15.809	38.744	2.03
9	CG79-180	6064428	445896	22.825	16.006	40.226	2.09
10	CG79-545	6055014	448758	22.606	15.933	38.804	2.01
11	CG79-251A	6064380	455290	19.632	15.647	38.513	1.97
12	CG79-269	6056502	467782	21.001	15.782	38.515	2.01
13	CG79-273	6053945	470242	20.160	15.756	37.759	2.07
14	CG79-578R	6065530	477730	21.874	15.906	38.247	1.98
15	CG79-316	6042764	489499	17.521	15.446	37.431	2.06
16	CG79-308	6047705	491525	18.147	15.537	37.264	2.01
North Old							
17	CG79-484	6064971	425293	21.898	15.721	40.143	2.25
18	CG79-571	6051234	460997	20.630	15.731	37.941	2.23
Cape Harrison South							
20	CG83-631	6052011	347622	19.877	15.624	39.850	2.00
21	CG79-407	6051275	387947	30.110	16.767	43.124	1.98
22	CG79-530	6050201	420027	18.806	15.528	36.811	1.98
23	CG79-535	6050870	433781	23.023	15.998	39.446	2.09
24	CG79-554	6047206	439090	17.371	15.395	36.051	1.97
25	CG79-629	6037702	441757	20.346	15.706	38.311	2.03
26	CG79-579	6043785	453307	18.818	15.610	47.353	2.04
27	CG79-753	6033425	464589	n/a	n/a	n/a	1.95
28	CG79-611	6038950	472163	19.503	15.628	36.785	2.04
29	CG79-383	6035226	475994	16.829	15.384	37.116	1.98
30	CG79-613	6041387	478200	17.617	15.387	36.085	2.10
31	CG79-320	6039116	487472	16.664	15.363	35.770	2.03
32	CG79-349	6029356	494992	19.092	15.621	38.265	2.10
33	CG79-339	6036974	497682	17.464	15.463	38.033	2.11
34	CG79-344	6035178	505163	16.794	15.349	37.990	1.99
South Old							
19	CG83-121A	6039400	319010	19.841	15.617	39.294	2.17
35	CG79-564	6047171	445460	18.822	15.646	37.904	2.21
36	CG79-591	6042204	463732	24.513	16.165	38.792	2.26
37	CG79-594	6040510	447257	24.973	16.178	41.816	2.64

Table 2.2. Major and trace element data for samples from the Cape Harrison domain from Moumblow (2014).

Sample #	CG79-130	CG79-180	CG79-196	CG79-198A	CG79-201	CG79-251A	CG79-269	CG79-273	CG79-308	CG79-316	CG79-320
SiO2	70.70	71.10	61.20	65.30	67.80	65.70	67.50	58.50	72.20	70.90	71.40
TiO2	0.43	0.37	0.67	0.67	0.49	0.69	0.64	0.70	0.24	0.30	0.18
Al2O3	15.05	15.70	16.05	16.70	15.95	16.45	16.30	19.45	15.20	15.00	15.25
FeO	1.15	1.61	4.11	2.70	1.78	3.27	2.48	3.38	1.21	1.55	0.87
Fe2O3	1.56	0.86	1.40	1.24	1.03	1.01	0.66	2.36	0.65	0.68	0.80
MnO	0.05	0.06	0.11	0.06	0.07	0.07	0.05	0.10	0.04	0.05	0.03
MgO	0.79	0.65	2.99	1.58	0.90	1.98	1.05	2.18	0.43	0.70	0.48
CaO	2.37	2.19	4.55	3.62	2.55	3.85	2.69	5.19	1.76	2.13	2.09
Na2O	4.07	4.60	4.11	4.44	4.50	4.14	4.23	4.99	4.10	4.01	4.05
K2O	4.12	4.03	3.94	3.91	4.42	3.70	4.80	3.00	4.53	4.07	4.28
P2O5	0.07	0.02	0.02	0.01	0.01	0.02	0.01	0.07	0.01	0.07	0.05
LOI	0.68	0.84	1.06	0.81	1.23	0.95	0.46	0.95	1.03	0.93	0.90
Total	101.04	102.03	100.21	101.04	100.73	101.83	100.87	100.87	101.40	100.39	100.38
Cr	41.0	19.0	89.0	32.0	14.0	29.0	88.0	4.0	-1.0	22.0	15.0
Ni	4.0	2.0	20.0	3.0	-1.0	7.0	5.0	4.0	-1.0	2.0	-1.0
Rb	147.0	125.0	136.0	144.0	72.0	120.0	122.0	89.0	116.0	112.0	95.0
Ba	803.0	589.0	688.0	878.0	1020.0	974.0	1253.0	1494.0	1169.0	985.0	1533.0
Th	24.0	16.0	12.0	11.0	5.0	9.0	4.0	2.0	9.0	4.0	-1.0
U	5.6	3.2	4.0	6.0	1.9	3.6	4.1	4.1	2.1	1.8	0.9
Ce	65.0	109.0	86.0	71.0	88.0	80.0	97.0	83.0	62.0	49.0	34.0
Cu	2.0	5.0	21.0	10.0	6.0	10.0	10.0	13.0	27.0	5.0	2.0
F	920.0	560.0	1480.0	1640.0	652.0	1084.0	811.0	1080.0	336.0	480.0	252.0
Ga	10.0	26.0	21.0	25.0	22.0	25.0	27.0	19.0	16.0	11.0	14.0
La	37.0	58.0	41.0	36.0	31.0	41.0	43.0	43.0	31.0	22.0	17.0
Li	26.2	35.8	30.2	34.1	17.7	31.0	23.7	30.4	16.9	15.2	8.0
Mo	4.0	4.0	6.0	6.0	4.0	4.0	4.0	5.0	5.0	4.0	4.0
Nb	10.0	11.0	13.0	10.0	22.0	10.0	15.0	7.0	9.0	12.0	5.0
Pb	26.0	18.0	14.0	14.0	16.0	14.0	14.0	18.0	20.0	15.0	18.0
Sr	449.0	251.0	480.0	577.0	309.0	650.0	472.0	917.0	440.0	495.0	588.0
V	25.0	23.0	97.0	55.0	13.0	60.0	39.0	86.0	12.0	25.0	18.0
Y	11.0	23.0	23.0	16.0	83.0	16.0	18.0	15.0	10.0	11.0	7.0
Zn	68.0	79.0	88.0	81.0	93.0	73.0	56.0	82.0	46.0	56.0	34.0
Zr	164.0	201.0	211.0	186.0	223.0	189.0	329.0	315.0	181.0	150.0	133.0

Table 2.2. Continued

Sample #	CG79-339	CG79-344	CG79-349	CG79-383	CG79-407	CG79-484	CG79-493	CG79-500	CG79-530	CG79-535	CG79-545
SiO2	58.10	65.90	70.00	66.90	73.80	72.20	66.60	68.20	60.80	70.30	77.10
TiO2	0.74	0.42	0.27	0.43	0.30	0.31	0.53	0.49	1.09	0.34	0.08
Al2O3	16.40	17.50	15.90	16.70	13.65	12.55	15.80	14.95	16.40	16.20	12.35
FeO	4.18	1.91	1.54	2.09	1.28	1.31	2.93	2.65	4.09	1.03	1.61
Fe2O3	3.09	1.59	0.40	1.15	0.70	1.12	0.61	1.10	1.28	0.32	0.63
MnO	0.15	0.06	0.03	0.06	0.04	0.07	0.09	0.07	0.13	0.02	0.02
MgO	4.71	0.94	0.57	0.91	0.32	0.26	1.16	1.71	1.52	0.47	0.05
CaO	6.53	3.28	2.13	2.46	0.86	0.98	2.41	2.76	3.41	2.33	0.34
Na2O	3.18	4.29	4.11	4.28	4.23	4.16	4.07	3.99	4.60	4.16	3.37
K2O	1.65	4.08	4.36	4.76	4.83	4.82	4.61	2.81	4.48	4.69	5.75
P2O5	0.33	0.13	0.05	0.15	0.05	0.03	0.13	0.09	0.40	0.04	0.00
LOI	1.25	0.76	0.75	1.04	0.67	1.04	0.74	0.93	0.46	0.49	0.85
Total	100.31	100.86	100.11	100.93	100.73	98.85	99.68	99.75	98.66	100.39	102.15
Cr	237.0	-1.0	8.0	-1.0	2.0	33.0	17.0	131.0	202.0	-1.0	3.0
Ni	27.0	2.0	2.0	2.0	2.0	-1.0	3.0	11.0	3.0	3.0	5.0
Rb	57.0	94.0	152.0	101.0	156.0	191.0	149.0	152.0	97.0	108.0	122.0
Ba	436.0	1884.0	1393.0	1131.0	767.0	250.0	1057.0	437.0	1548.0	1488.0	1033.0
Th	-1.0	6.0	5.0	8.0	23.0	16.0	18.0	15.0	8.0	17.0	12.0
U	1.5	0.7	2.2	1.5	8.1	5.9	4.7	4.0	3.8	5.0	5.8
Ce	81.0	86.0	59.0	92.0	94.0	282.0	62.0	64.0	105.0	46.0	73.0
Cu	2.0	3.0	2.0	7.0	20.0	2.0	13.0	12.0	12.0	7.0	17.0
F	1520.0	424.0	760.0	716.0	368.0	3400.0	1160.0	2920.0	1160.0	296.0	880.0
Ga	32.0	21.0	17.0	29.0	23.0	29.0	28.0	22.0	23.0	13.0	19.0
La	36.0	47.0	28.0	48.0	40.0	141.0	23.0	27.0	52.0	20.0	39.0
Li	21.5	26.6	26.9	20.3	9.3	1.9	29.6	88.8	18.1	16.3	30.7
Mo	5.0	3.0	5.0	5.0	5.0	5.0	7.0	4.0	6.0	4.0	6.0
Nb	6.0	6.0	10.0	8.0	27.0	42.0	11.0	13.0	18.0	12.0	13.0
Pb	5.0	13.0	19.0	14.0	28.0	10.0	46.0	12.0	14.0	20.0	17.0
Sr	858.0	813.0	584.0	603.0	192.0	45.0	535.0	211.0	425.0	501.0	615.0
V	130.0	33.0	23.0	37.0	11.0	6.0	42.0	43.0	63.0	11.0	43.0
Y	23.0	5.0	8.0	10.0	25.0	66.0	16.0	22.0	30.0	11.0	13.0
Zn	104.0	69.0	52.0	68.0	45.0	153.0	297.0	92.0	105.0	30.0	63.0
Zr	156.0	255.0	210.0	222.0	278.0	1004.0	213.0	188.0	474.0	221.0	158.0

Table 2.2. Continued

Sample #	CG79-554	CG79-564	CG79-571	CG79-578	CG79-579	CG79-591	CG79-594	CG79-611	CG79-613	CG79-629	CG79-753
SiO2	56.40	70.70	61.40	69.60	74.90	69.40	73.10	58.70	57.00	57.40	57.50
TiO2	0.75	0.36	0.55	0.21	0.29	0.41	0.20	1.00	0.83	0.91	0.69
Al2O3	20.00	14.75	17.40	15.35	11.75	15.30	13.90	18.60	18.15	18.20	16.95
FeO	3.58	1.60	2.75	1.06	0.92	1.59	0.96	4.02	4.11	4.35	4.38
Fe2O3	2.84	0.93	1.57	0.59	1.06	0.68	0.40	1.86	2.66	2.17	1.98
MnO	0.14	0.05	0.09	0.04	0.01	0.02	0.04	0.10	0.11	0.11	0.13
MgO	2.08	0.61	1.63	0.51	0.58	0.77	0.26	1.85	3.00	2.40	3.08
CaO	4.84	2.02	3.12	1.49	0.90	2.07	0.89	4.56	5.05	4.95	5.69
Na2O	5.32	3.78	4.72	4.22	2.00	3.64	3.80	4.59	4.36	4.18	4.18
K2O	3.33	5.40	4.12	4.68	5.69	4.89	5.57	3.95	3.49	4.28	2.94
P2O5	0.38	0.09	0.14	0.05	0.19	0.14	0.10	0.34	0.30	0.23	0.30
LOI	0.97	0.71	0.95	0.94	0.72	0.70	0.46	1.16	0.66	0.95	0.77
Total	100.63	101.00	98.44	98.74	99.01	99.61	99.68	100.73	99.72	100.13	98.59
Cr	-1.0	63.0	75.0	-1.0	31.0	29.0	79.0	17.0	39.0	107.0	115.0
Ni	2.0	2.0	5.0	3.0	5.0	2.0	3.0	5.0	10.0	6.0	12.0
Rb	53.0	151.0	114.0	130.0	188.0	132.0	211.0	105.0	85.0	134.0	72.0
Ba	1721.0	719.0	1275.0	1175.0	871.0	1030.0	386.0	1644.0	1378.0	2062.0	1123.0
Th	4.0	10.0	9.0	10.0	86.0	10.0	32.0	3.0	-1.0	9.0	-1.0
U	1.7	3.3	3.1	2.4	3.1	5.3	6.2	3.6	1.7	3.4	3.3
Ce	68.0	87.0	77.0	66.0	115.0	68.0	48.0	56.0	78.0	62.0	67.0
Cu	10.0	2.0	15.0	9.0	2.0	4.0	2.0	15.0	23.0	28.0	37.0
F	860.0	740.0	1640.0	372.0	516.0	480.0	336.0	1220.0	1220.0	1040.0	660.0
Ga	19.0	26.0	25.0	20.0	10.0	17.0	22.0	24.0	29.0	16.0	24.0
La	31.0	24.0	37.0	37.0	59.0	19.0	13.0	17.0	33.0	27.0	35.0
Li	12.1	29.2	31.0	20.4	16.4	20.0	8.0	18.6	19.5	20.6	17.6
Mo	3.0	3.0	6.0	4.0	3.0	4.0	5.0	7.0	7.0	7.0	5.0
Nb	4.0	16.0	9.0	12.0	6.0	13.0	17.0	14.0	8.0	8.0	4.0
Pb	7.0	22.0	10.0	21.0	33.0	18.0	22.0	10.0	7.0	10.0	8.0
Sr	816.0	308.0	683.0	464.0	188.0	450.0	112.0	711.0	819.0	676.0	754.0
V	88.0	23.0	66.0	15.0	15.0	33.0	9.0	64.0	120.0	107.0	133.0
Y	17.0	27.0	20.0	9.0	3.0	13.0	14.0	17.0	16.0	15.0	18.0
Zn	94.0	63.0	65.0	42.0	32.0	40.0	32.0	96.0	97.0	77.0	81.0
Zr	312.0	196.0	197.0	174.0	204.0	226.0	199.0	352.0	279.0	313.0	83.0

Chapter 3:
Paleoproterozoic Evolution of the SW Grenville Province: Evidence from Whole-Rock Pb Isotope Analysis

3.1. Introduction

The Great Proterozoic Accretionary Orogen (GPAO) along the Laurentian continental margin represents a major crust-forming event between 2.0-1.0 Ga (Condie, 2013). Here, evidence of Paleoproterozoic crustal growth is observed in Colorado, Wisconsin, Labrador, southern Greenland, and Scandinavia (Garde et al., 2002; Patchett and Kouvo, 1986; Bennett and DePaolo, 1987; Barovich et al., 1989; Moumblow et al., submitted). The Grenville Province comprises the southeastern margin of the Canadian Shield and contains a mosaic of crustal terranes accreted to the Laurentian margin during the GPAO (Fig. 3.1a). However, the Archean-Proterozoic boundary in the Grenville Province remains poorly defined due to high-grade metamorphism associated with the 1.2-1.0 Ga Grenville orogeny that erased much of the pre-Grenvillian history of the region.

Archean and Paleoproterozoic rocks of the southeastern Laurentian margin (yellow shading, Fig. 3.1b) are exposed in the parautochthonous belt across the northern Grenville Province from Georgian Bay to southeastern Labrador (Rivers et al., 1989). This Archean-Paleoproterozoic margin can be linked with the bordering Makkovik Province (Fig. 3.1c), which contains remnants of Paleoproterozoic crust accreted to the Archean craton during the 1.9-1.7 Makkovikian orogeny (e.g., Kerr and Fryer, 1994; Ketchum et al., 2002; Moumblow et al., submitted). The similarity in Archean-Paleoproterozoic ages suggests that the Archean continental margin of the Grenville and

Makkovik Provinces represent adjacent parts during an active accretionary orogen along the southeastern Laurentian craton during the Paleoproterozoic.

In eastern Labrador, a combination of whole-rock Pb and Nd isotope data were used in a reconnaissance study of the Makkovik Province to interpret the crustal formation history of this region during the Paleoproterozoic (Moumblow et al., submitted). Nd isotope data suggest that juvenile Makkovik crust was generated in the Cape Harrison domain during a single crust-forming event and accreted to the Laurentian margin by 1.90 Ga. Likewise, Pb isotope data show Paleoproterozoic crustal signatures for the Cape Harrison that are largely different than the Archean signatures of the Aillik domain (Fig. 3.1c), but very similar to the Ketilidian mobile belt of Greenland. As a result, Moumblow et al. (submitted) defined the boundary between the two domains as a cryptic Archean-Proterozoic suture (red line, Fig. 3.1c).

In the SW Grenville Province, studies by Dickin and McNutt (1989; 1990) and Dickin (1998a) linked the southern limit of Archean basement in Ontario with a sharp decrease in Nd model ages approximately 50-60km SE of the Grenville Front (Fig. 3.2). This break in model ages was equated with a cryptic collisional suture between the Archean foreland and an accreted Paleoproterozoic arc (red line, Fig. 3.2). On the south side of the boundary, ca. 1.90 Ga Nd model ages were interpreted as the crustal extraction age of an oceanic arc formed over a southerly dipping subduction zone (Dickin and McNutt, 1989). Dickin (2000) named this arc 'Barillia' based on the location of U-Pb dated material in the Pointe au Baril area.

DeWolf and Mezger (1994) attempted to use Pb isotope analyses on feldspars across the Archean-Proterozoic suture in Ontario to test the model proposed by Nd model age mapping (squares, Fig. 3.2). They claimed that several samples from south of the suture had Pb compositions that were indicative of Archean provenance rather than Proterozoic provenance. However, Dickin (1995) argued that the discrepancies between Nd and Pb isotope data were due to a lack of consideration of the geologic context of the samples analyzed by DeWolf and Mezger (1994).

Nevertheless, Pb isotope analysis of plutonic orthogneisses that are representative of average crust can be used to test the location of the Archean-Proterozoic suture proposed on the basis of Nd model age mapping. When used in conjunction with Nd isotope data, Pb signatures on orthogneisses can provide information regarding the timing of magma extraction from the mantle, thus differentiating reworked Archean crust from Paleoproterozoic crust derived solely from a juvenile mantle-derived source. Hence, the aim of this study is to contribute new whole-rock Pb isotope data for Paleoproterozoic crust from across the SW Grenville Province in order to place additional constraints on the Proterozoic history of the region.

3.2. Geologic Setting

The Grenville Province is a one billion year old orogenic belt in the Canadian Shield that contains older reworked crustal terranes of Archean to Mesoproterozoic age that were metamorphosed and tectonized during the Grenville Orogenic Cycle (Rivers et al., 1989; 2002). The Grenville Front marks the northern limit of a series of northwest-directed thrust sheets that telescoped the earlier Archean-Paleo-Mesoproterozoic margin of Laurentia (Fig. 3.2).

To the south of the Grenville Front, Rivers et al. (1989) divided the Province into two major longitudinal belts, the parautochthonous and allochthonous belts (Fig. 3.2). The Allochthon Boundary Thrust (ABT) represents a major thrust zone, which separates the parautochthonous belt to the northwest from the overriding allochthonous terranes to the southeast (Fig. 3.2). The parautochthonous belt comprises part of the Laurentian foreland that was highly metamorphosed and tectonized during the Rigolet event (Rivers et al., 2002), but, remained relatively in situ compared to the overriding allochthonous belt that was transported to the northwest during the Ottawan collisional event.

Nd isotope mapping by Dickin (2000) in the SW Grenville Province revealed three distinct T_{DM} model age groups in the parautochthonous belt that correlate with those mapped across the Makkovik Province (e.g., Kerr and Fryer, 1994; Moumblow et al., submitted). In the Makkovik Province, these distinct age suites are represented by i) Archean model ages (> 2.5 Ga) attributed to remelting of pristine foreland crust, ii) intermediate model ages (2.15-2.49 Ga) attributed to Proterozoic magmatism with a variable Archean crustal Nd component, and iii) Paleoproterozoic model ages (< 2.14 Ga) attributed to juvenile Makkovikian crust. The Paleoproterozoic T_{DM} model ages are uniform across the Cape Harrison domain SE of the Archean-Proterozoic suture, indicating that the Cape Harrison domain represents an accreted Paleoproterozoic arc (e.g., Kerr et al., 1994; Moumblow et al., submitted).

The first age suite in the SW Grenville Province is located directly south of the Grenville Front with crustal formation ages older than 2.5 Ga. These T_{DM} model ages are attributed to metamorphosed equivalents of the Archean Superior Province basement (Dickin, 2000). Reworking of the Laurentian foreland during the Mesoproterozoic subjected the relatively pristine Archean basement to extensive plutonism and migmatization. The mixing of Archean and Mesoproterozoic magmatic sources led to the generation of the second age suite comprised of reworked Archean crust with Nd model ages from 2.0 to 2.5 Ga (e.g., Dickin, 2000; Dickin and Guo, 2001). The final age suite was recognized south of the reworked Archean suite having ca. 1.8-2.0 Ga Nd model ages. This crustal belt was attributed to a Paleoproterozoic juvenile arc terrane accreted onto the Laurentian margin during the 1.85 Ga Penokean orogeny. A collisional suture separates this Paleoproterozoic crust from the Archean margin, which has been mapped in detail across the SW Grenville Province (e.g., Dickin, 1998a; Guo and Dickin, 1996; Dickin and Guo, 2001; Moore and Dickin, 2011; Fig. 3.2).

In Ontario, the parautochthon shows a widespread episode of Proterozoic granitic plutonism, likely emplaced during the Killarnean magmatic event. Plutonic rocks of this 1.70-1.75 Ga suite include the Killarney granite north of the Grenville Front, the Grondine and Fox River complexes within the Grenville Front Tectonic Zone, and granitoid orthogneisses near Pointe du Baril (van Breemen and Davidson, 1988; Davidson et al., 1992; Krogh et al., 1992; Ketchum et al., 1994). In addition, the petrology of the Key Harbour gneiss association reveals a suite of 1.70 Ga plutonic rocks intruded into previously metamorphosed and migmatised gneissic country rocks (Corrigan et al., 1994). This metamorphosed country rock suggests a significant geological history prior to 1.70 Ga. The widespread episode of Proterozoic reworking on the continental margin in Ontario is comparable with Labradorian orogenesis in southeastern Labrador that significantly reworked Makkovik crust south of the Grenville Front (Gower et al., 2008).

In western Quebec the allochthon was thrust northwards over the Archean parautochthon, where the complex surface trace of the ABT delineates the footwall of two major NW trending nappes. These nappes are termed the Lac Watson and Lac Dumoine terranes (Indares and Martignole, 1990; Indares and Dunning, 1997; Fig. 3.2). These thrust sheets have been recognized to consist of an upper and lower structural deck. The upper thrust deck is largely allochthonous, while the lower deck is a slice of parautochthonous crust that was entrained onto the bottom of the allochthon. Here, crustal formation ages revel a segment of Paleoproterozoic crust sandwiched between Archean and Mesoproterozoic aged crust. This implies that the Archean-Proterozoic boundary closely follows the lobate shape of the ABT, forming a tectonic duplex (Dickin et al., 2012; Fig. 3.2).

3.3. Sampling and Analytical Methods

Whole-rock Pb isotope data were determined for 84 Paleoproterozoic gneisses from across the SW Grenville Province, in order to test the variability of the Pb isotope signatures in juvenile Paleoproterozoic crust. The data are presented in Table 3.1. Samples were selected based on 1.85-2.0 Ga Nd model ages, with a preference for tonalite and granodiorite gneisses, as these rock types are thought to form the earliest crustal arc terranes.

Sample localities are plotted in Fig. 3.2 and are subdivided into four suites. These suites include: i) the suture suite (green diamonds) attributed to samples along the southern margin of the Archean-Proterozoic suture; ii) the duplex suite (purple diamonds) attributed to samples in western Quebec adjacent to the ABT; iii) the southern suite (red diamonds) attributed to samples from the southern Paleoproterozoic parautochthon; and iv) the North Bay A-type suite (light blue diamonds) attributed to anorogenic samples from the North Bay orthogenesis area of Holmden and Dickin (1995). Samples disturbed during younger Grenvillian orogenesis are indicated as white diamonds. Sample localities for feldspar separates by DeWolf and Mezger (1994) are also indicated as squares in Fig. 3.2, however their pelites were excluded in this study as their provenance is unknown.

Pb isotope analysis followed the previous procedures of Dickin (1998b) using finely powdered whole-rock samples. After dissolution in HF, HNO_3 and HCl, Pb extraction for unleached samples followed standard techniques, using Savillex 'bomb' dissolution and anion exchange in HBr. Samples were loaded with silica gel and phosphoric acid onto single Re filaments and analyzed on a VG 354 mass spectrometer at McMaster University. Average within-run precision on samples was .02% (1σ) with the reproducibility of $^{207}Pb/^{204}Pb$ estimated at 0.1% (2σ). All data were fractionation corrected (average 0.12% per amu) based on frequent analysis of NBS 981.

For comparative purposes, several unleached samples were replicated using the leaching procedure of Dickin (1998b) to test for any variations between the two methods (Table 3.1). Samples that were leached were placed in warm 6 M HCl over night prior to dissolution in order to remove sulfide phases that may contain remobilized Pb. This process may also leach radiogenic Pb from U-rich minerals such as biotite. However, no significant difference was observed between the Pb ratios of the unleached samples and their replicated leached counterparts, with all samples falling within geologic scatter of the main Paleoproterozic arrays (Fig. 3.3).

3.4. Pb-Pb Isochron

Whole-rock Pb isotope data from the SW Grenville Province are plotted on a series of Pb-Pb isochron diagrams, following the same symbology established in Fig. 3.2. A single-stage Pb mantle growth curve is plotted on each diagram using a typical Proterozoic mantle value of 8.0. Gneisses from the Paleoproterozoic suture suite define an array that is collinear with published Pb data from the juvenile Makkovik Province (orange circles, Moumblow et al., submitted) when plotted in Fig. 3.4. The Pb signatures from the juvenile Makkovik suite demonstrate a crustal component derived solely from a Paleoproterozoic mantle-derived source resembling the ca. 1.9-1.75 Ga Ketilidian mobile belt of Greenland (light blue circles, Kalsbeek and Taylor, 1985).

Assuming closed-system Pb isotope evolution, samples from the Paleoproterozoic suture suite fall along a 1.74 reference isochron with a similar degree of geologic scatter as the juvenile Makkovik array. The Pb-Pb slope age of ca. 1.74 Ga for the suture suite is consistent with evidence of Killarnean plutonism dated at 1,742 ±1.4 Ma by van Breemen and Davidson (1988). The Pb signatures for disturbed samples that lie outside the main array are attributed to the remobilization of Pb during younger Grenvillian orogenesis (white diamonds, Fig. 3.4).

When plotted on a Pb-Pb isochron diagram (Fig. 3.5), Paleoproterozic gneisses from the duplex suite (purples diamonds) define an array that is collinear with the suture suite. In contrast, the North Bay A-type suite (light blue diamonds) scatters below the 1.74 Ga regression line, implying a period of post-Paleoproterozoic magmatism that reworked the parautochthon in this region. On the other hand, the regression line for the North Bay A-type array projects back to the growth curve yielding a Paleoproterozoic Pb model age that is consistent with the suture and duplex suites.

Pb signatures for gneisses from the southern suite (red diamonds, Fig. 3.6) were plotted alongside published Pb isotope data from Loewy et al. (2003) for samples of Labradorian age to show the influence of mid-Proterozoic magmatism on the Pb signatures of crust along the original Paleoproterozoic continental margin. The Labradorian reference suite denotes the timing of late Paleoproterozoic magmatism on the Archean-Paleoproterozoic continental margin that extensively reworked older Makkovikian aged crust (Gower et al., 2008). Samples from the southern suite in Ontario show a degree of geologic scatter that can be attributed to younger reworking during the late Paleoproterozoic. This would have caused these samples to move toward the Labradorian array (black circles). This is to be expected as Nd model age mapping shows a southerly increase in Proterozoic deformation and metamorphism along the Paleoproterozoic continental margin in Ontario (Dickin and North, 2015).

The Southern Grenville Array of DeWolf and Mezger (1994) is colinear with the Labradorian array when plotted on Fig. 3.6 (yellow squares). Gneisses from the Southern Grenville Array represent allochthonous crust just south of the ABT in Ontario. Likewise, the ‘transitional’ samples of DeWolf and Mezger (1994) have Pb isotope ratios that overlap with the Labradorian array, thus resembling Paleoproterozoic arc crust that was reworked extensively during the mid-Proterozoic (blue squares).

Pb isotope ratios for gneisses from the Archean parautochthon of Ontario (Dickin, 1998b) are plotted on the Pb-Pb isochron diagram in Fig. 3.7 (black crosses). The slope of the Archean suite yields a much steeper array relative to the Paleoproterozoic suture suite and juvenile Makkovik suite. On the other hand, Pb in the galena ores from the Aillik domain of the Makkovik Province have an Archean source and plot collinear with the Archean array (blue crosses, Wilton, 1991).

Archean samples from the Northern Grenville Array of DeWolf and Mezger (1994) show a significant degree of scatter relative to the Archean array of Dickin (1998b) when plotted on Fig. 3.7 (red squares). This shows that suitably selected whole-rock samples show more coherent Pb ratios than feldspar separates from a wide variety of rock types. Here, whole-rock Pb data show a clear boundary between Archean and Paleoproterozoic crust in the SW Grenville Province that is comparable with the boundary between the reworked Archean margin and accreted juvenile Makkovik crust in Labrador.

When plotted on a thorogenic versus uranogenic Pb diagram (Fig. 3.8), gneisses from the four Proterozoic Grenville suites show a wide distribution with significant overlap with the juvenile Makkovik suite. The higher U/Th ratio for the juvenile Makkovik suite is characteristic of extensive ensialic arc reworking, as magmatism along the continental margin would result in a substantial decoupling of Th and U and a significant scatter across thorogenic and uranogenic space. The high U/Th ratios for the disturbed samples in Ontario are again attributed to extensive reworking during younger Grenvillian orogenesis.

3.5. Petrochemical Data

The petrology of Paleoproterozoic crust across the SW Grenville Province can be characterized using the petrochemical Streckeisen grid of Debon and LeFort (1983)(Fig. 3.9). The aim of this diagram is to describe the petrological affinity of each sample using their Q (quartz) and P (plagioclase vs. K-feldspar) indices. Archean gneisses from western Quebec trend across the left of the diagram, through the quartz diorite and tonalite fields (black crosses, Fig. 3.9). This reference suite represents lateral equivalents of Superior Province crust, whose petrological signatures are attributed to the accretion of arc fragments during the Kenoran orogeny (Guo and Dickin, 1996). In contrast, the juvenile Makkovik suite shows a more alkaline character and trend diagonally across the middle of the diagram. Samples from this reference suite are characteristic of a more mature continental arc setting, as these gneisses were formed from ensialic arc magmatism, following the accretion of a juvenile Makkovikian arc to the Archean continental margin (Moumblow et al., submitted).

Major element whole-rock data for the Proterozoic Grenville samples were obtained from the published sources indicated in Table 3.1. A significant overlap with the juvenile Makkovik suite shows that the Proterozoic gneisses analyzed in this study have a more alkaline character than the Archean crust. This is indicative of reworking of the accreted Paleoproterozoic terrane by ensialic arc magmatism during the Paleoproterozoic and Mesoproterozoic. Samples from the North Bay A-Type suite cluster within the granite field, which is representative of their more evolved geologic history (Holmden and Dickin, 1995).

When plotted on a TAS diagram (La Bas et al., 1986), a difference in silica saturation can be observed between the Archean foreland and reworked Proterozoic margin (Fig. 3.10). The Archean reference suite spans across the silica-oversaturated field with a majority of samples clustered near the rhyolite field. In contrast, the juvenile Makkovik suite spans across the silica-saturated field. A majority of the Paleoproterozoic Grenville gneisses overlap with the juvenile Makkovik suite, indicating a slightly more alkaline character that is less saturated with silica relative to the Archean foreland. This is again indicative of reworking of the accreted Paleoproterozoic terrane by ensialic arc magmatism.

Trace element identification, using Y versus Nb and Y+Nb versus Rb discrimination diagrams, supports an orogenic tectonic environment for the Paleoproterozoic Grenville gneisses (Fig. 3.11). In both plots, samples from the Paleoproterozoic Grenville suites lie within the volcanic arc granite field (VAG), overlapping with the juvenile Makkovik suite. This is consistent with previous interpretations that these gneisses were once part of an island arc that was reworked in a continental arc setting (Dickin and McNutt, 1989; 1990). Three samples from the North Bay A-Type suite with higher Y and Nb contents (53, 55, 56, light blue diamonds) lie in the within plate granite field (WPG). These samples are part of the North Bay area orthogneisses and therefore are representative of younger plutonic rocks with disturbed Pb signatures (Holmden and Dickin, 1995).

3.6. Discussion

Isotopic data from Wisconsin, Labrador and southern Greenland suggest an Archean-Paleoproterozoic collisional regime along the Laurentian continental margin between 2.0-1.8 Ga (Kalsbeek and Taylor, 1985; Barovich et al., 1989; Moumblow et al., submitted). Whole-rock Pb-Pb data presented in this study differentiate Proterozoic juvenile crust in the SW Grenville Province of Ontario from the Archean craton, and suggests a solely Proterozoic crustal source for Pb in the four Proterozoic Grenville suites discussed above. Therefore, the following discussion will focus on the Pb Proterozoic history of the region and the tectonic inferences that can be made.

3.6.1. Southern Limit of Archean Basement

DeWolf and Mezger (1994) claimed that three samples of possible Archean provenance lie to the south of our proposed suture (DM55, DM59 and DM60, Fig. 3.12). They proposed a boundary for the southern limit of 'Archean crustal influence' based on their Pb data on feldspars (blue dotted line, Fig. 3.12). However, the Pb ratio of sample DM60 plots collinear with our Proterozoic data in Fig. 3.7. A Proterozoic provenance for this sample is almost inevitable as it is located south of the ABT in the Mesoproterozoic allochthonous belt (Dickin et al., 2014).

Of the two remaining samples with possible Archean Pb signatures in question, sample DM59 is located immediately south of the suture near North Bay (Fig. 3.12). It was argued by Dickin (1995) that this granite might have been generated by melting of the Archean basement below the plane of the suture at depth, as the boundary near North Bay appears to dip moderately to the south. On the other hand, the Pb compositions for all orthogneisses from the suture suite near North Bay suggest derivation from a solely Proterozoic mantle-derived source with no Archean influence. This is in agreement with the absence of Nd model ages above 2.0 Ga south of the suture.

The final sample with possible Archean affinity (DM55, Fig. 3.12) represents a screen of country rock within the Mesoproterozoic Bonfield Batholith. However, the Pb ratio of this sample is itself ambiguous, as it does not correspond to either the Archean or Paleoproterozoic suites. This sample is from an amphibolite and is therefore not reliable for determining that the crust in this area is of Archean provenance.

The three samples of DeWolf and Mezger (1994) with possible mixed provenance (DM46, DM53, DM57, Fig. 3.12) have Pb isotope ratios that lie alongside the Proterozoic array in Fig. 3.6). This is significant as all three samples lie within our Paleoproterozoic terrane. The lack of Archean Nd model ages and Pb signatures south of the suture provides strong evidence for no Archean basement below the Paleoproterozoic terrane at the time of formation. This is comparable to the accreted juvenile arc in the Makkovik Province (Moumblow et al., submitted).

3.6.2. Paleoproterozic Evolution of the SW Grenville Province

Utilizing the model of Dickin and McNutt (1990), the crustal evolution of the SW Grenville Province during the Paleoproterozoic can be explained, showing numerous similarities with the Makkovik Province of Labrador (Fig. 3.13). Homogenous

Proterozoic Pb signatures and Nd model ages (ca. 1.85-2.14 Ga) for the Cape Harrison domain suggest that the crust was derived from a juvenile mantle source (e.g., Kerr and Fryer, 1994; Moumblow et al, submitted). This is largely different from the Archean Pb signatures of the Aillik domain (Wilton, 1991). Pb signatures south of the proposed suture in Ontario strongly resemble those from the Cape Harrison domain, and thus make it plausible that the crust represents an oceanic island arc accreted to the Archean foreland along the same collisional regime.

Early stages of Paleoproterozoic crustal evolution in the SW Grenville Province began with the southeast subduction of oceanic crust beneath an approaching outboard arc prior to the Penokean event (Fig. 3.13a). The Pb data reveal the absence of an Archean component in the Paleoproterozoic parautochthon, which would be required if the crust were emplaced through an Archean margin by northward dipping subduction. Southerly dipping subduction would account for the lack of Penokean-aged plutonism (ca. 1.9-1.8 Ga) on the Archean foreland, as argued by Dickin and McNutt (1990).

The attempt to subduct the foreland margin under an accreted arc can explain the preservation of older passive margin material on the foreland zone (Dickin, 1998b). The Archean foreland in the French River area of Ontario (FR, Fig. 3.2) exhibits radiogenic Pb signatures immediately north of the Archean-Proterozoic suture (Dickin, 1998b). The new Paleoproterozoic Pb data from south of the suture strengthen the argument of Dickin (1998b) that the Archean margin was over-ridden during the Paleoproterozoic by a Penokean arc (Fig. 3.13b), thus preserving Archean upper crustal material in the foreland zone (see Beaumont et al., 1996).

Nd model ages across the Grenville parautochthon delineate crust of Archean provenance northwest of the suture from crust of Paleoproterozoic provenance to the southeast. This is in agreement with the new Pb data in Fig. 3.7 that illustrates a clear distinction between Archean and Proterozoic crustal signatures north and south of the suture respectively. This break in Nd and Pb isotopic signatures are consistent with that across the Archean-Proterozoic boundary in the Makkovik Province, which is interpreted as a cryptic suture between the Laurentian margin and an accreted Paleoproterozoic arc (e.g., Moumblow et al., submitted).

Metasedimentary gneisses containing abundant quartzite overlies the Archean margin near the French River, Temiscaming, and the Ontario-Quebec border north of Mattawa (Holmden and Dickin, 1995; Dickin, 1998b; Dickin and Guo, 2001; Fig. 3.2). Nd isotope evidence by Holmden and Dickin (1995) revel a range of isotopic compositions for these rocks attributed to mixing of sediment from Archean and Paleoproterozoic sources. The accretion of a Penokean arc would have caused loading of the continental margin and subsequent depression in the back arc region forming a foreland basin (Fig. 3.13c). A similar scenario is observed behind the accretionary margin of the Makkovik Province, in which the supracrustal units from the Aillik Group were deposited in a retro-arc basin at ca. 1.86-1.85 Ga (e.g., Ketchum et al., 2002; Moumblow et al., submitted).

The evidence for a Paleoproterozoic crustal source in the SW Grenville province is further constrained by the Kiosk quartzite south of the proposed Penokean arc. Detrital zircons in this crust reveal a maximum U-Pb age of 1850 Ma (Culshaw et al., 2016). The Paleoproterozoic age of these zircons suggests inheritance from a near by Penokean terrane, thus validating our argument for the accretion of a Penokean arc in the SW Grenville Province during the GPAO between ca. 1.8-2.0 Ga.

Following the accretion of the Penokean arc to the Archean craton, a flip to cratonward subduction would result in the formation of a long-lived ensialic margin on the Archean-Paleoproterozoic margin (Fig. 3.13d). This change in subduction is constrained by the timing of igneous activity on the Archean-Paleoproterozoic composite margin dated at ca. 1.75-1.70 Ga (e.g., van Breemen and Davidson, 1988; Krogh et al., 1992; Ketchum et al., 1994). These intrusions, corresponding to the Killarnean magmatic event, are analogous with the timing of long-lived ensialic arc activity in both the Makkovik Province and Ketilidian mobile belt (Garde et al, 2002; Moumblow et al., submitted). Extensive Killarnean plutonism south of the Penokean suture is reflected in the Pb-Pb slope age for the Paleoproterozoic Grenville arrays. However, an average ca. 1.90 Ga Nd model age for crust south of the suture emphasizes melting of mafic rock at the base of the Penokean arc rather than juvenile mantle derived magmatism (e.g., Dickin and McNutt, 1989; 1990; Holmden and Dickin, 1995; Guo and Dickin, 1996; Dickin, 1998a; Dickin and Guo, 2001; Moore and Dickin, 2011).

The homogenous Pb signatures between the suture suite and the duplex suite in Fig. 3.5 suggest a similar origin for the Paleoproterozoic crust in Ontario and western Quebec. However, the Archean-Proterozoic boundary in western Quebec represents a Grenvillian thrust zone rather than a collisional suture. The thin sliver of Paleoproterozoic crust sandwiched between the Archean parautochthon and ABT can be interpreted as a tectonic duplex that was entrained onto the base of the allochthon from parautochthonous Paleoproterozoic basement further south (Dickin et al., 2012).

The anorogenic chemistry of the North Bay A-Type suite suggests a complex geologic history for the crust near the Archean-Proterozoic suture. Moreover, the Pb isotope data indicates no Archean inheritance for these samples. Therefore, it can be confirmed that these gneisses were produced through Paleoproterozoic orogenesis. The anorogenic nature of the North Bay A-Type suite is likely the result of post-tectonic magmatism on the accreted Paleoproterozoic terrane. However, further investigation is necessary to better understand the post-Paleoproterozoic history of this orthogneiss suite.

Overall, the Pb isotope signatures presented here show evidence of juvenile crustal addition and extensive migmatization throughout the early- and mid- Proterozoic. This suggests that the SW Grenville Province shares a similar Proterozoic evolution with the Makkovik-Ketilidian orogeny to the northeast (e.g., Kalsbeek and Taylor, 1985; Moumblow et al., submitted). The addition of a Penokean arc to the Laurentian margin was followed by a span of nearly 500 million years of intermittent ensialic arc magmatism and crustal growth, which was brought to an end during the terminal Grenville orogeny (Dickin and McNutt, 1990).

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3.8. Figures

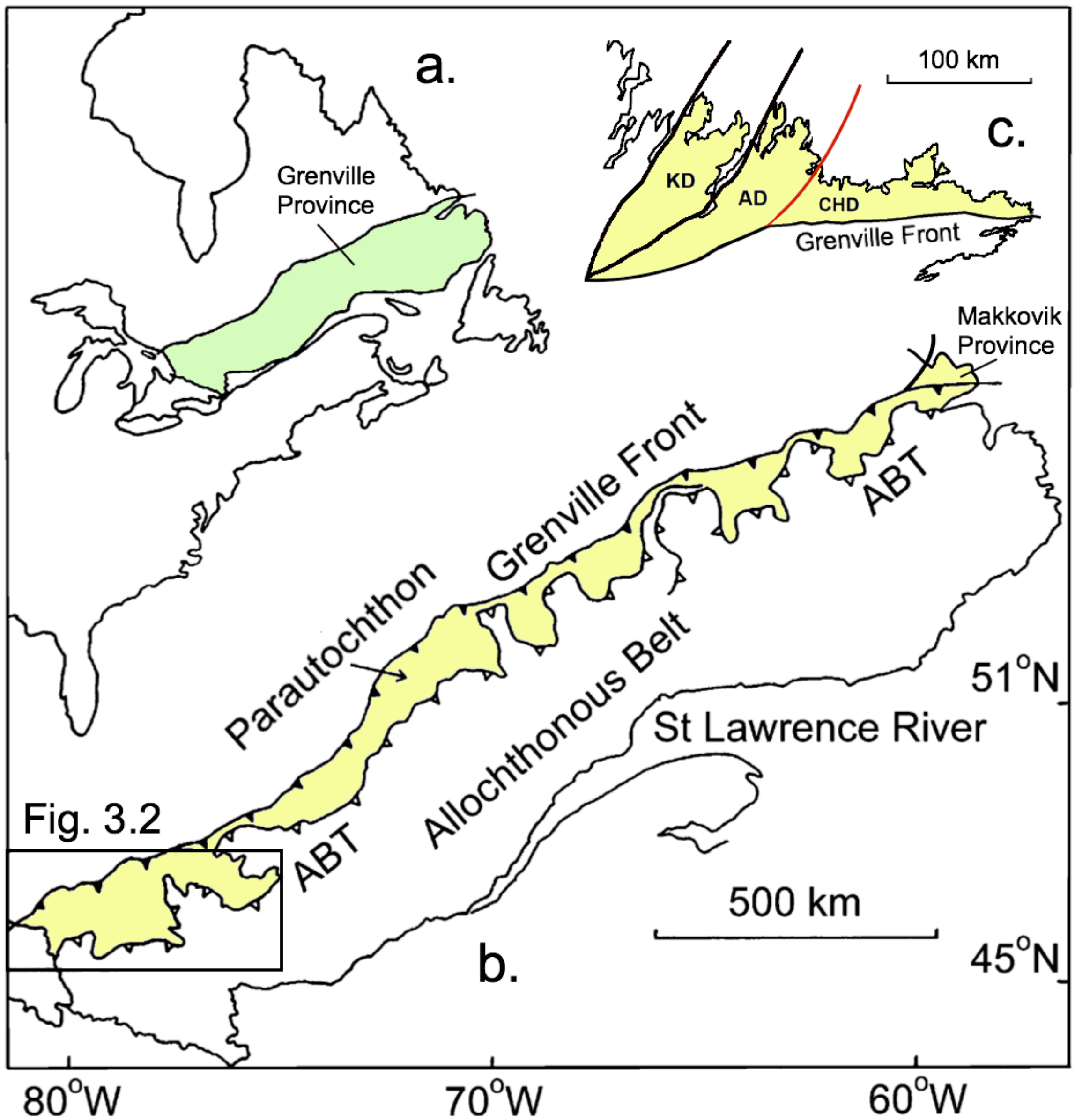

Fig. 3.1. View of the southeast Canadian Shield showing (a) the location of the Grenville Province of eastern Canada (green shading); (b) major tectonic belts of the Grenville Province after Rivers et al. (1989): Allochthon Boundary Thrust (ABT); Archean and Paleoproterozoic crust (yellow shading); and (c) the tectonic domains of the Makkovik Province after Moumblow et al. (submitted): Aillik domain (AD); Archean-Proterozoic suture (red line); Cape Harrison domain (CHD); Kaipokok domain (KD). Box shows the area of Fig. 3.2. Modified from Dickin et al. (2008).

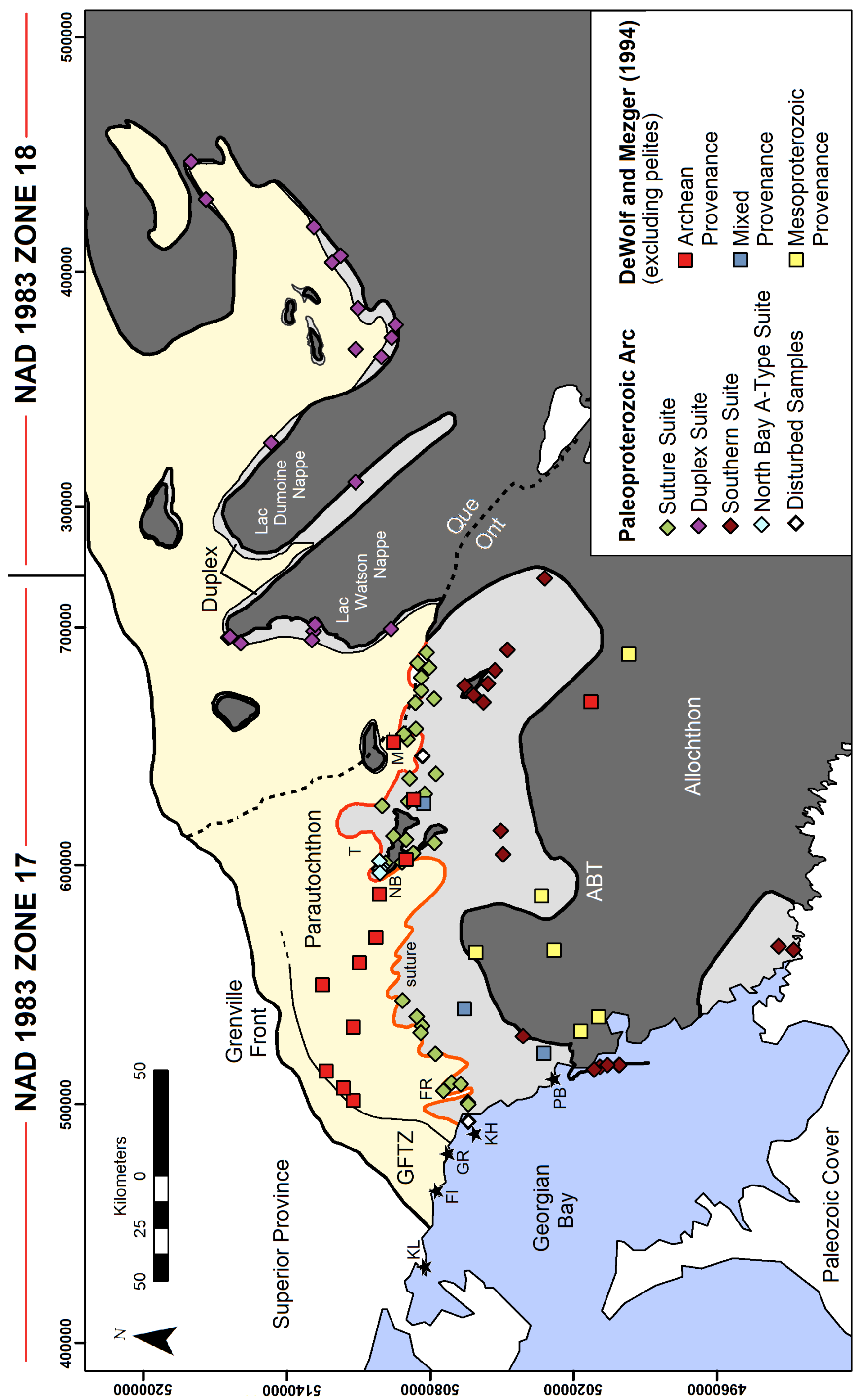

Fig. 3.2. Map of the SW Grenville Province and its major tectonic units. Boundaries: Allochthon Boundary Thrust (ABT); Archean parautochthon (yellow shading); Archean-Proterozoic suture (solid red line); Grenville Front Tectonic Zone (GFTZ); Paleoproterozoic parautochthon (light grey shading). Locations: French River (F); Mattawa (M); North Bay (NB); Temiscaming (T). Plutons: Fox Islands (FI); Grondine (GR); Key Harbour (KH); Killarney (KL); Pointe au Baril (PB). Boundaries after Dickin et al. (2014).

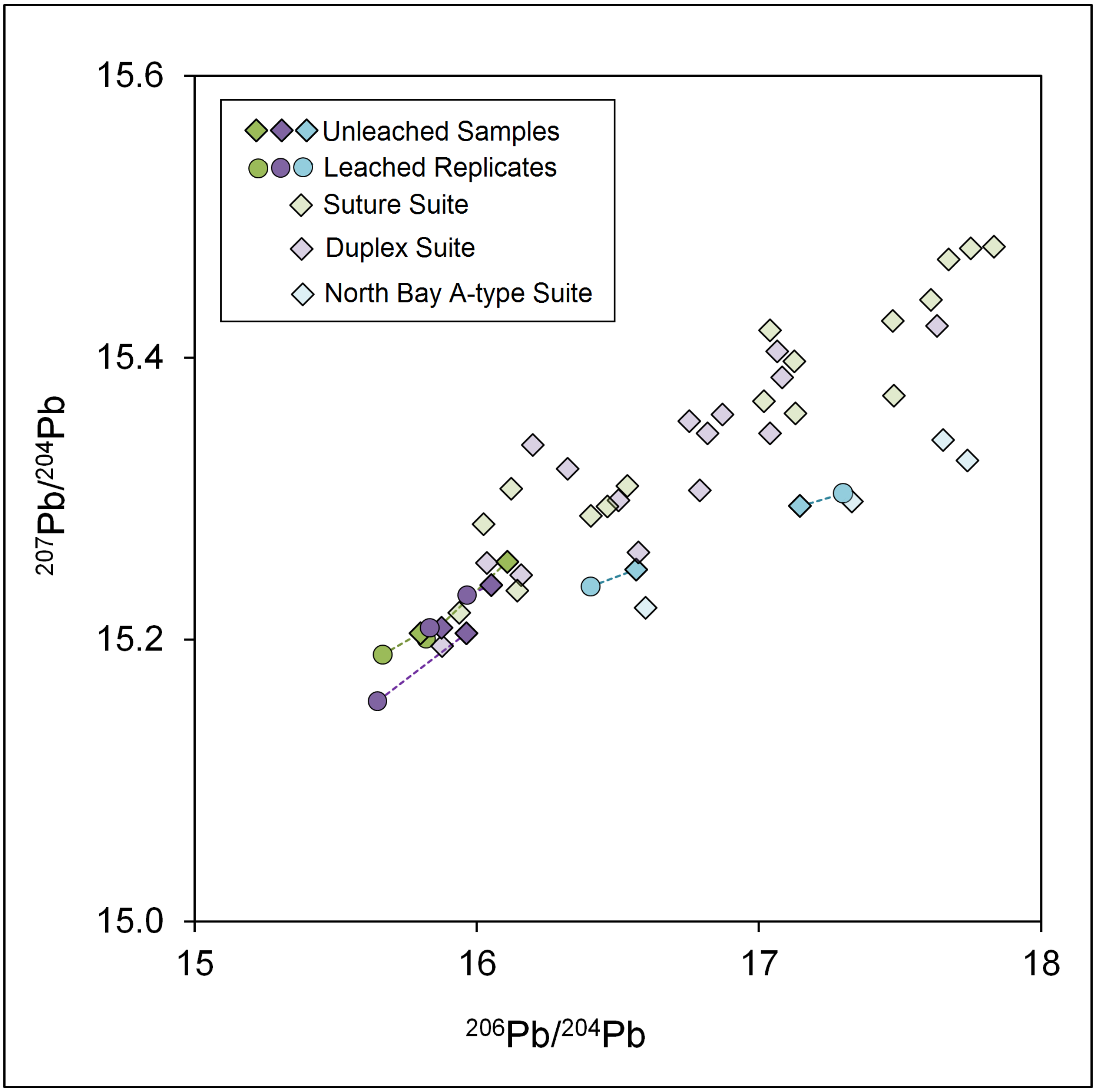

Fig. 3.3. Pb-Pb isochron diagram showing the Pb ratios of replicated leached duplicates relative to their unleached counterparts. Unleached-leached pairs are plotted along Pb isotope data from the corresponding suture, duplex and North Bay A-type suites.

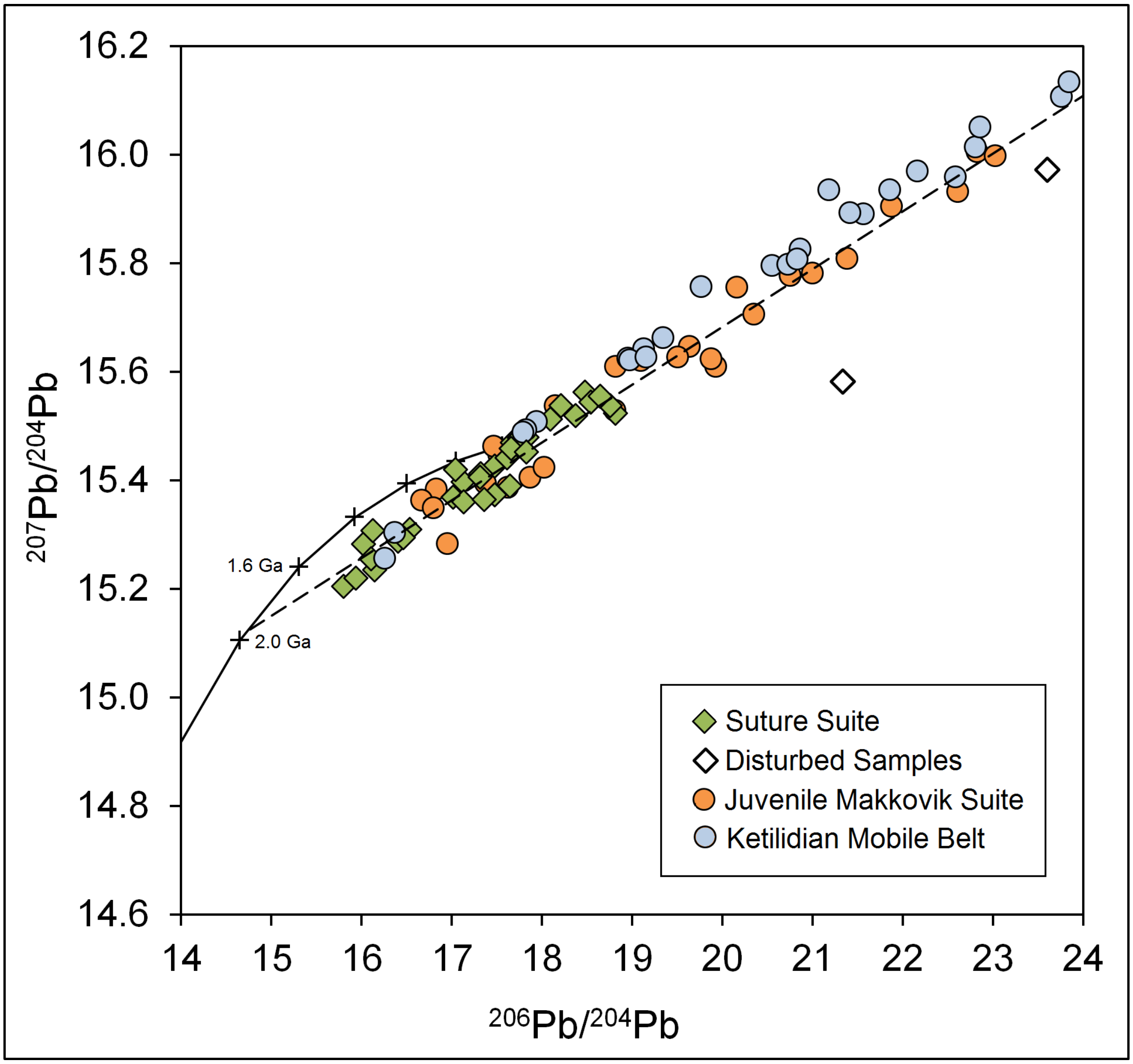

Fig. 3.4. Pb-Pb isochron diagram showing samples from the Paleoproterozoic suture suite and disturbed samples compared with published data from the juvenile Makkovik Province (Moumblow et al., submitted) and the Ketilidian mobile belt (Kalsbeek and Taylor, 1985).

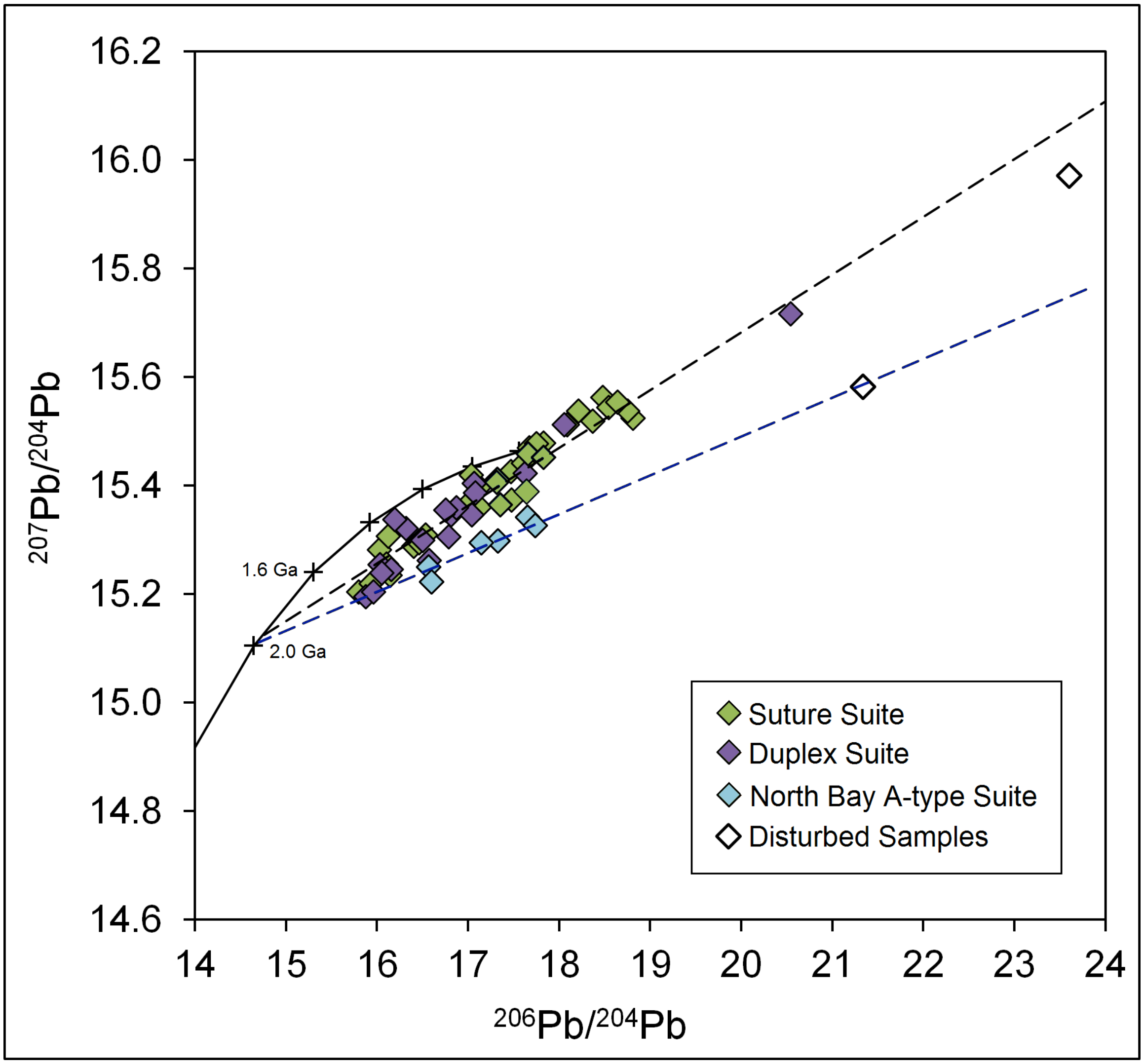

Fig. 3.5. Pb-Pb isochron diagram showing Paleoproterozoic samples from the duplex suite and North Bay A-Type suite compared with the suture suite and disturbed samples. Pb data plotted against the 1.74 Ga reference line from Fig. 3.4 (black dotted line). Post-Paleoproterozoic open system evolution shown by blue dotted line.

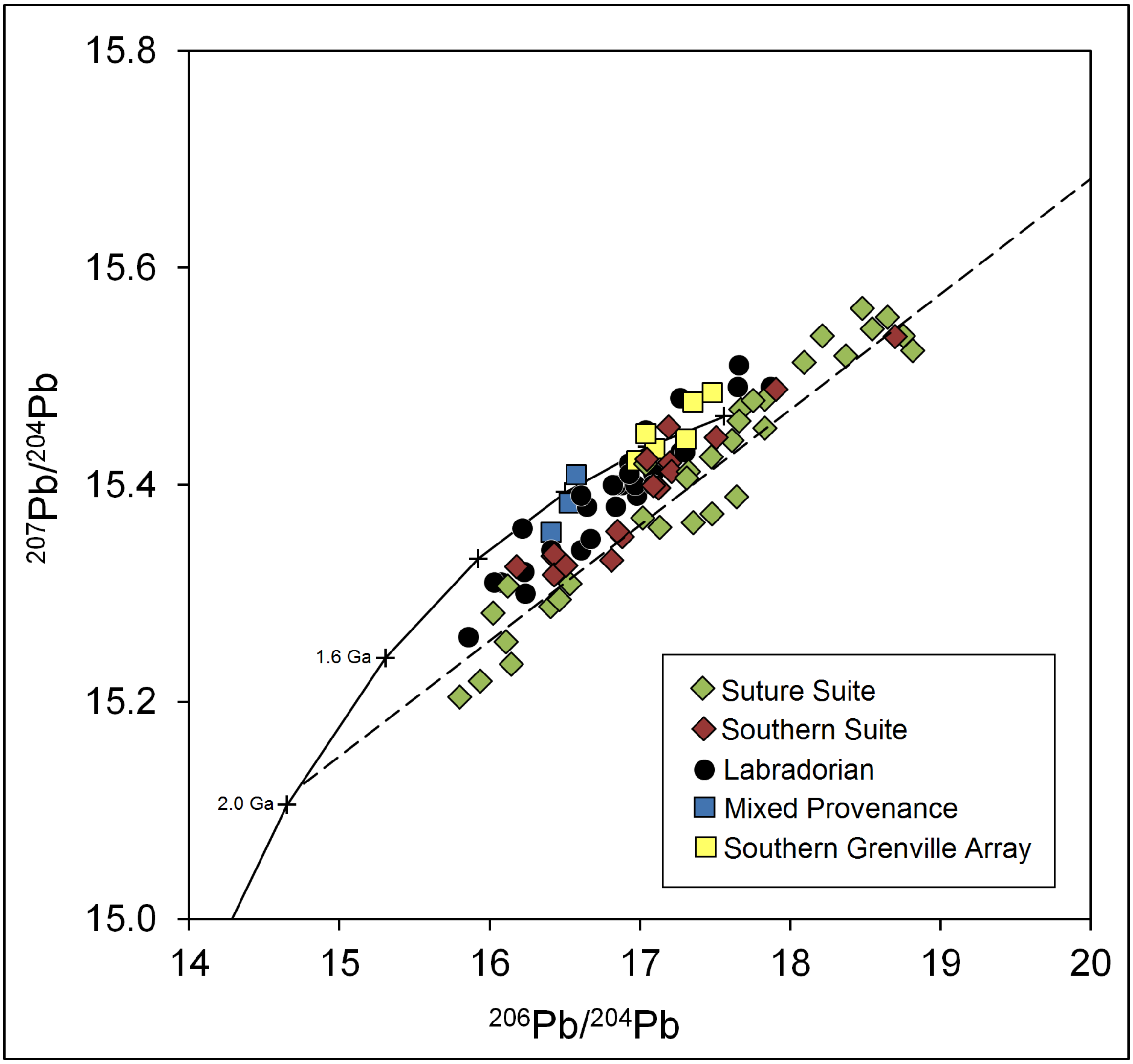

Fig. 3.6. Pb-Pb isochron diagram showing published Pb data from the Labradorian array (Loewy et al., 2003) and Southern Grenville Array (DeWolf and Mezger, 1994) plotted alongside samples from DeWolf and Mezger (1994) of mixed provenance and Proterozoic Pb data from the suture suite and southern suite. Pb data plotted against the 1.74 Ga reference line from Fig. 3.4. Axes adjusted relative to Figs. 3.4 and 3.5.

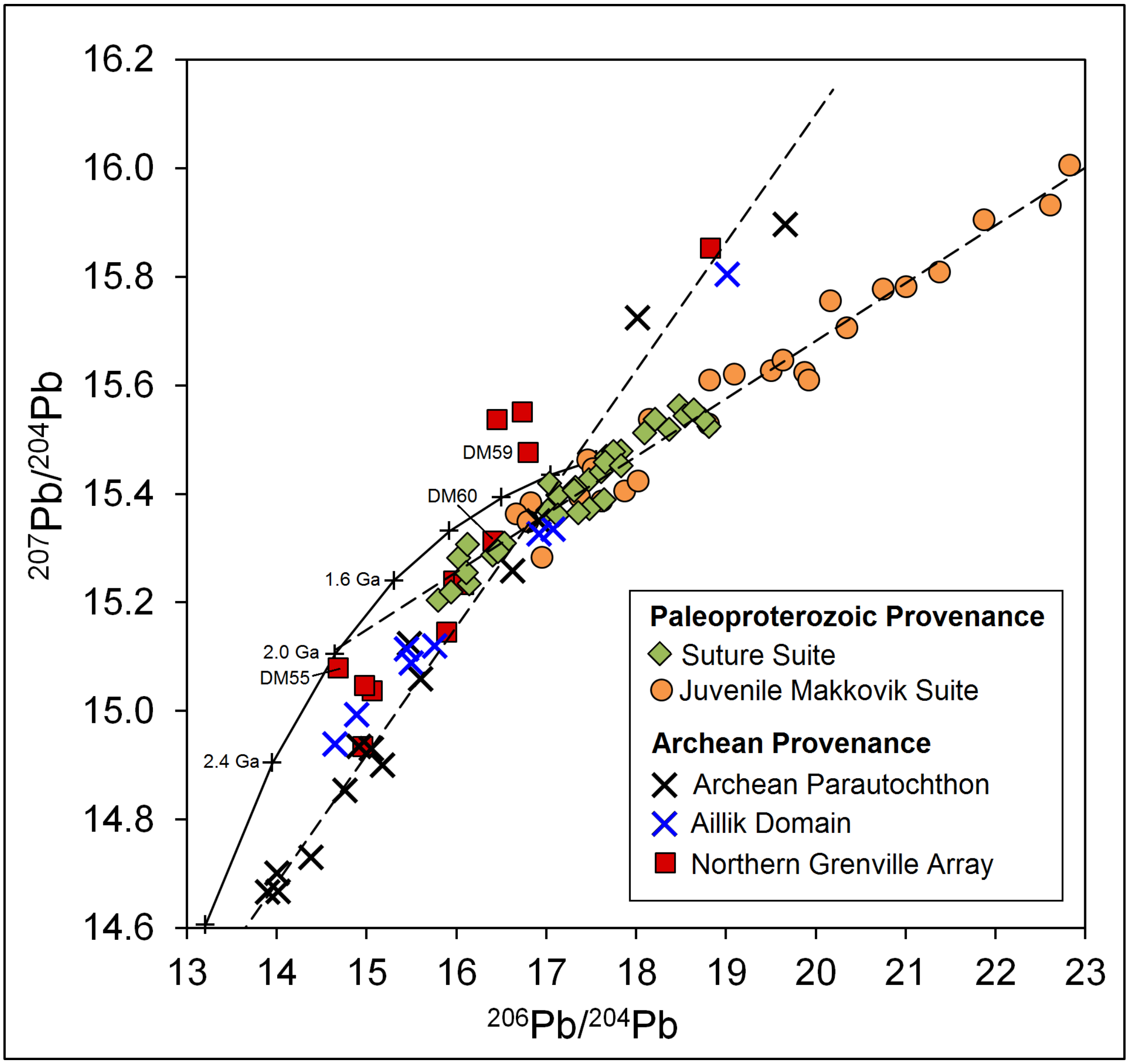

Fig. 3.7. Pb-Pb isochron diagram of published Pb data for orthogneisses from the Archean parautochthon in Ontario (Dickin, 1998b), Northern Grenville Array of DeWolf and Mezger (1994), and galena separates from the Aillik domain in the Makkovik Province (Wilton, 1991) demonstrating Pb arrays that project back to the Archean. Published Pb data is plotted against Paleoproterozoic samples from the suture suite and the juvenile Makkovik Province (Moumblow et al., submitted) for reference. Horizontal axis shifted down relative to Fig. 3.4 and 3.5.

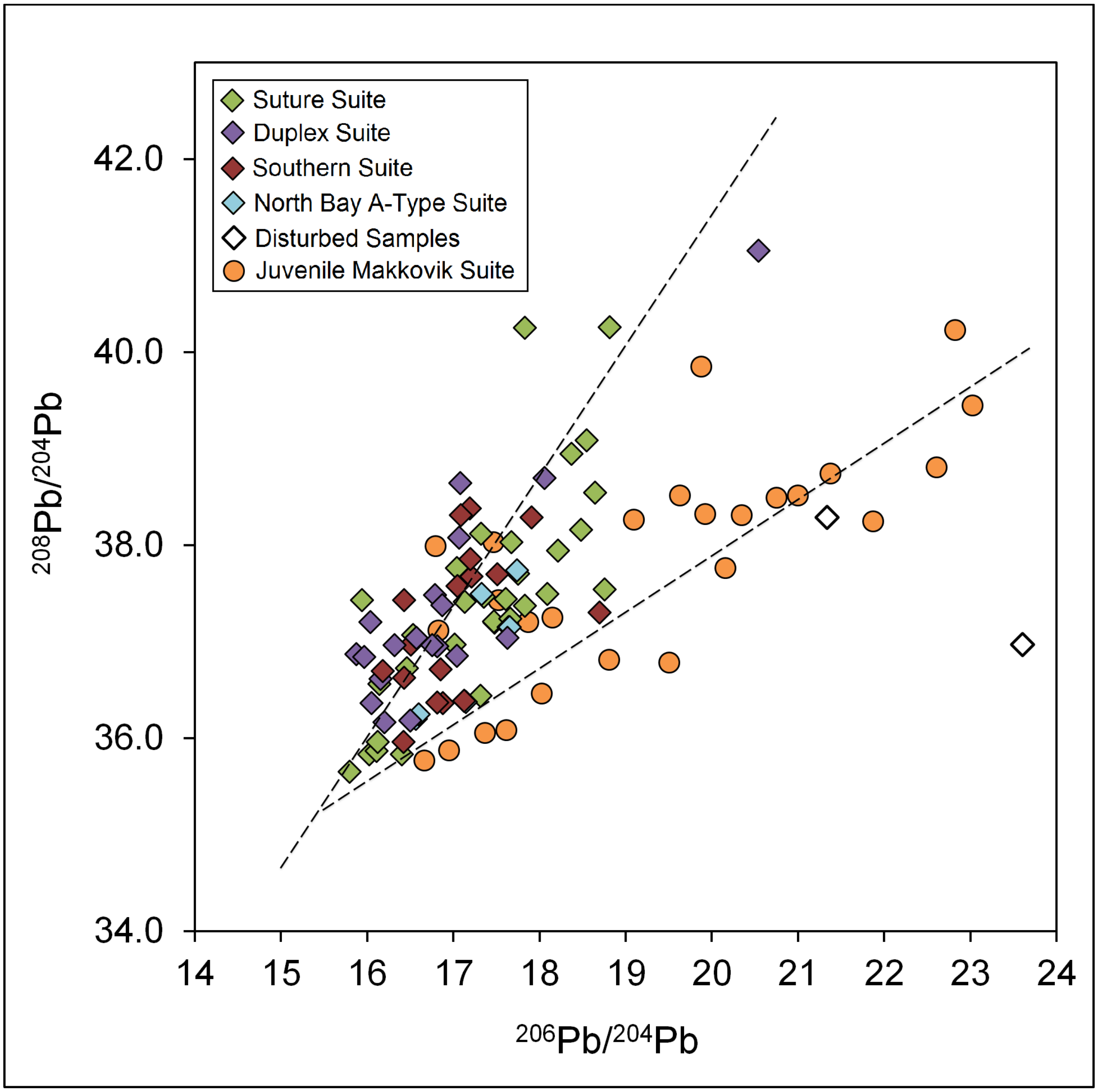

Fig. 3.8. Plot of thorogenic versus uranogenic Pb showing Proterozoic samples from the four SW Grenville suites compared with published data from the juvenile Makkovik Province (Moumblow et al., submitted).

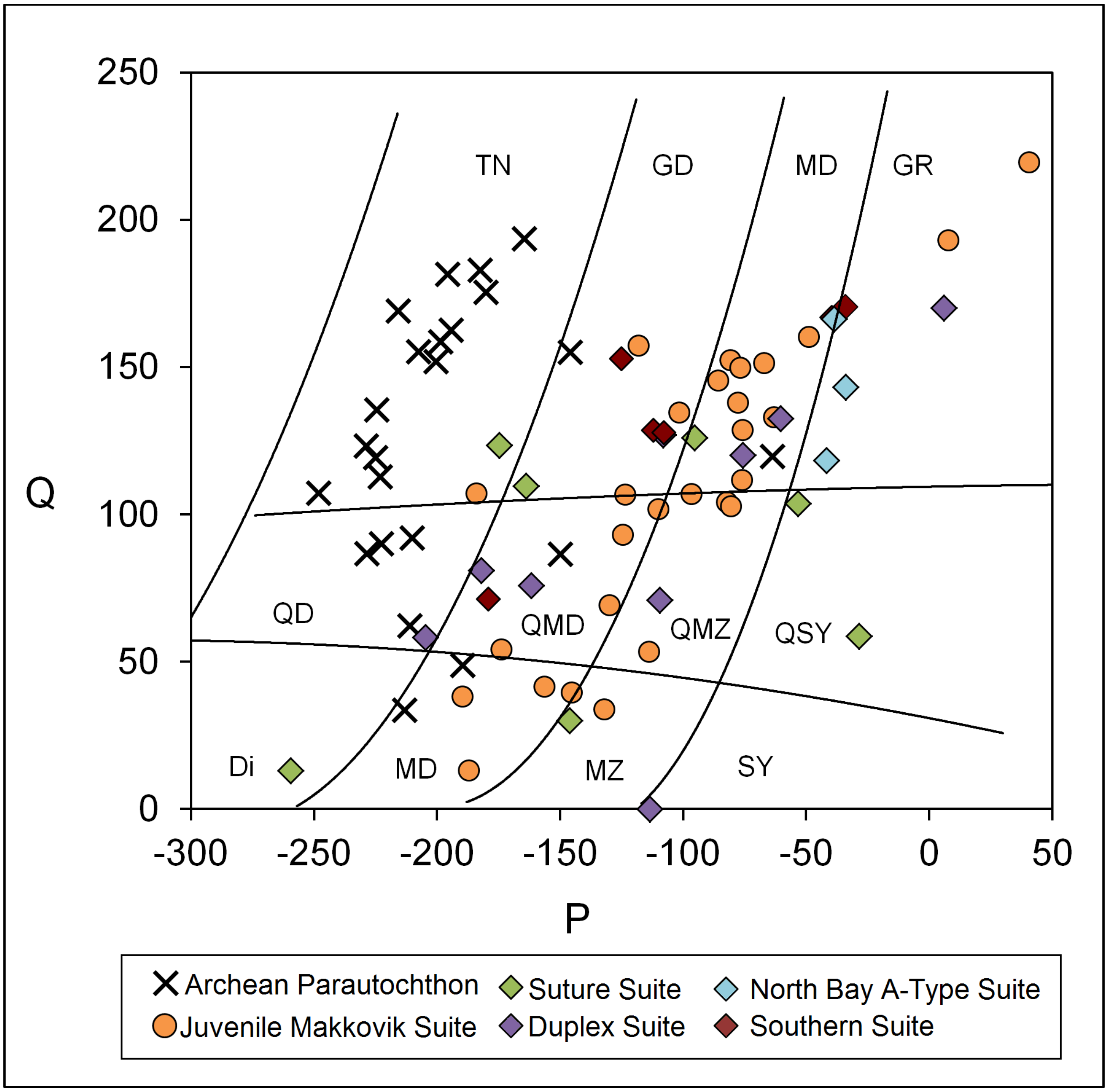

Fig. 3.9. Petrochemical grid of Debon and LeFort (1983) for the chemical Streckeisen classification of granitoid rocks. Q, 1/3 Si-(K+Na+2/3Ca); P, K-(Na+Ca). Tonalite (TN), granodiorite (GD), monzogranite (MG), granite (GR), quartz diorite (QD), quartz monzodiorite (QMD), quartz monzonite (QMZ), quartz syenite (QSY), diorite (DI), monzodiorite (MD), monzonite (MZ), syenite (SY). Published data for the Archean parautochthon (Guo and Dickin, 1996) and juvenile Makkovik Province (Moumblow et al., submitted).

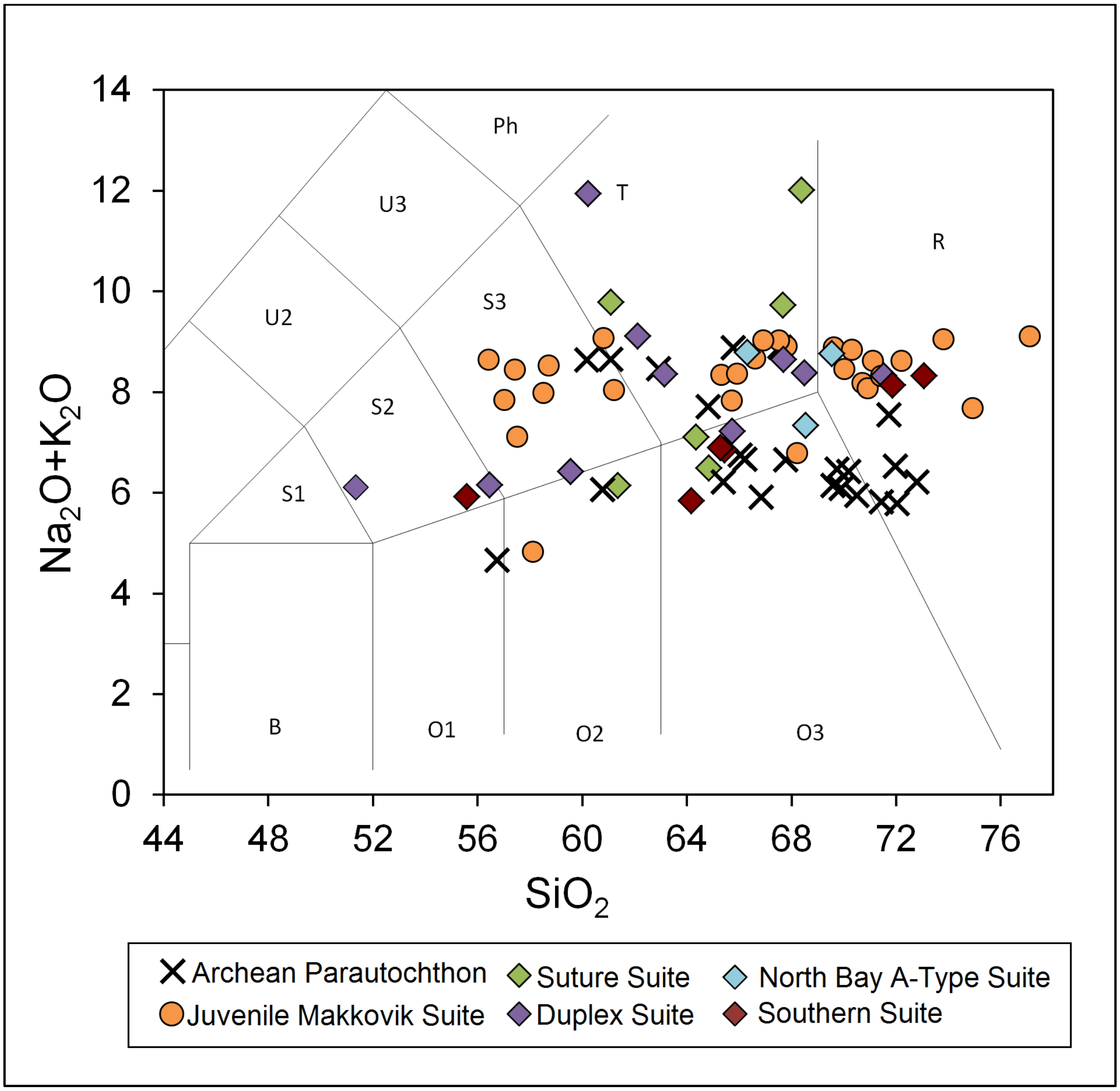

Fig. 3.10. TAS diagram after Le Bas et al. (1986) comparing total alkalis and SiO_2. Silica under saturated (U2, U3); Phonolite (Ph); Silica saturated (S1, S2, S3); Trachyte (T); Basalt (B); Silica over saturated (O1, O2, O3); Rhyolite (R). Published data for the Archean parautochthon (Guo and Dickin, 1996) and juvenile Makkovik Province (Moumblow et al., submitted).

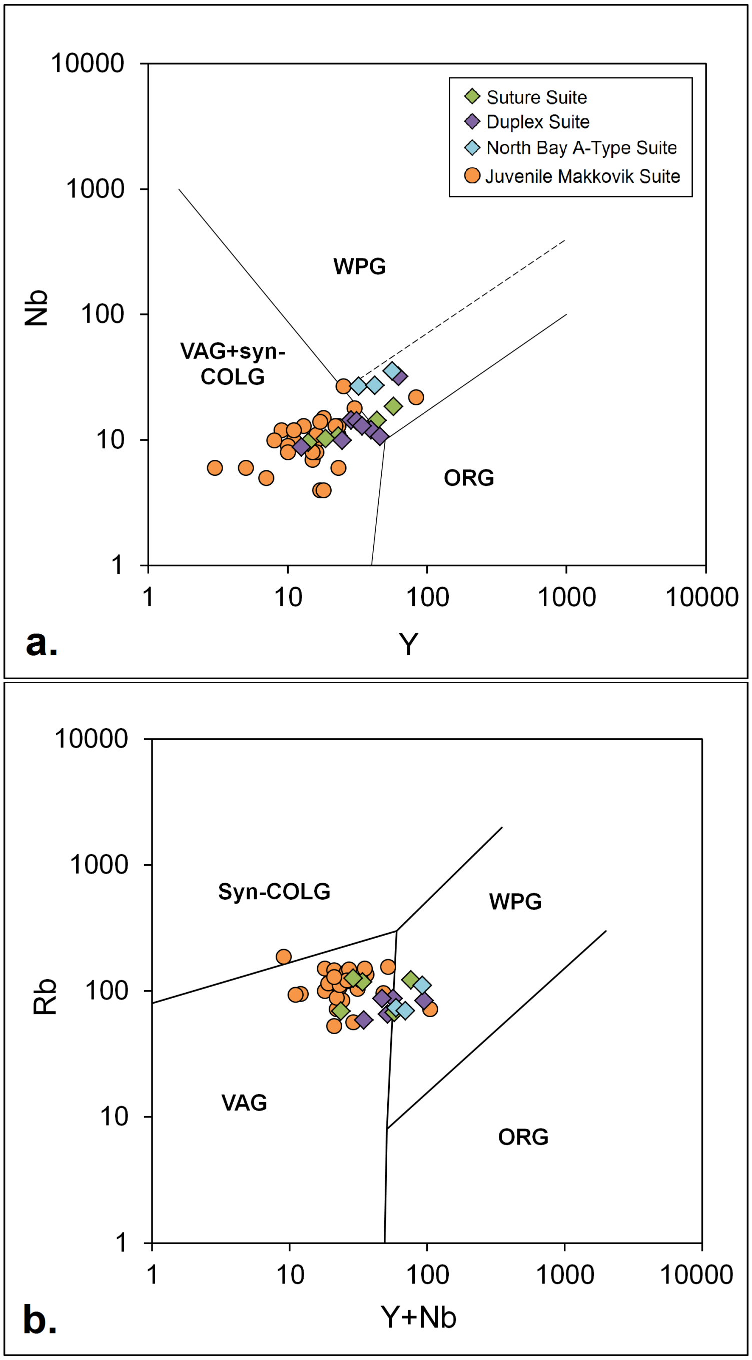

Fig. 3.11. Discrimination diagrams of (a) Y versus Nb and (b) Y+Nb versus Rb after Pearce et al. (1984). Volcanic arc granites (VAG); syn-collisional granites (Syn-COLG); orogenic granites (ORG); within plate granites (WPG). Published data for the juvenile Makkovik Province (Moumblow et al., submitted).

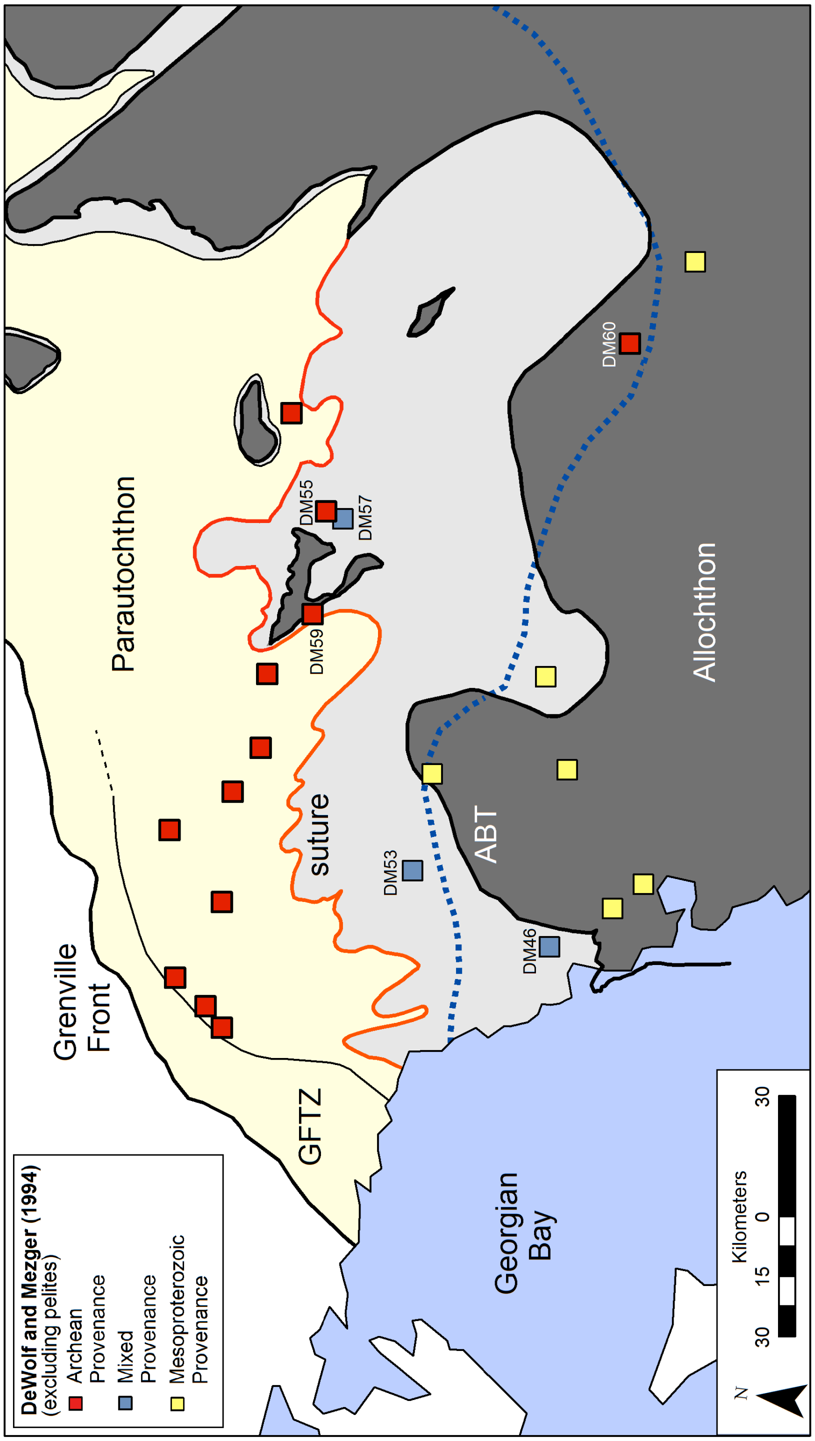

Fig. 3.12. Map of the SW Grenville Province based on the Pb isotope data of DeWolf and Mezger (1994) showing their boundary for the southern limit of Archean crustal material (blue dotted line). Other boundaries after Dickin et al. (2014): Allochthon Boundary Thrust (ABT); Archean parautochthon (yellow shading); Archean-Proterozoic suture (solid red line); Grenville Front Tectonic Zone (GFTZ); Paleoproterozoic parautochthon (light grey shading).

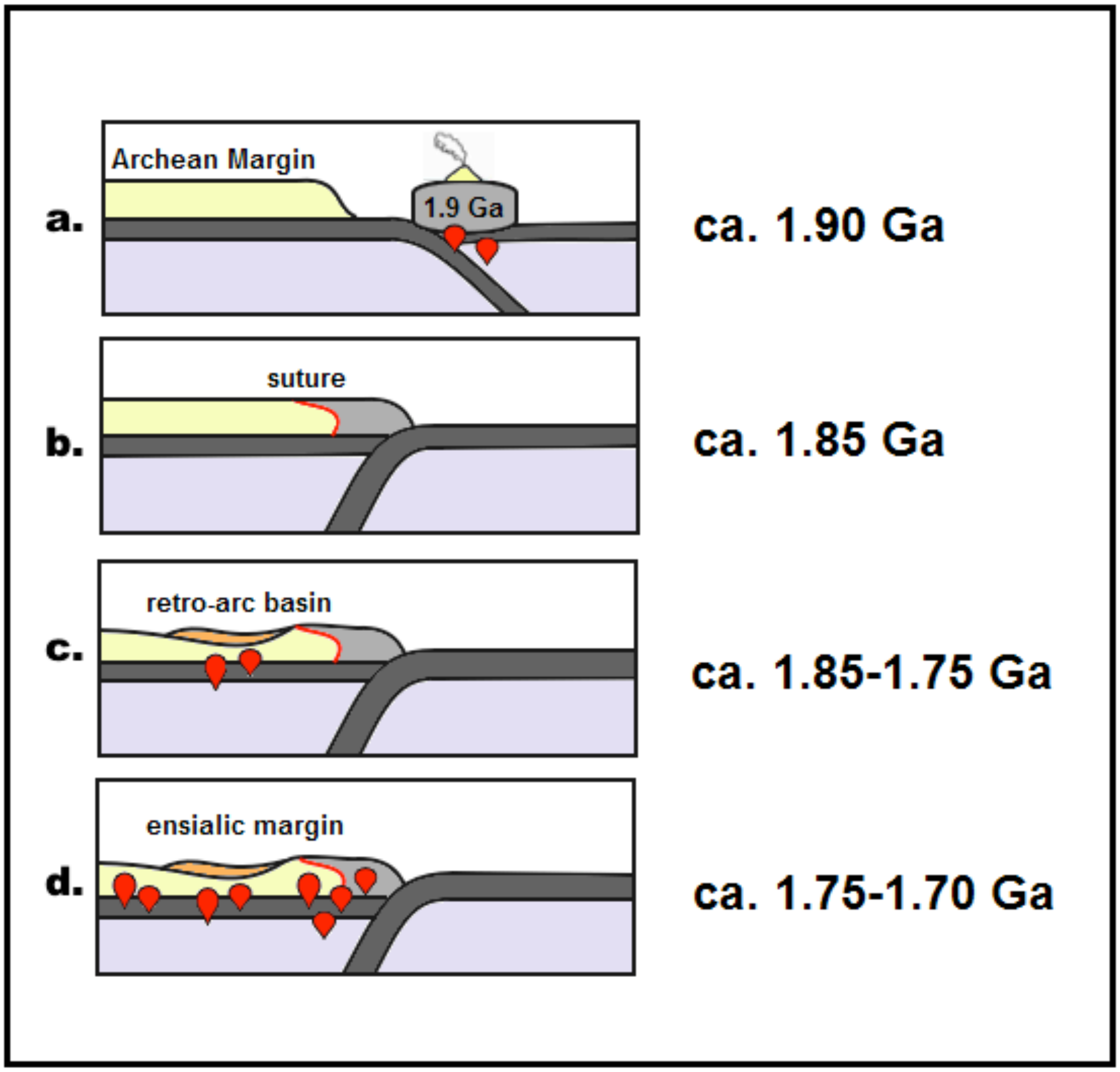

Fig. 3.13. Proposed model for the Paleoproterozoic evolution of the SW Grenville Province based on the interpretation of Dickin and McNutt (1990).

3.9. Tables

Table 3.1. Pb isotope data for samples from the SW Grenville Paleoproterozoic parautochthon.

	Locational Information								
Sample ID	**UTM N NAD 83**	**UTM E NAD 83**	**Source**	**$^{206}Pb/^{204}Pb$**	**$^{207}Pb/^{204}Pb$**	**$^{208}Pb/^{204}Pb$**	**T_{DM} (Ga)**	**Q**	**P**
Suture Suite									
1 GF63 *°	5089600	532600	Dickin, 1998a	18.480	15.562	38.159	1.92	138	-88
2 GF67 *°	5085700	532600	Dickin, 1998a	17.018	15.369	36.967	1.91	124	-176
3 PW5	5092500	528600	Dickin, 1998a	17.039	15.419	37.764	1.91	104	-127
4 KR4	5081600	525400	Dickin, 1998a	18.093	15.513	37.494	1.91	117	-123
5 KR3	5081200	524600	Dickin, 1998a	17.672	15.470	38.033	1.86	146	-158
6 KR11	5080100	517400	Dickin, 1998a	23.603	15.972	36.967	1.92	182	-190
7 FE11.4	5098200	543600	Dickin, 1998a	17.479	15.373	37.197	2.00	158	-92
8 NV11	5105700	551600	Dickin, 1998a	17.611	15.441	37.439	1.86	62	-252
9 NV25	5105700	554600	Dickin, 1998a	18.645	15.554	38.545	1.86	143	-86
10 NV1	5108500	558100	Dickin, 1998a	17.474	15.426	37.207	1.91	171	-41
11 BO5	5125800	647900	Dickin & Guo, 2001	16.405	15.288	35.831	1.95	195	12
12 BO1	5122600	649200	Dickin & Guo, 2001	16.024	15.282	35.829	1.93	191	24
13 BO2	5119500	652200	Dickin & Guo, 2001	16.108	15.255	35.867	1.95	0	-174
14 TA32 *	5116000	661300	Dickin & Guo, 2001	16.123	15.307	35.963	1.93	30	-146
15 MT88	5126700	657800	Dickin & Guo, 2001	18.544	15.544	39.084	1.86	118	-115
16 MT2 *°	5130300	674000	Dickin & Guo, 2001	18.212	15.537	37.941	1.88	109	-196
17 MT55	5132100	676100	Dickin & Guo, 2001	17.833	15.479	40.252	1.86	135	-213
18 TA3 *°	5129300	689900	Dickin & Guo, 2001	17.130	15.361	37.413	1.94	104	-54
19 MT71	5127600	695500	Dickin & Guo, 2001	16.534	15.309	37.070	1.94	166	-188
20 MT68	5128500	700900	Dickin & Guo, 2001	16.143	15.235	36.562	1.93	79	-153
21 MT5 *	5125700	705500	Dickin & Guo, 2001	15.800	15.205	35.651	1.92	12	-260
22 TA21 *°	5130800	706700	Dickin & Guo, 2001	15.938	15.219	37.431	1.92	91	-63
23 MT65	5127800	711800	Dickin & Guo, 2001	18.814	15.524	40.256	1.88	173	-177
24 BO8	5136500	644300	Dickin & McNutt, 2003	18.370	15.519	38.948	1.88		
25 BO85	5124500	621900	Dickin & McNutt, 2003	17.643	15.389	37.149	1.89		
26 BO23	5120500	626600	Dickin & McNutt, 2003	17.357	15.365	37.462	1.88		
27 BO 34	5129800	632500	Dickin & McNutt, 2003	17.323	15.412	38.119	1.88		
28 BO43	5124300	631700	Dickin & McNutt, 2003	17.831	15.452	37.373	1.95		
29 BO70	5131500	620600	Dickin & McNutt, 2003	17.658	15.459	37.237	1.92		
30 PO12	5112160	632250	Moore & Dickin, 2011	17.314	15.406	36.439	1.98		

Published major element (*) and trace element (o) data used in Figs. 3.10 and 3.11.

Table 3.1. Continued

	Locational Information								
Sample ID	UTM N NAD 83	UTM E NAD 83	Source	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	T_{DM} (Ga)	Q	P
31 NV17	5115400	564000	Moore & Dickin, 2011	18.754	15.537	37.538	1.98		
32 TG14	5127330	678812	Moore & Dickin, 2011	17.752	15.478	37.705	1.90		
33 TG13	5121531	692799	Moore & Dickin, 2011	16.464	15.294	36.723	1.91		
Duplex Suite									
34 LV2 *°	5169500	393500	Guo & Dickin, 1996	16.037	15.254	37.201	1.98	76	-162
35 LV3 *°	5169100	376100	Guo & Dickin, 1996	16.158	15.246	36.615	1.93	58	-204
36 MAW6 *°	5153000	387700	Guo & Dickin, 1996	16.817	15.346	36.951	2.00	120	-76
37 MAW8 *°	5154300	382200	Guo & Dickin, 1996	16.322	15.321	36.962	1.87	132	-60
38 Vo163.2 *°	5182100	412200	Guo & Dickin, 1996	16.199	15.338	36.165	1.91	81	-182
39 RB2 *°	5178700	415300	Guo & Dickin, 1996	16.590	15.396	36.479	1.96	130	-104
40 ZP 9	5237800	435000	Guo & Dickin, 1996	20.541	15.717	41.054	1.95	309	-7
41 ZP12 *°	5245400	450600	Guo & Dickin, 1996	15.877	15.195	36.871	1.89	-11	-114
42 MAW9 *	5158000	373700	Guo & Dickin, 1996	17.066	15.404	38.076	1.93	170	6
43 LF2	5176800	709700	Herrell et al., 2006	17.040	15.346	36.854	1.96		
44 LF8	5176700	713400	Herrell et al., 2006	18.057	15.513	38.697	1.99		
45 LF10	5176600	716400	Herrell et al., 2006	16.574	15.262	37.037	1.96		
46 DR25 *°	5144300	719400	Herrell et al., 2006	16.754	15.355	36.962	1.97		
47 LW13	5212227	705282	Moore & Dickin, 2011	16.871	15.360	37.379	1.90		
48 LW12	5211586	705669	Moore & Dickin, 2011	16.052	15.239	36.361	1.96		
49 LW4	5206556	703599	Moore & Dickin, 2011	17.631	15.423	37.041	1.93		
50 MZ7	5164763	319468	Dickin et al., 2012	15.964	15.205	36.840	1.93		
51 LB2	5202110	333410	Dickin et al., 2012	16.790	15.306	37.480	1.95		
52 BR90.9	5190900	426700	unpublished	17.083	15.386	38.641	1.98		
North Bay A-Type Suite									
53 CH28 *°	5133900	617700	Holmden & Dickin, 1995	17.653	15.342	37.150	1.91		
54 NB102	5134200	621000	Holmden & Dickin, 1995	16.598	15.223	36.247	1.89		
55 NB12 *°	5132800	619600	Holmden & Dickin, 1995	17.738	15.327	37.736	1.93		
56 NB6 *°	5133200	616000	Holmden & Dickin, 1995	16.565	15.250	36.201	1.95	118	-180
57 BO69	5132700	618700	Dickin & McNutt, 2003	17.329	15.298	37.495	1.93		
58 BO67	5133300	617700	Dickin & McNutt, 2003	17.146	15.295	36.377	2.04		

Published major element (*) and trace element (°) data used in Figs. 3.10 and 3.11.

Table 3.1. Continued

Sample ID	UTM N NAD 83	UTM E NAD 83	Source	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	T_{DM} (Ga)	Q	P
	Locational Information								
Southern Suite									
59 SB56.7 *	5062650	556670	Dickin et al., 2008	17.126	15.397	36.384	2.00	153	-125
60 KW1	5082600	631700	Moore & Dickin, 2011	16.811	15.331	36.367	1.98		
61 KW3	5085000	641500	Moore & Dickin, 2011	16.180	15.325	36.697	1.96		
62 AG6	5081460	284800	Dickin et al., 2012	17.090	15.399	38.309	1.96		
63 AG1	5093890	718150	Dickin et al., 2012	17.048	15.424	37.575	1.97		
64 AQ6	5100600	694400	Dickin et al., 2014	16.643	15.336	37.430	1.90		
65 AQ4	5105250	696850	Dickin et al., 2014	16.431	15.317	36.625	1.92		
66 AQ10	5109600	700250	Dickin et al., 2014	17.211	15.412	37.677	1.92		
67 AQ42	5100000	702700	Dickin et al., 2014	17.192	15.453	38.382	1.92		
68 SH2*	5030600	547300	Dickin & North, 2015	16.882	15.352	36.361	1.90		
69 SH9A*	5025300	549900	Dickin & North, 2015	16.420	15.334	35.960	1.87		
70 SH12*	5028400	548700	Dickin & North, 2015	17.907	15.488	38.286	1.93		
71 SI11*	5020360	550730	Dickin & North, 2015	17.200	15.420	37.856	1.95		
72 SI12*	5020470	550700	Dickin & North, 2015	17.508	15.444	37.700	1.91		
73 GH9	4961020	610588	unpublished	16.852	15.357	36.710	1.88		
74 GH14	4954406	610035	unpublished	18.699	15.537	37.302	1.87		
75 AQ35	5097900	708700	unpublished	16.508	15.326	36.970	1.94		
Disturbed Samples									
76 KR11	5080100	517400	Dickin, 1998a	23.603	15.972	36.967	1.92	182	-190
77 TG17	5122757	667988	Moore & Dickin, 2011	21.338	15.582	38.287	1.98		
Leached Duplicates									
78 NB6	5133200	616000	Holmden & Dickin, 1995	16.403	15.238	35.734	1.95		
79 ZP12	5245400	450600	Guo & Dickin, 1996	15.833	15.209	35.891	1.89		
80 BO2	5119500	652200	Dickin & Guo, 2001	15.821	15.200	35.531	1.95		
81 MT5	5125700	705500	Dickin & Guo, 2001	15.666	15.189	35.394	1.92		
82 BO67	5133300	617700	Dickin & McNutt, 2003	17.298	15.304	35.843	2.04		
83 LW12	5211586	705669	Moore & Dickin, 2011	15.966	15.232	35.661	1.96		
84 MZ7	5164763	319468	Dickin et al., 2012	15.648	15.156	35.686	1.93		

Published major element (*) and trace element (o) data used in Figs. 3.10 and 3.11.

Chapter 4:
Assessing Crustal Burial and Exhumation of the Archean Parautochthon in the SW Grenville Province using Whole-Rock Pb Isotope Analysis

4.1. Introduction

The high mobility of uranium during regional metamorphism typically causes the continental crust to become stratified in U-Pb ratio, as the U-Pb system is strongly susceptible to open system behavior. As a result, uranium is preferentially transported from lower crustal levels into the upper crust relative to Pb (Doe and Zartman, 1979). Over geologic time, the decay of uranium to radiogenic lead leads to variation in the $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios of the crust, creating distinctive unradiogenic and radiogenic signatures in the lower and upper crust respectively.

The above scenario has been documented in several Archean high-grade gneiss terranes where early crustal stratification in U-Pb ratios has 1) led to the development of unradiogenic Pb signatures in the crust relative to those generated during younger crustal forming events (e.g., Moorbath and Taylor, 1981), and 2) been used to distinguish lower and upper units of Archean crust of the same age (e.g., Dickin, 1998b).

In situations where the original imprint of Archean metamorphism has been preserved, mineral geothermobarometry can be used as a means of estimating the original burial depth and subsequent uplift of the crust. However, these P-T estimates can often be overprinted in regions that have been subjected to a younger high-grade metamorphic event, erasing much of the original mineral assemblage of the rock. Since uranium depletion tends to be irreversible on a whole-rock scale, Pb isotope ratios can be used to look past this younger metamorphic imprint and map the exhumation and uplift history in areas where conventional geothermobarometry information is lacking.

In a case study from the SW Grenville Province (Dickin, 1998b), whole-rock Pb isotope data were collected for Grenville gneisses in order to investigate the burial-uplift history of Archean basement. Archean crustal blocks in the Grenville Province were extracted from the mantle and subjected to metamorphic stratification (up to granulite grade) during the Kenoran orogeny (2.7 to 2.6 Ga). During the later Grenville orogeny (1.2 to 1.0 Ga), the crust was subjected to secondary metamorphism, again taking metamorphic grade as high as granulite facies. However, since Pb isotope signatures are resistant to metamorphic overprinting, the unradiogenic Pb signatures developed during the Kenoran orogeny would be largely resistant to younger Grenvillian metamorphism and hence preserved in the deep crust. Similarly, any upper crustal units that were enriched in uranium during the Kenoran orogeny would develop such a radiogenic Pb signature that later Grenvillian metamorphism would not be able to overprint this signature. Based on these assumptions, Dickin (1998b) demonstrated the reliability of using Pb isotope ratios as a tool for mapping Archean crustal burial depths and subsequent Proterozoic uplift history in highly metamorphosed orogenic belts such as the Grenville Province.

4.2. Geologic Context

The Grenville Province represents the youngest major division of the Canadian Shield and is characterized by the exhumed remains of the 1.2-1.0 Ga Grenville Orogenic

Cycle (Rivers et al., 1989; 2002). Structural divisions within the Grenville Province follow the nomenclature of Rivers et al. (1989), which represent the final stages in crustal evolution that transported pre-Grenvillian crustal terranes to the northwest over the Archean craton. The Grenville Front marks the northern limit of this widespread thrusting, which separates rocks that were metamorphosed and tectonized during Grenvillian orogenesis from Archean rocks of the Superior Province.

South of the Grenville Front, the Grenville Province comprises of two major longitudinal belts: the parautochthon and allochthon (Rivers et al., 1989). The parautochthon represents rocks of Archean-Paleoproterozoic ages that were highly metamorphosed and tectonized during the Rigolet episode of the Grenville orogeny (River et al., 2002), but remained relatively in situ relative to the Laurentian foreland. Running sub-parallel to the Grenville Front, the Allochthon Boundary Thrust (ABT) is a major Ottawan age thrust zone which separates the parautochthon to the northwest from the overriding Mesoproterozoic allochthonous terranes to the southeast (Fig. 4.1).

Rivers et al. (1989) originally mapped the ABT along much of its length based on a sharp break in aeromagnetic signatures in the crust. The Archean foreland displays ‘quiet’ signatures that reflect its simple geologic history, while ‘noisy’ signatures in the allochthon reflect a more complex geologic history during the Proterozoic. However, use of this method proved to be more difficult in defining the ABT in Ontario and western Quebec, where Rivers et al. (1989) attributed the lack of a clear magnetic boundary to extensive younger plutonism that contributed to a noisy magnetic signature on both sides of the boundary.

As a result, several different methods have been used to infer the location of the ABT in the SW Grenville Province. Various authors attempted to map the non-overlapping extents of different metabasic rock suites on either side of the boundary (e.g., Culshaw et al., 1994; Ketchum and Davison, 2000), as well as geologic mapping of lithological observations that are characteristic of large-scale thrust zones (e.g., Currie and van Breemen, 1996; Indares and Dunning, 1997; van Breemen and Currie, 2002). However, the reliability of these methods is inhibited in areas where the boundary juxtaposes areas composed only of high-grade grey gneiss, particularly in western Quebec. This has led to various interpretations for the location of the ABT (detailed discussion in Moore and Dickin, 2011).

An alternate method for mapping the ABT was proposed by Dickin (2000) based on distinct crustal formation ages of the grey gneisses on either side of the boundary determined by Nd isotope analysis. When calculated with the depleted mantle model of DePaolo (1981), Nd model ages accurately estimate the time at which the crustal precursor of the sample was extracted from the upper mantle and incorporated into the crust (discussed in detail by Dickin, 2000; Dickin et al., 2008). The parautochthon consists of Archean to Paleoproterozoic aged crust with Nd model ages > 1.8 Ga. This is in contrast to the Mesoproterozoic aged crust of the allochthon with Nd model ages < 1.8 Ga. Consequently, this break in Nd model ages, when coupled with surficial geologic evidence, has assisted in the detailed mapping of the ABT across Ontario (e.g., Dickin et al., 2000; Dickin et al., 2008) and western Quebec (e.g., Guo and Dickin, 1996; Moore and Dickin, 2011; Dickin et al., 2012).

In Ontario, the ABT runs sub-parallel to the Archean-Proterozoic suture that defines the southern limit of the Archean foreland (red line, Fig. 4.1). Whole-rock Pb isotope ratios from Archean gneisses near the Archean-Proterozoic suture in the French River area (Dickin, 1998b) provide constraints for the nature of the collision that gave rise to the suture. The preservation of radiogenic upper crustal Pb signatures north of the suture suggests that the continental margin was over-ridden by an accreted Paleoproterozoic arc, as previously modeled by Dickin and McNutt (1989; 1990) and Dickin (1998a). Dickin (1998b) argued that the accretion of a Paleoproterozoic arc following a south-dipping subduction would create a depression in the cratonic margin, and thus preserve Archean upper crustal material north of the suture. This interpretation was adapted from the numerical modeling of the Alpine collision by Beaumont et al. (1996).

In western Quebec the allochthon extends northwards over the Archean parautochthon, defining two major nappes termed the Lac Watson and Lac Dumoine terranes (Indares and Martignole, 1990; Indares and Dunning, 1997; Fig. 4.1). These terranes have been recognized to consist of an upper deck that is largely allochthonous, and a lower deck comprising of a slice of parautochthonous crust that was entrained onto the bottom of the allochthon. This structure is in agreement with Nd model ages that show a segment of Paleoproterozoic crust sandwiched in between Archean and Mesoproterozoic aged crust (Dickin et al., 2012). This suggests that the Archean-Proterozoic boundary in western Quebec forms a tectonic duplex that closely follows the complex surface trace of the ABT (Fig. 4.1).

If the Archean-Proterozoic boundary in western Quebec represents a Grenvillian thrust zone rather than a pre-Grenvillian suture, the Pb isotope ratios from Archean gneisses adjacent to the ABT should demonstrate unradiogenic signatures consistent with the exhumation of deeply buried crust rather than radiogenic Pb signatures preserved adjacent to the suture. Hence, the objective of this study was to determine the Pb isotope signatures of Archean gneisses from near the Archean-Proterozoic boundary in the SW Grenville Province and use it as a method for better defining the uplift-burial history of the crust, and in turn the tectonic evolution of the boundary itself.

4.3. Sample Selection and Petrology

Since the objective of this study was to determine the burial-uplift history of the Archean parautochthon using crustal Pb isotope stratification, selected samples were screened petrologically and geochemically to minimize interfering signals from processes other than Kenoran metamorphism. Sampling in the field was limited to 'I-type' granitoid orthogneisses showing minimal degrees of migmatization. When possible, mafic gneisses were excluded due to the increased chance of a younger mantle-derived component in these rock types. Metasedimentary gneisses were excluded from the main sample suite, as these may represent a younger depositional event. However, a few selected metasedimentary gneisses (quartzites) from the Mattawa region were analyzed because these rocks were deposited in a foreland basin on the Archean basement and are therefore a feature of regional interest (Table 4.1).

Where major element data were available, samples were characterized using the petrochemical Streckeisen grid of Debon and LeFort (1983). Therefore, these samples were preferentially selected for analysis. Tonalitic and granodioritic gneisses are believed to represent the best examples of primitive arc crust (which was later assembled to form the continents). For this study, these rocks are attributed to the accretion of oceanic arc fragments during the Kenoran orogeny. Most samples plot within the tonalite and granodiorite fields with smaller amounts of quartz diorite and monzodiorite (Fig. 4.2). A few samples with more crustal K-feldspar were analyzed, based on their location, but they were not analyzed for major elements. These more granitic rocks reflect a more complex geologic evolution, but usually still preserve the Pb isotope signatures developed during Kenoran metamorphism and therefore are still reliable for this study.

All samples are believed to be orthogneisses, but additional screening through Nd isotope analysis was used to check for Archean crustal formation ages. Since no direct correlation was identified between the $^{206}Pb/^{204}Pb$ ratios and respective Q (quartz) and P (plagioclase vs. K-feldspar) indices, Archean crustal formation ages can be used to better indicate either an Archean formation age or a rock that incorporated a younger crustal component. Samples with pristine Archean models ages (T_{DM} >2.5Ga) were selected to avoid sampling younger plutons that were emplaced in Archean crust and incorporate a younger Nd crustal component (T_{DM} < 2.5Ga).

Where no major element data were available, the Nd content was used to further test for samples that represent a pristine Archean crystallization age formed through a juvenile crust-forming event (< 40ppm) versus a crustally-derived anatectic granitoid formed through later re-melting of Archean crust (< 60ppm; Dickin and McNutt, 1990).

In this study, several samples were analyzed with slightly higher Nd contents, likely representing re-melted crust with a partially disturbed Pb isotope signature (e.g., BR9, GF6, MZ7, NB9, and SF9, Table 4.1). However, these samples have been retained as they may still provide an approximate signature of the crustal precursor as shown by Dickin (1998b).

4.4. Analytical Techniques

All Pb isotope analysis followed the procedures of Dickin (1998b) using finely powdered whole-rock samples. For comparative purposes, both leached and unleached samples were used in this study. Samples that were leached were placed in warm 6 M HCl overnight in order to remove sulfide phases that may contain remobilized Pb. This process may also leach radiogenic Pb from U-rich minerals such as biotite. Pb extraction followed standard techniques, using Savillex 'bomb' dissolution and anion exchange in HBr. Samples were loaded with silica gel and phosphoric acid onto single Re filaments and analyzed on a VG 354 mass spectrometer at McMaster University. Average within-run precision on samples was .02% (1σ) with the reproducibility of $^{207}Pb/^{204}Pb$ estimated at 0.1% (2σ). All data was fractionation corrected based on frequent analysis of NBS 981(average 0.10-0.15% per amu).

4.5. Pb-Pb Isochron

Whole-rock Pb isotope data were determined for 84 Archean gneisses from across the SW Grenville Province in Ontario and western Quebec and are presented in Table 4.1. When plotted on the Pb-Pb isochron diagram in Fig. 4.3, both leached samples and unleached (closed and open circles respectively) define an array colinear with published Pb data for the Levack gneisses near Sudbury and Grenvillian gneisses from the parautochthon in Ontario (Dickin, 1998b). Several of the unleached samples were replicated using the leaching procedure to test for any variations between the two methods. However, the replicated leached samples are barely outside analytical error of their unleached counterparts and fall along the main Archean array (black circles, Fig. 4.3).

Overall, the slope age of the leached and unleached arrays assuming a single-stage Pb model for each sample are ca. 2.93 Ga and 2.79 Ga respectively. A difference in age between the two arrays is attributed to younger reworking during Grenvillian orogenesis, as remobilized Pb was not removed from unleached samples. On the other hand, the intersection of the regression lines for both arrays merge at the single-stage Pb mantle growth curve ($\mu = 7.9$), yielding a Pb model age of ca. 2.8 Ga. This is in close agreement with the average 2.75 Ga T_{DM} model age of the samples (Dickin, 2000).

Archean gneisses from this study are subdivided into four colour-coded groups based on their $^{206}Pb/^{204}Pb$ ratios. The least radiogenic of these samples are identified as red and orange circles in Fig. 4.3. These unradiogenic Pb signatures are comparable to the least radiogenic of the published Levack and Grenvillian gneisses of Dickin (1998b).

The Levack gneisses near Sudbury sample Archean basement exhumed by impact related crustal rebound (Grieve et al., 1991). Likewise, published Grenvillian Archean gneisses in Ontario represent lateral equivalents of deep Superior basement that were exhumed from mid crustal levels during the Grenville orogeny (Dickin, 1998b). The similarity in unradiogenic Pb signatures between these published suites and the Archean crust sampled in the present study show evidence that the latter represent deeply exhumed Archean basement.

The most radiogenic of the SW Grenville Archean gneisses are identified as blue circles in Fig. 4.3. These radiogenic Pb signatures correspond with the most radiogenic of the published Grenville gneisses in Ontario located immediately south of the Grenville Front, as well as immediately north of the inferred Paleoproterozoic suture in the French River area (blue squares, Dickin, 1998b). The Pb ratios for these published samples are attributed to the preservation and erosion of uranium-rich upper Archean crustal levels. The similarity in radiogenic Pb signatures between the published Grenvillian gneisses and Archean gneisses analyzed in the present study shows that the latter were sampled from areas where Archean upper crustal levels are preserved.

Metasedimentary gneisses north of Mattawa along the Ontario-Quebec border show radiogenic signatures that are comparable to the upper crustal Archean gneisses (blue diamonds, Fig. 4.4). These radiogenic signatures demonstrate derivation from upper crustal sources; however, projection of the regression line back to the growth curve yields a Pb-Pb age of ca. 1.80 Ga. This implies that these samples have a Paleoproterozoic provenance but overlie the Archean foreland.

Archean gneisses from this study show a wide distribution across thorogenic and uranogenic space having significant overlap with the published Levack and Grenvillian gneisses (Fig. 4.5). The scatter in the data implies a substantial decoupling of Th and U, likely during intense magmatism and deformation during younger Proterozoic orogenesis.

4.6. ^{206}Pb/^{204}Pb Interpolation

Several interpolated contour maps of Pb isotope ratios from the Archean parautochthon were generated through ESRI ArcMap 10.2 using the inverse distance weighting (IDW) method (Figs. 4.6, 4.7 and 4.8). Moore and Dickin (2011) previously used the IDW method to successfully map the extent of crustal boundaries in the SW Grenville Province using Nd model ages. For the present study, the spatial distributions of Archean Pb signatures from across the SW Grenville Province were interpolated using ^{206}Pb/^{204}Pb ratios. This was most informative using a power parameter of 4, which gives samples in close proximity to an unsampled location only slightly more influence than those further away. This creates a smooth contour surface that emphasizes regional patterns. These regional patterns provide a spatial visualization of the SW Grenville Province that emphasizes the major areas of unradiogenic crust (e.g., GFTZ in Fig. 4.6, and W, D, B in Fig. 4.7) and radiogenic crust (e.g., R, F in Fig. 4.6, and the Ontario-Quebec border in Fig. 4.8).

4.7. Discussion

Regions of abnormally radiogenic and unradiogenic Pb are of particular interest in the present study because they imply extremes of upper and lower crustal exposure respectively. Therefore, the following discussion will focus on these regions and the tectonic inferences that can be drawn.

Near Georgian Bay in Ontario, the Archean parautochthon shows radiogenic $^{206}Pb/^{204}Pb$ ratios (>18.0) along the Grenville Front that progressively drop to unradiogenic values (<15.0) to the south (Fig. 4.6). Dickin (1998b) attributed the sudden drop of Pb ratios across the GFTZ to the location of a major tectonic ramp in which lateral equivalents of deep superior basement where exhumed. This is consistent with the tectonic model of Rivers et al. (1993) who interpreted the Grenville Front as a deeply eroded basement ramp; however, the major ramp lies farther to the south, where the crust exhibits abnormally unradiogenic Pb signatures (red and orange squares, Fig. 4.6).

Observations by Rivers et al. (1993) suggest that the Grenville Front near River Valley (R, Fig. 4.6) marks the northern limit of a narrow fold-thrust belt, where the GFTZ is located approximately 4km south of the Grenville Front. This is consistent with the preservation of radiogenic signatures along the front that progressively become less radiogenic to the south. In this model, the less radiogenic signatures would constrain the location of major shear, along which deep crustal rocks have been exhumed through a major reverse-sense shear zone (Rivers et al., 1993). However, an increase of shear within the River Valley pluton toward the west suggests the location of major shear steps structurally downwards until it is located along the Grenville Front, as seen on the seismic profile GLIMCE line J (Green et al., 1988). Dickin (1998b) argued that the stepping down of the major shear would help relieve stress created from the curvature of the Grenville Front.

The Parry Sound domain is an erosional klippe lying above the allochthon that was separated from its root during one or multiple thrusting events (Strong, 2015; Fig. 4.6). The emplacement of the Parry Sound domain onto the allochthon would add additional weight onto the underlying rigid Archean parautochthon, causing crustal exhumation during the Rigolet event to be exaggerated directly north of the tectonic outlier. This could account for the isolated pocket of deeply exhumed crust in the GFTZ near Georgian Bay, which becomes less pronounced further to the east.

South of the GFTZ in Ontario, a transition to more radiogenic crustal signatures is apparent approaching the proposed Archean-Proterozoic suture in the French River area (Fig. 4.6). In this case, the Pb data supports a model in which the Archean margin was over-ridden by an accreted Penokean age arc by means of a southeast dipping subduction zone (Dickin and McNutt, 1989; 1990). Following the numerical model by Beaumont et al. (1996), the above scenario would result in a depressed cratonic margin and the preservation of Archean upper crust on the north side of the suture.

Farther east in western Quebec (Fig. 4.7), the Archean-Proterozoic boundary in the Lac Watson (W), Lac Dumoine (D) and Baskatong (B) regions closely follows the ABT and thus has a different origin. Here, the boundary represents a Grenvillian thrust structure that transported Mesoproterozoic allochthonous crust over the Archean parautochthon. Published Nd model ages (Dickin et al., 2012) show a thin sheet of Paleoproterozoic crust sandwiched between Archean and Mesoproterozoic crust (Black circles; Fig. 4.7). This can be interpreted as a tectonic duplex, which was entrained onto the base of the allochthon from parautochthonous Paleoproterozoic basement further south. Near Lac Watson (W, Fig. 4.7), unradiogenic Archean Pb ratios equivalent to the less radiogenic ratios near the GFTZ in Ontario are found along this Archean-Proterozoic duplex adjacent to the ABT (e.g., GA9, GA14). Since the unradiogenic nature of these samples demonstrates deep crustal levels during Kenoran metamorphism, the crust must have been exhumed from the lower crust, likely entrained onto the base of the allochthon and brought back to the surface during uplift after the Grenville orogeny.

In contrast to such areas of deep exhumation, radiogenic signatures north of Mattawa (M) in western Quebec suggest the preservation of Archean upper crust in the parautochthon (blue circles, Fig. 4.8). Likewise, analyzed Grenville metasediments also show radiogenic Pb analogous to metasediments of the Huronian Supergroup analyzed by Dickin (1998b). When superimposed onto the interpolated map, the radiogenic signatures of the metasediments (blue diamonds, Fig. 4.8) show a strong spatial correlation to the radiogenic signatures of the Archean gneisses (blue contouring). This correlation supports a model for a Paleoproterozoic sedimentary basin that was buried under the Grenvillian allochthon and later exhumed back to the present surface, exposing an unconformity over the shallow Archean upper crust (Krogh, 1989). The formation of a back-arc basin in the Archean foreland is consistent with the accretion of a Penokean arc to the Laurentian margin in the SW Grenville Province (Dickin and McNutt, 1989; 1990; Dickin, 1998a).

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4.9. Figures

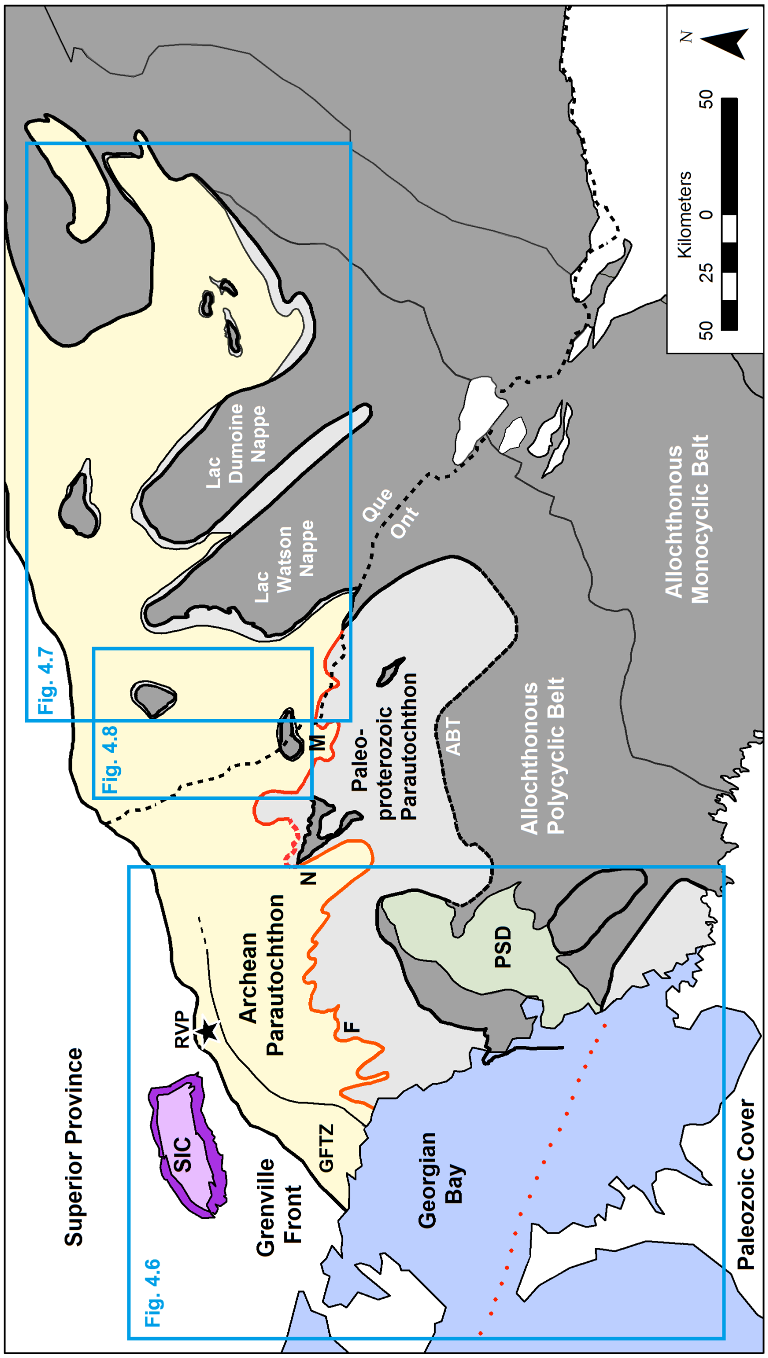

Fig. 4.1. Map of the SW Grenville Province and its major tectonic units. Allochthon Boundary Thrust (ABT); Archean-Proterozoic suture (solid red line); French River (F); GLIMPCE Lithoprobe Line J (dotted red line); Grenville Front Tectonic Zone (GFTZ); Mattawa (M); North Bay (N); Parry Sound domain (PSD); River Valley Pluton (RVP); Sudbury Igneous Complex (SIC). Boundaries after Dickin et al. (2014).

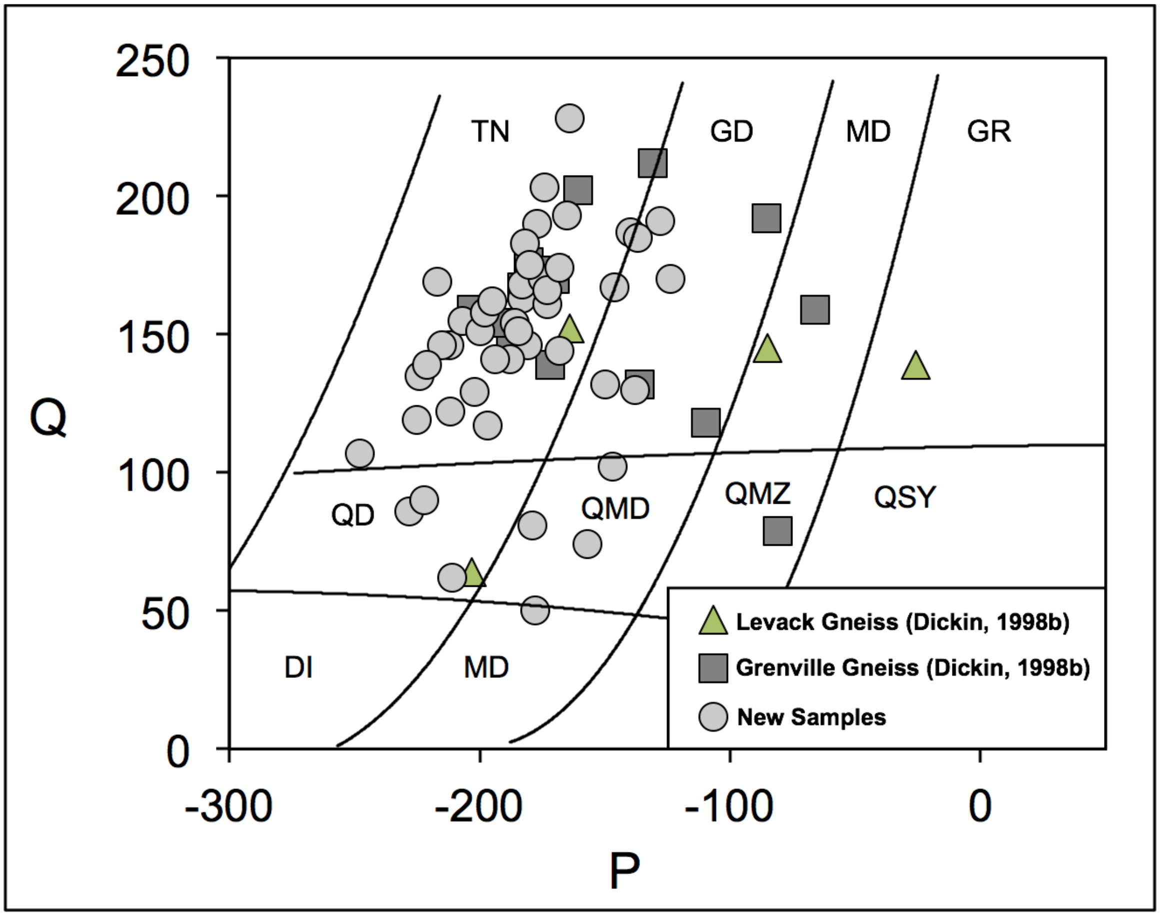

Fig. 4.2. Petrochemical grid of Debon and LeFort (1983) for the chemical Streckeisen classification of granitoid rocks. Q, 1/3 Si-(K+Na+2/3Ca); P, K-(Na+Ca). Tonalite (TN), granodiorite (GD), monzogranite (MG), granite (GR), quartz diorite (QD), quartz monzodiorite (QMD), quartz monzonite (QMZ), quartz syenite (QSY), diorite (DI), monzodiorite (MD). Published data from Dickin (1998b).

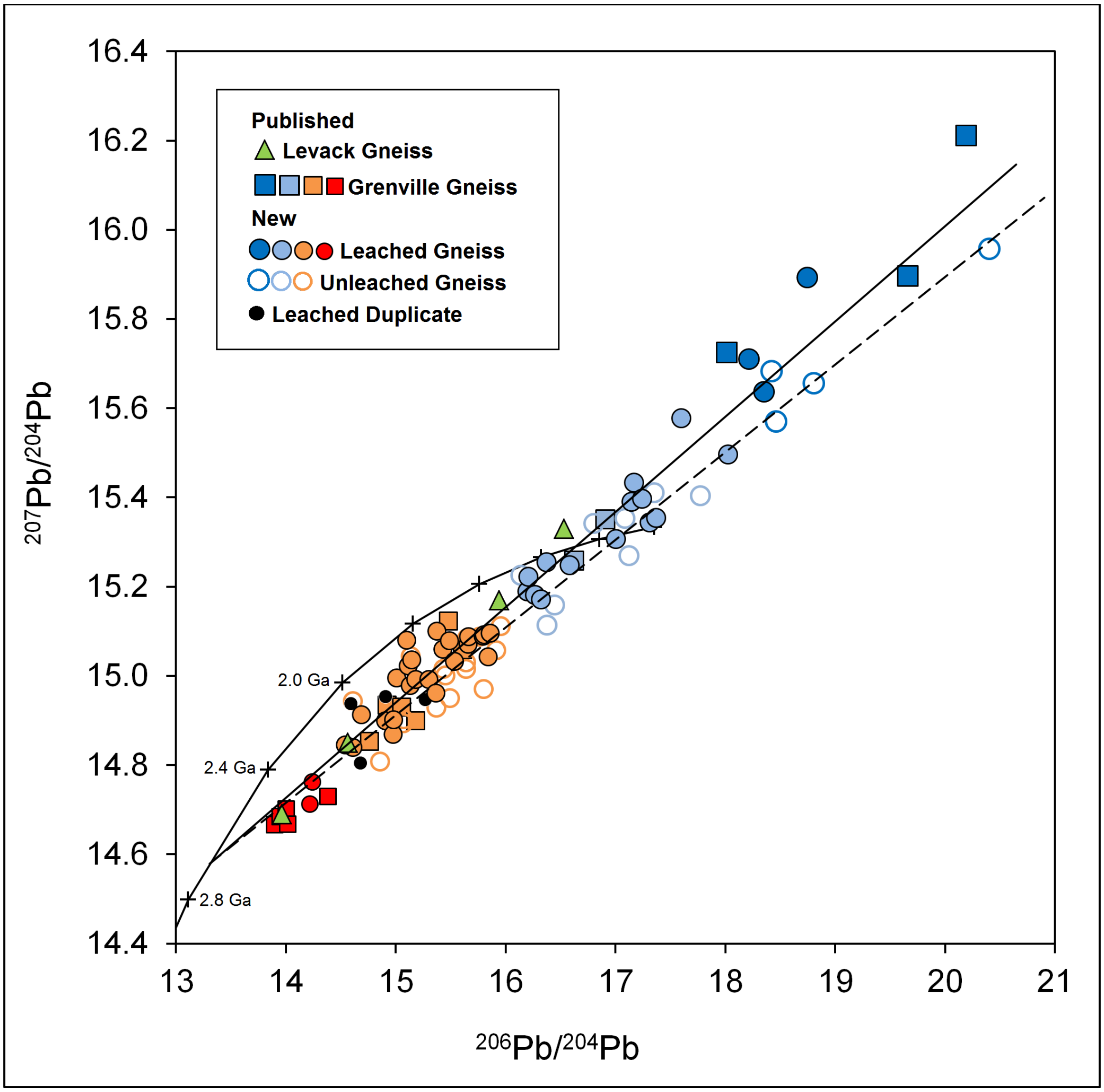

Fig. 4.3. Pb-Pb isochron diagram for leached and unleached Grenvillian Archean gneisses relative to a single stage mantle model growth curve (μ=7.9). Archean gneisses are subdivided into four colour-coded groups based on their $^{206}Pb/^{204}Pb$ ratios: unradiogenic (red) to radiogenic (blue). Leached duplicates of selected unleached samples shown as black circles. Published data from Dickin (1998b).

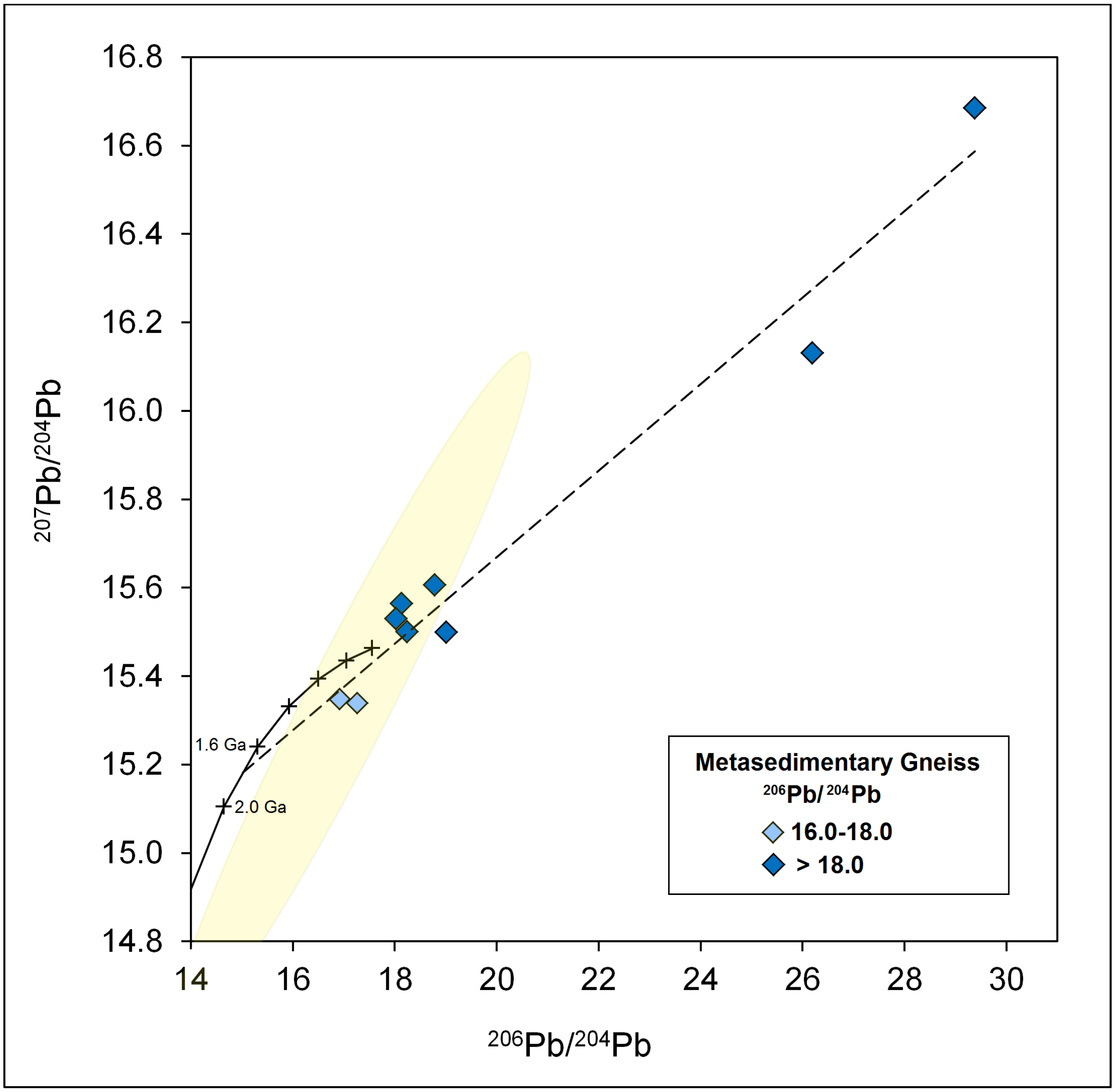

Fig. 4.4. Pb-Pb isochron diagram showing metasedimentary gneisses from the SW Grenville Archean parautochthon. Archean array from Fig. 4.3 denoted as yellow reference zone.

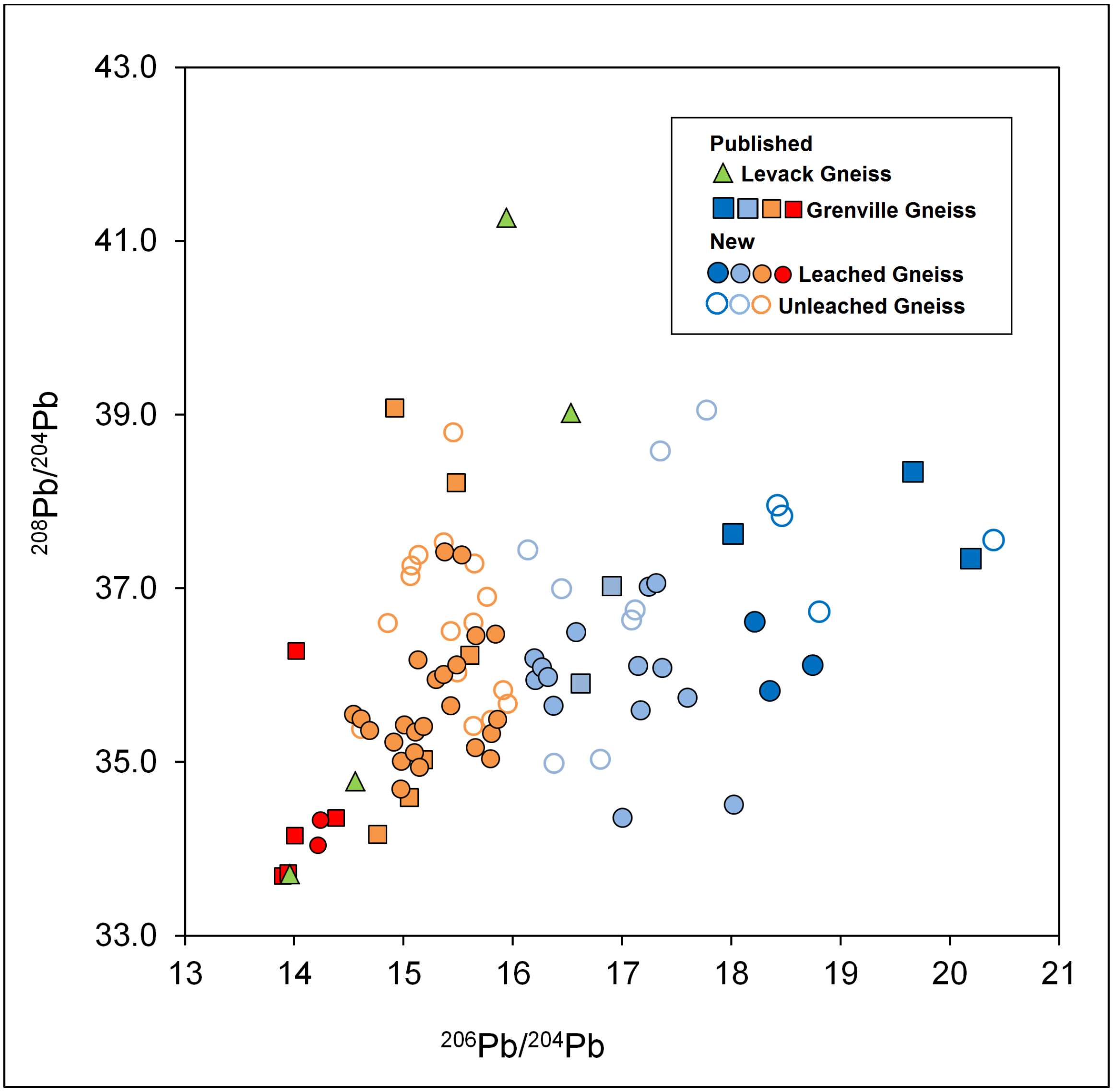

Fig. 4.5. Diagram of thorogenic versus uranogenic Pb for leached and unleached Grenville Archean gneisses. Archean gneisses are subdivided into four colour-coded groups based on their $^{206}Pb/^{204}Pb$ ratios: unradiogenic (red) to radiogenic (blue). Published data from Dickin (1998b).

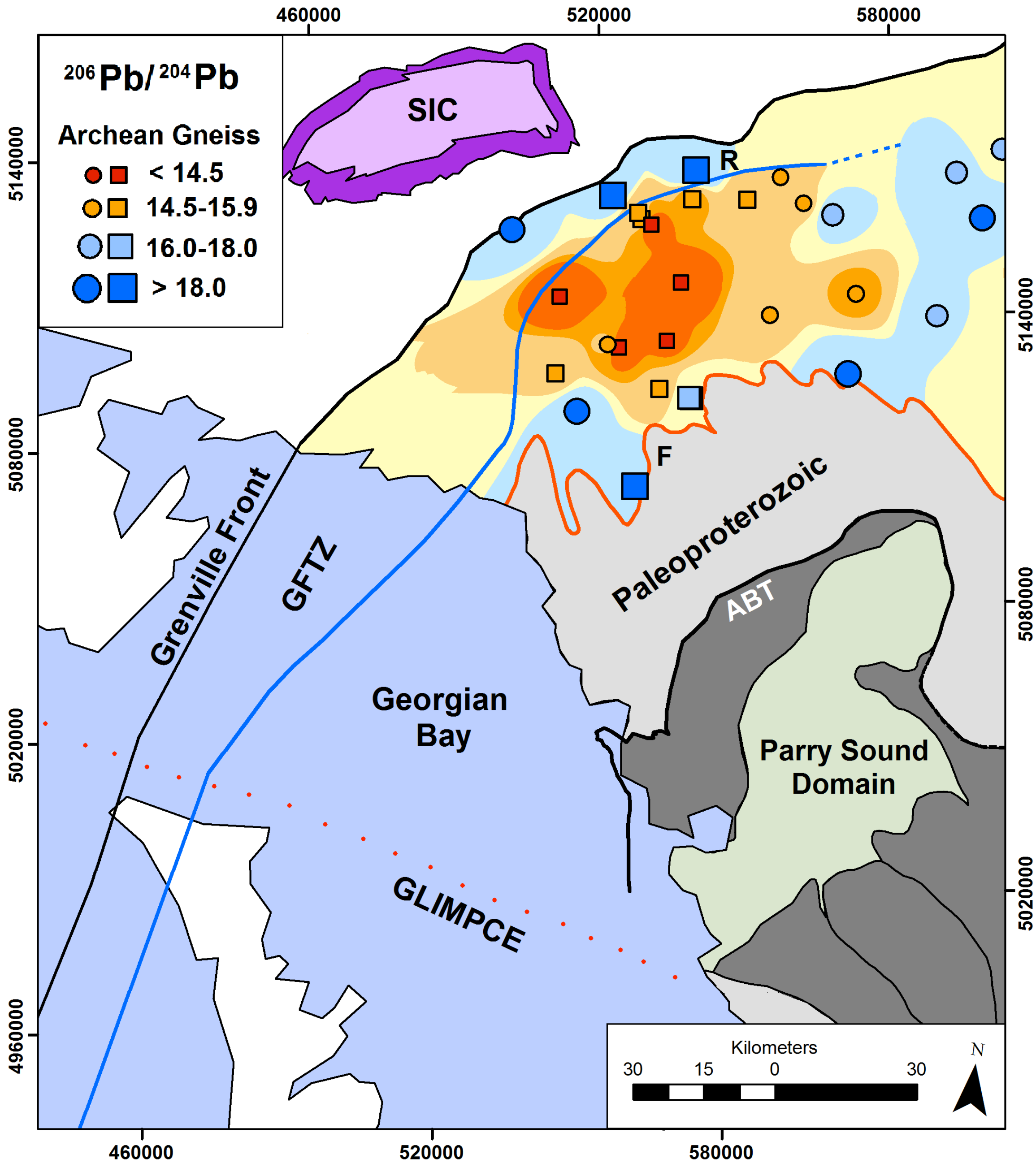

Fig. 4.6. Interpolated $^{206}Pb/^{204}Pb$ inverse distance weighted map of the Georgian Bay area in Ontario. Allochthon Boundary Thrust (ABT); Archean-Proterozoic suture (solid red line); French River (F); Grenville Front Tectonic Zone (GFTZ); River Valley (R); Sudbury Igneous Complex (SIC). Boundaries after Dickin et al. (2014).

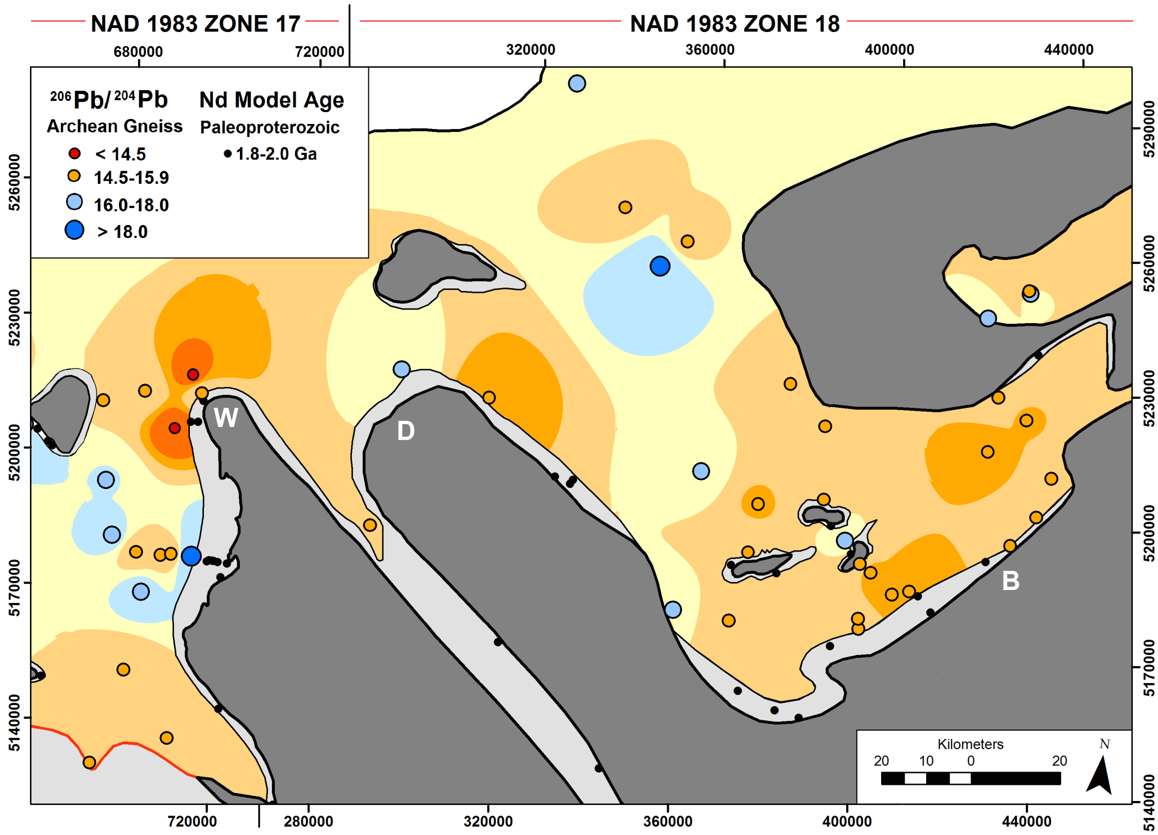

Fig. 4.7. Interpolated $^{206}Pb/^{204}Pb$ inverse distance weighted map of western Quebec with published ca. 1.85-2.0 Ga T_{DM} model ages (black circles, Dickin et al., 2012). Baskatong (B); Lac Dumoine Nappe (D); Lac Watson Nappe (W). Boundaries after Dickin et al. (2014).

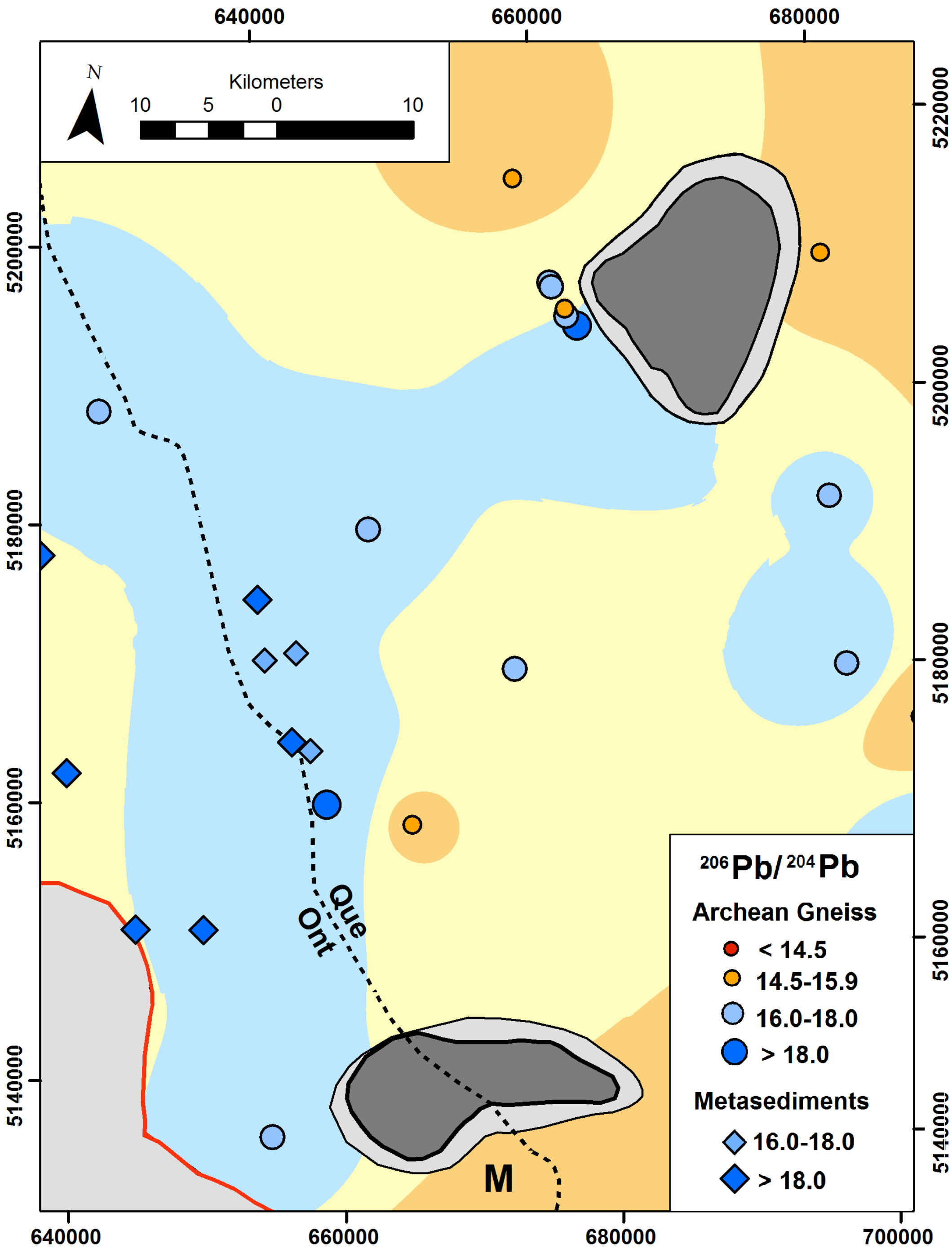

Fig. 4.8. Interpolated $^{206}Pb/^{204}Pb$ inverse distance weighted map near Mattawa (M). Boundaries after Dickin et al. (2014).

4.10. Tables

Table 4.1. Pb isotope data for Archean samples from the SW Grenville parautochthon.

	Locational Information									
Sample ID	**UTM N NAD 83**	**UTM E NAD 83**	**Source**	**$^{206}Pb/^{204}Pb$**	**$^{207}Pb/^{204}Pb$**	**$^{208}Pb/^{204}Pb$**	**T_{DM} (Ga)**	**Nd (ppm)**	**Q**	**P**
Unleached Samples										
1 CH3	5188800	633300	Holmden & Dickin, 1995	17.088	15.353	36.634	2.53	4.06		
2 BR12	5194900	431900	Guo & Dickin, 1996	15.068	14.903	37.269	2.71	10.49	86	-228
3 RB5	5183000	410100	Guo & Dickin, 1996	14.607	14.945	35.382	2.46	6.84	122	-212
4 X886	5218300	388600	Guo & Dickin, 1996	15.490	14.951	36.033	2.72	15.82	135	-224
5 GA4	5208300	683500	Dickin & Guo, 2001	15.910	15.057	35.829	2.57	27.10	74	-157
6 GA8	5211800	692400	Dickin & Guo, 2001	15.365	14.929	37.536	2.64	3.56	228	-164
7 MT4	5128100	692800	Dickin & Guo, 2001	15.134	15.045	37.390	2.72	25.96	144	-168
8 NB46	5163000	654100	Dickin & Guo, 2001	18.806	15.656	36.730	2.79	12.82	190	-177
9 LF1	5177000	708300	Herrell et al., 2006	20.401	15.957	37.558	2.72	24.70		
10 EM9	5173576	607185	Moore & Dickin, 2011	16.381	15.113	34.983	2.82	41.10		
11 LW11	5213234	705066	Moore & Dickin, 2011	15.431	15.016	36.512	2.72	15.90		
12 NP8B	5122100	582350	Moore & Dickin, 2011	18.420	15.683	37.959	2.67	18.40		
13 SF9	5136900	599000	Moore & Dickin, 2011	17.776	15.403	39.047	2.67	69.80		
14 SF3	5138930	581530	Moore & Dickin, 2011	14.854	14.809	36.605	2.68	15.40		
15 TG12	5138483	653850	Moore & Dickin, 2011	17.124	15.269	36.749	2.68	26.30		
16 TG3	5162512	660457	Moore & Dickin, 2011	15.953	15.112	35.674	2.75	25.10		
17 ADKS2	5174900	357800	Dickin et al., 2012	16.448	15.158	36.990	2.67	43.20		
18 BU1	5167430	698390	Dickin et al., 2012	17.354	15.410	38.580	2.80	27.60		
19 MZ20	5188544	288972	Dickin et al., 2012	15.451	15.002	38.801	2.73	73.70		
20 DC9	5188980	373580	Dickin et al., 2014	15.636	15.017	36.608	2.73	18.50		
21 RZ12	5201950	389553	Dickin et al., 2014	15.799	14.971	35.489	2.76	9.60		
22 VO57.4	5251100	349100	Dickin et al., 2014	18.463	15.570	37.838	2.87	20.80		
23 VO6.6	5290300	327400	Dickin et al., 2014	16.804	15.342	35.030	2.84	23.90	167	-146
24 CD32	5245080	423100	unpublished	16.140	15.226	37.442	2.69			
25 DB16	5257055	354768	unpublished	15.760	15.089	36.908	2.72			
26 LP3	5201600	437200	unpublished	15.637	15.031	35.420	2.72			
27 T73.85	5173830	399460	unpublished	15.647	15.085	37.291	2.69			
28 TS76.1	5176100	399200	unpublished	15.063	14.895	37.141	2.73			

Table 4.1. Continued

Sample ID	UTM N NAD 83	UTM E NAD 83	Source	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	T_{DM} (Ga)	Nd (ppm)	Q	P
	Locational Information									
Leached Samples										
29 GF0.8	5141200	508300	Dickin & McNutt, 1989	18.215	15.710	36.614	2.78	41.72		
30 MR23.3	5167300	598500	Dickin & McNutt, 1989	17.245	15.396	37.016	2.72	29.90		
31 WB70	5105700	527500	Dickin & McNutt, 1989	18.025	15.496	34.507	2.60	4.60	163	-183
32 MR35.2	5158700	605300	Holmden & Dickin, 1995	18.353	15.637	35.819	2.72	23.20	161	-173
33 BR9	5210500	439900	Guo & Dickin, 1996	15.532	15.033	37.386	2.69	65.03		
34 GF4	5199900	375000	Guo & Dickin, 1996	14.974	14.869	34.694	2.57	9.17	155	-207
35 GF6	5206200	361800	Guo & Dickin, 1996	16.324	15.171	35.977	2.56	59.30	62	-211
36 LV5	5173500	370400	Guo & Dickin, 1996	15.130	14.979	36.181	2.86	17.95	162	-195
37 RB11	5215400	425300	Guo & Dickin, 1996	14.538	14.846	35.550	2.73	10.83	158	-198
38 RB14	5227700	426700	Guo & Dickin, 1996	15.655	15.071	35.170	2.67	20.94	90	-222
39 RB16	5251300	432200	Guo & Dickin, 1996	16.584	15.248	36.494	2.63	10.75	183	-182
40 RB17	5251900	431800	Guo & Dickin, 1996	15.142	15.037	34.994	2.70	16.72	107	-248
41 RB21	5223000	433400	Guo & Dickin, 1996	14.980	14.903	35.010	2.54	4.40	193	-165
42 RB6	5182000	406300	Guo & Dickin, 1996	14.608	14.840	35.499	2.61	9.86	175	-180
43 RB8	5186500	401200	Guo & Dickin, 1996	14.907	14.900	35.232	2.60	10.90	151	-200
44 VO136	5193200	395000	Guo & Dickin, 1996	16.269	15.181	36.089	2.70	12.54	169	-217
45 X802	5227200	380200	Guo & Dickin, 1996	15.803	15.093	35.332	2.76	15.67	119	-225
46 NE3	5120500	531700	Dickin, 1998a	15.109	15.023	35.350	2.78	48.70	50	-178
47 DR18	5149700	697100	Dickin & Guo, 2001	15.298	14.993	35.955	2.85	45.17	81	-179
48 GA13	5190900	686900	Dickin & Guo, 2001	17.007	15.307	34.354	2.76	7.60	154	-186
49 GA14	5204600	700300	Dickin & Guo, 2001	14.219	14.713	34.040	2.69	7.69	146	-181
50 GA9	5217000	702500	Dickin & Guo, 2001	14.241	14.762	34.334	2.61	10.92	153	-201
51 KP1	5210200	660500	Dickin & Guo, 2001	15.365	14.962	36.009	2.66	17.77	170	-175
52 KP10	5200300	666800	Dickin & Guo, 2001	18.745	15.894	36.116	2.71	25.24	130	-138
53 KP11	5201400	665700	Dickin & Guo, 2001	15.658	15.088	36.456	2.69	15.76	203	-174
54 KP12	5200900	665900	Dickin & Guo, 2001	17.600	15.577	35.739	2.72	12.01	187	-140
55 KP5	5203100	664300	Dickin & Guo, 2001	17.148	15.390	36.101	2.67	21.90	170	-124
56 KP6	5202800	664500	Dickin & Guo, 2001	16.208	15.222	35.943	2.69	26.24	129	-202
57 NB54	5174900	666100	Dickin & Guo, 2001	16.198	15.189	36.191	2.61	6.74	141	-188
58 NB66	5183300	654000	Dickin & Guo, 2001	17.172	15.432	35.590	2.73	16.05	117	-197

Table 4.1. Continued

	Locational Information									
Sample ID	UTM N NAD 83	UTM E NAD 83	Source	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	T_{DM} (Ga)	Nd (ppm)	Q	P
59 TA24	5136100	709000	Dickin & Guo, 2001	15.096	15.081	35.112	2.61	15.02	185	-137
60 TM1	5179000	690000	Dickin & Guo, 2001	17.315	15.344	37.055	2.77	10.70	132	-150
61 TM3	5176000	695900	Dickin & Guo, 2001	15.429	15.060	35.649	2.73	19.12	146	-212
62 TM5	5176200	701400	Dickin & Guo, 2001	15.859	15.096	35.492	2.69	17.62	146	-215
63 TM6	5176800	703700	Dickin & Guo, 2001	15.180	14.993	35.411	2.75	17.44	141	-194
64 SF24	5154550	574200	Moore & Dickin, 2011	17.370	15.354	36.083	2.71	10.10	166	-173
65 SF30	5156000	567800	Moore & Dickin, 2011	15.794	15.089	35.042	2.73	6.10	151	-184
66 SF40	5160700	562200	Moore & Dickin, 2011	15.004	14.996	35.431	2.72	35.00	102	-147
67 DU17	5218900	313300	Dickin et al., 2012	14.686	14.914	35.368	2.64	23.10	174	-168
68 DU19	5223700	293300	Dickin et al., 2012	16.376	15.255	35.644	2.78	15.10	139	-221
69 DC11	5188340	398700	Dickin et al., 2014	15.373	15.101	37.422	2.69	28.40		
70 VO41	5263500	340300	Dickin et al., 2014	15.485	15.079	36.123	2.84	26.70	191	-128
71 WB11.3	5131850	564300	unpublished	15.841	15.043	36.474	2.81		168	-183
Metasedimentary Gneiss										
72 CH 2	5178500	631000	Holmden & Dickin, 1995	26.193	16.131	47.377	1.92	46.79		
73 Ch10	5167100	650900	Holmden & Dickin, 1995	18.126	15.565	39.689	2.07	28.84		
74 NB28	5162400	635000	Holmden & Dickin, 1995	19.006	15.500	37.312	2.27	33.03		
75 NB33	5152600	646600	Holmden & Dickin, 1995	18.780	15.606	39.022	1.90	51.66		
76 NB36	5151900	641700	Holmden & Dickin, 1995	18.237	15.501	38.626	2.06	19.32		
77 NB38	5172700	648000	Holmden & Dickin, 1995	16.918	15.348	37.275	1.94	31.84		
78 NB 40	5174100	652000	Holmden & Dickin, 1995	29.378	16.686	42.794	1.93	13.58		
79 NB45A	5166700	652300	Holmden & Dickin, 1995	17.265	15.339	37.333	2.16	39.32		
80 TQ 6.2	5177500	647400	Holmden & Dickin, 1995	18.017	15.530	37.316	2.08	37.14		
Leached Duplicates										
81 BR12	5194900	431900	Guo & Dickin, 1996	14.905	14.955	35.960	2.71	10.49		
83 RB5	5183000	410100	Guo & Dickin, 1996	14.591	14.939	35.050	2.46	6.84		
82 GA8	5211800	692400	Dickin & Guo, 2001	15.266	14.948	36.663	2.64	3.56		
84 SF3	5138930	581530	Moore & Dickin, 2011	14.675	14.805	35.081	2.68	15.40		

Chapter 5: Conclusion

5.1. Chapter Summary

The major focus of this thesis was to develop a greater understanding of the accretionary history of the Makkovik and Grenville Provinces during the development of the Paleoproterozoic southeastern Laurentian margin. Whole-rock Pb isotope data, in combination with published Nd isotope, U-Pb, and geochemical data, reveals a detailed Paleoproterozoic history in southern Labrador and the SW Grenville Province, which will be summarized below.

In Chapter 2, whole-rock Pb isotope signatures show a petrogenetic distinction between the reworked Archean continental margin and accreted juvenile Paleoproterozoic crust of eastern Labrador. Pb signatures from the juvenile Cape Harrison domain point to a crustal component derived from a juvenile Paleoproterozoic mantle source. This contrasts with published Pb signatures for galena ores from the Aillik Group (Wilton, 1991), which point to an Archean origin for the basement of the Aillik domain that is similar to the pre-Makkovikian Laurentian foreland. Moreover, Pb isotope data presented in this chapter constrain the revised model of Moumblow et al. (submitted), and make the Paleoproterozoic evolution for the Makkovik orogeny comparable with Paleoproterozoic crustal growth in the adjacent Ketilidian mobile belt of southern Greenland (e.g., Garde et al., 2002).

In Chapter 3, whole-rock Pb isotope data for crust south of the proposed Archean-Proterozoic suture in the SW Grenville Province revel a solely Proterozoic mantle-derived source for Pb. The absence of an Archean Pb component in this crust differentiates these rocks from the reworked Archean craton to the northwest, thus constraining the boundary between the Archean margin and accreted Paleoproterozoic arc inferred by Nd isotope mapping (e.g., Dickin and McNutt, 1989; Guo and Dickin, 1996; Dickin, 1998a; Dickin and Guo, 2001; Moore and Dickin, 2011). In addition, Pb signatures revel a southerly increase in Mesoproterozoic reworking in the Paleoproterozoic parautochthon that is comparable to extensive ensialic arc magmatism during the Killarnian magmatic event (e.g., van Breemen and Davidson, 1988; Krogh et al., 1992; Ketchum et al., 1994). Overall, the new whole-rock Pb isotope data in the present study provides evidence for juvenile crustal addition and extensive ensialic arc magmatism in the SW Grenville Province that is comparable with the timing of long-lived ensialic arc activity in the Makkovik-Ketilidian orogeny (e.g., Garde et al., 2002; Moumblow et al., submitted).

In Chapter 4, whole-rock Pb isotope data were used to investigate the burial-uplift history of the Archean foreland in the SW Grenville Province. This work extends a pilot study by Dickin (1998b) in the French River area, which provided evidence for progressive exhumation of the Archean basement across the GFTZ with a major ramp exhumed from a crustal depth of >20km. In western Quebec, unradiogenic Pb signatures adjacent to the ABT provide evidence of deep crustal burial. Here, Paleoproterozoic Nd model ages for crust sandwiched between the Archean parautochthon and Mesoproterozoic allochthon are interpreted as a tectonic duplex that was entrained onto the base of the allochthon from parautochthonous Paleoproterozoic basement further south (Dickin et al., 2012). In contrast, samples near a proposed Archean-Proterozoic suture in the French River area shown by Dickin (1998b) to have radiogenic Pb signatures that are consistent with the preservation of Archean upper crustal material. North of Mattawa, large areas of quartzite gneiss support a model for a Paleoproterozoic sedimentary basin that developed during the collision between a proposed Paleoproterozoic arc and Archean margin. This crust was buried under the Grenvillian allochthon and later exhumed back to the surface, exposing an unconformity over the shallow Archean upper crust (Krogh, 1989).

5.2. Crustal Structure of the Archean-Proterozoic Margin in the Makkovik and SW Grenville Provinces

Whole-rock Pb isotope data presented in the three chapters of this thesis can be integrated in order to reconstruct the upper crustal structure of the Archean-Proterozoic margin in the Grenville Province and adjacent Makkovik Province. Three transects are presented in Fig. 5.1 with corresponding crustal cross-sections shown in Fig. 5.2.

In the Makkovik Province, Pb and Nd isotope evidence constrain the collisional suture to the boundary between the Aillik and Cape Harrison domains (Fig. 5.1a). The Aillik domain defines a very narrow crustal zone less than 30km wide (Fig. 5.2a). The narrow width of this crustal zone creates a geometric constraint that suggests the Aillik domain represents a reworked segment of the Archean margin rather than an accreted juvenile arc terrane. On the other hand, the large width of the Cape Harrison domain (> 150km, Fig. 5.2a) is comparable to other oceanic arc terranes accreted to the southeastern Laurentian margin during the Great Proterozoic Accretionary Orogen (e.g., Labradoria in southern Labrador and Quebecia in central Quebec, Dickin, 2000). Therefore, the geometry of the Aillik domain and Cape Harrison domain encourage a single accretionary arc evolution model for the Makkovik Province during the Paleoproterozoic.

In the SW Grenville Province, crustal growth and intermittent ensialic arc magmatism during the Proterozoic was brought to an end during the terminal Grenville orogeny. At this time, allochthonous gneisses were transported to the NW over the parautochthon following a ramp-flat geometry (Dickin et al., 2014). In Ontario, Pb isotope mapping constrains the location of the Archean-Proterozoic suture and the extent of Paleoproterozoic crust exposed at the surface between the Archean margin and ABT (Fig. 5.1b). In the subsurface, this Paleoproterozoic crust would extend southward into the Grenville Province beneath the overlying allochthon with a width that is comparable to the Paleoproterozoic arc terrane exposed in the Makkovik Province (Fig. 5.2b). However, crustal shortening and thickening of the parautochthon in Ontario during the Rigolet event would have cause the crust to be transported to the NW (Rivers et al., 2002), thus generating a steeply southeast dipping Archean-Paleoproterozoic boundary in the subsurface parallel to the Grenville Front. Likewise, transport of the Parry Sound domain onto the allochthon would add extra weight onto the underlying ridged Archean-Paleoproterozoic crust, causing crustal exhumation to be exaggerated in the parautochthon.

In western Quebec, unradiogenic Pb signatures for Archean crust near the ABT constrain the Archean-Proterozoic boundary as tectonic duplex rather than a collisional suture. Similarly, the Pb signatures presented for Paleoproterozoic crust along the Lac Watson and Lac Dumoine terranes shows that crust in the duplex was likely derived from the main body of Paleoproterozoic crust to the south and entrained onto the base of the overriding allochthon (Fig. 5.2c). In this case, the overriding allochthon would progressively cut out Paleoproterozoic crust towards the east.

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5.4. Figures

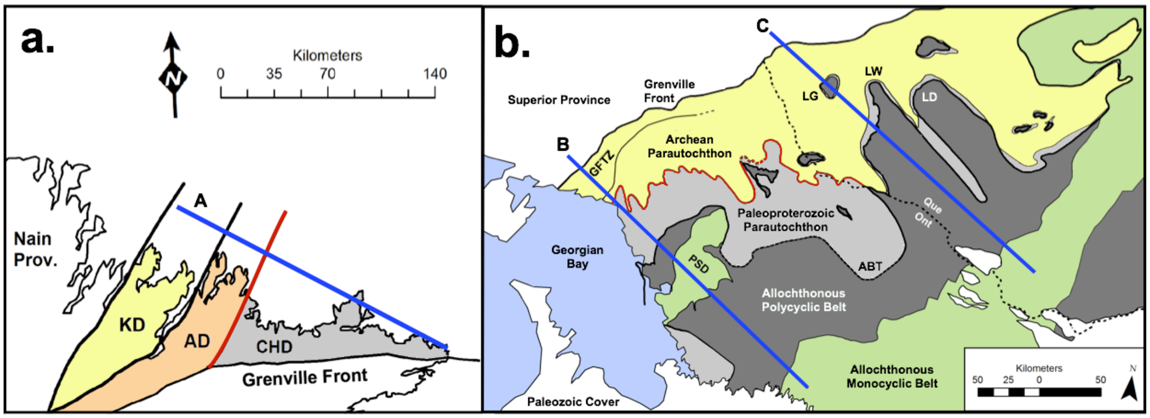

Fig.5.1. Structural map of (a) the Makkovik Province with major crustal boundaries after Ketchum et al. (2002): Aillik domain (AD); Archean-Proterozoic suture (red line); Kaipokok domain (KD); Cape Harrison domain (CD); and (b) the SW Grenville Province with tectonic boundaries after Dickin et al. (2014): Allochthon Boundary Thrust (ABT); Archean-Proterozoic suture (red line); Grenville Front Tectonic Zone (GFTZ); Lac Dumoine terrane (LD); Lac Gordon Klippe (LG); Lac Watson terrane (LW); Parry Sound domain (PSD). Transects labeled A-C (blue lines) are presented as cross-sections in Fig. 5.2.

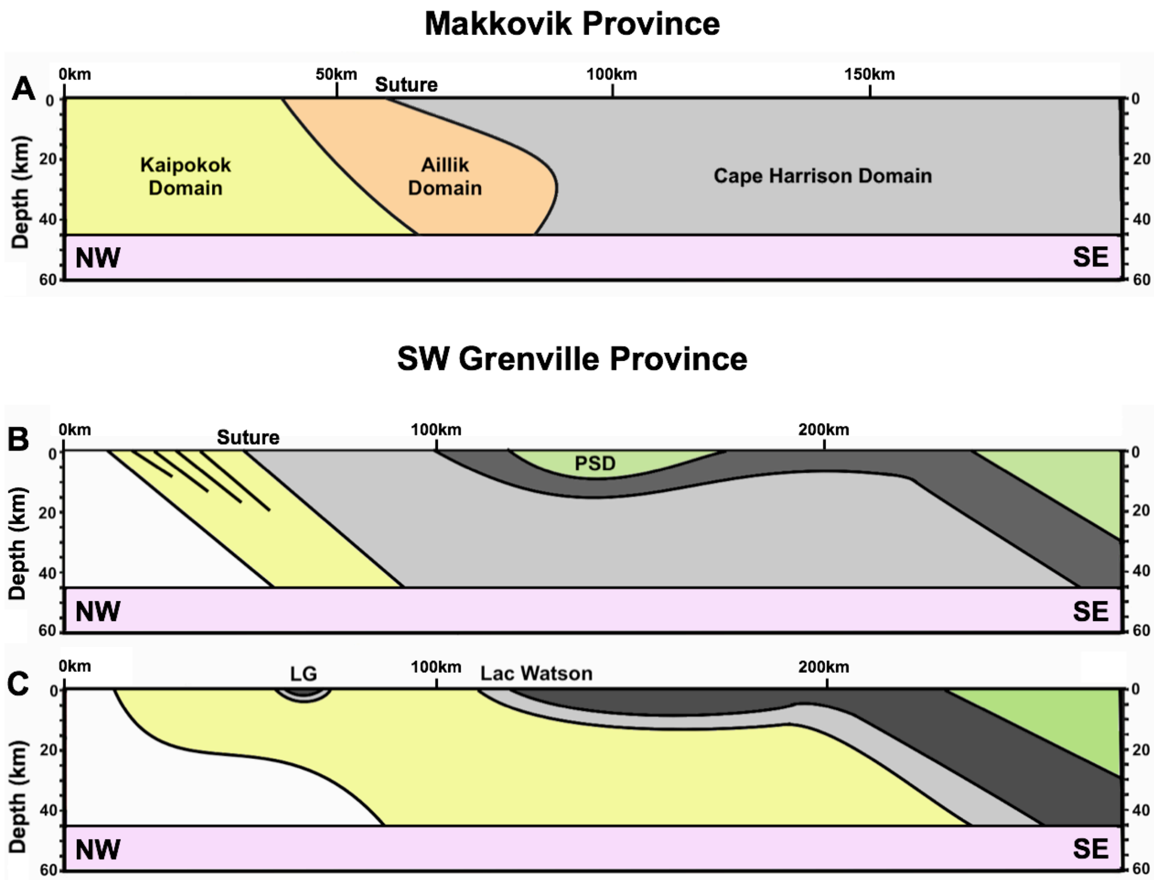

Fig. 5.2. Cross-sections of the Makkovik Province and SW Grenville Province along transect A, B and C in Fig. 5.1. Structural belts in the SW Grenville Province (cross sections B and C): Allochthonous Polycyclic Belt (dark grey shading); Allochthonous Monocyclic Belt (green shading); Archean parautochthon (yellow shading); Paleoproterozoic parautochthon (light grey shading); Superior Province (white shading). Subsurface boundaries for the Makkovik and Grenville Provinces after Hall et al. (2002) and Dickin et al. (2014) respectively.

Appendix A

Table A.1. Fractionation corrected measurements for NBS 981 Pb standard analyses

Standard	Date	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Frac. Corr. (% per amu)
NBS 981	Todt et al. (1996)	16.936	15.489	36.701	
NBS 981	November (2014)	16.942	15.485	36.716	0.140
NBS 981	February (2015)	16.948	15.486	36.730	0.140
NBS 981	March (2015)	16.950	15.493	36.746	0.120
NBS 981	May (2015)	16.943	15.492	36.696	0.100
NBS 981	June (2015)	16.943	15.491	36.729	0.100
NBS 981	July (2015)	16.947	15.492	36.697	0.100

*Fractionation correction based on the Pb isotope composition of Todt et al. (1996)