Refining the tectonic and magmatic history of the SW Grenville Province

By

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Abstract

The largest structural trend of the major lithotectonic boundaries in the Grenville Province is located in Ontario where all lithotectonic belts are deflected around Georgian Bay, termed the Big Bend. The thesis will explore some questions related to the formation of this structural feature such as; how the geometry of Grenville aged thrusting contributed to the Big Bend and what conditions led to the formation of the pre-Grenvillian Central Metasedimentary Belt whose geometrical shape may have controlled the development of the Big Bend.

First, the geometrical properties of the major lithotectonic boundaries are explored using a three-dimensional model in *SketchUp*. *SketchUp* was designed to visualize three-dimensional 1:1 scale real-world structures in Cartesian space. By utilizing refined isotope and geologic surface boundaries accompanied with seismic surveys a three-dimensional tectonic framework of the SW Grenville Province has been constructed. The three-dimensional model of the Grenville Front, Allochthon Boundary Thrust and Central Metasedimentary Belt boundary provides a visual understanding of how the thrust geometry was superimposed from the top-down, eventually producing the Big Bend.

Second, 60 new Nd isotope analyses are presented for plutonic orthogneisses from the Central Metasedimentary Belt (CMB), Grenville Province. The CMB has been identified as a back-arc aulacogen with blocks of rifted crustal basement (>1.35GaTDM) in a juvenile matrix of lavas, intrusions and supracrustal sequences (<1.35GaTDM). The Grimsthorpe domain is located in the center of the CMB in Ontario and contains large batholiths that exhibit older crustal formation ages known as the Weslemkoon and Elzevir batholiths. The presented Nd isotope analyses identify domains with older crustal formation ages separated by thin salients with younger crustal formation ages inside the Weslemkoon batholith. The intricate geometry of the isotope boundaries within the Weslemkoon batholith suggest that the Laurentian crustal basement was incorporated in the rift and later broken-up by rift related transtension. Continental rift and rifted-arc settings of the Danakil Depression and Gulf of California are explored as modern analogues along with rifted continental fragments known as the Danakil block and Isla Tiburon respectively.

Last, the Queensborough mafic-ultramafic complex (QC) is reviewed. The QC is located at the southern end of the Elzevir batholith. The QC was interpreted as a back-arc ophiolite based on REE ratios and MORB normalized spidergrams which were argued to be comparable to modern back-arc basalts. Upon review of the published major and trace element ratios there is a mantle component that is problematical to explain with a back-arc tectonic scenario. The geochemistry suggests that the QC could be partially derived from a mantle plume. The current tectonic models contend this part of Laurentia formed only from subduction related magmatism but based on the trace element data a plume may have been involved as well.

The evidence presented supports the identification of the CMB as a failed continental rift and that the failed continental rift created an embayment in Laurentia which governed ductile deformation during Grenvillian orogenic events leading to the formation of the Big Bend.

Acknowledgements

Alan has made the thesis a possibility by providing invaluable assistance with technical work and the fundamentals of isotope geology. With his help I have developed the skills required to conduct research independently. I can now appreciate all the work necessary for sample collection, sample analysis and the amount of time it takes to teach students.

I would like to thank the School of Geography and Earth Science and everyone that works in the office keeping the department running. I also thank the defense committee for their participation and for a thorough review of the thesis.

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Preface

This thesis contains three main chapters (2, 3 and 4) which are individual projects regarding the Big Bend in a sandwich format. The research presented in this dissertation was completed under the supervision of Dr. Alan Dickin in partial fulfillment of a Master's of Science. The candidate completed all work in the thesis with some aid from the supervisor for sample analysis and other technical assistance.

Chapter 1:

Introduction

History and Background

The Grenville Province is located towards the SE Canadian Shield where the roots of a Precambrian orogen are exposed spanning from Ontario to Newfoundland (Figure 1.1a). The SW Grenville Province in Ontario is comprised of a series of lithotectonic belts ranging in age from Archaean to Mesoproterozoic that were thrust over the Laurentian craton between 1.2-1.0Ga (Figure 1.1b). This involved mid crustal thrusting and subhorizontal transport for distances of at least 200km. Although the current understanding of the Grenville Province has evolved significantly since the 1950s there are still many unanswered questions. This thesis will attempt to address several of the outstanding questions which concern the whole SW Grenville Province.

In order to construct realistic and accurate models of crustal evolution it is necessary to have an accurate understanding of the crustal structure (Dickin, 2015). The first step towards understanding the Grenville Province was the synthesis of 'The Grenville Problem' which was a compilation of work and perspectives of the Grenville Province at the time (Thompson, editor, 1956). This volume presents the historical understanding of the Grenville Province before the application of the plate-tectonics paradigm. The title, 'The Grenville Problem' refers to a few different aspects associated with Grenvillian geology making meaningful tectonic interpretations unattainable at the time. For example, establishing relationships between gneiss complexes was limited or non-existent, many workers had a mindset of adopting terminology of the pioneers (Logan, 1863) and detailed mapping was focused on the low-grade sequences comprising marbles, metapelites, quartzites and amphibolites (see Rivers, 2015). Although these problems have largely been resolved by improvements in analytical capabilities, new problems have inhibited understanding the SW Grenville Province and will be addressed here.

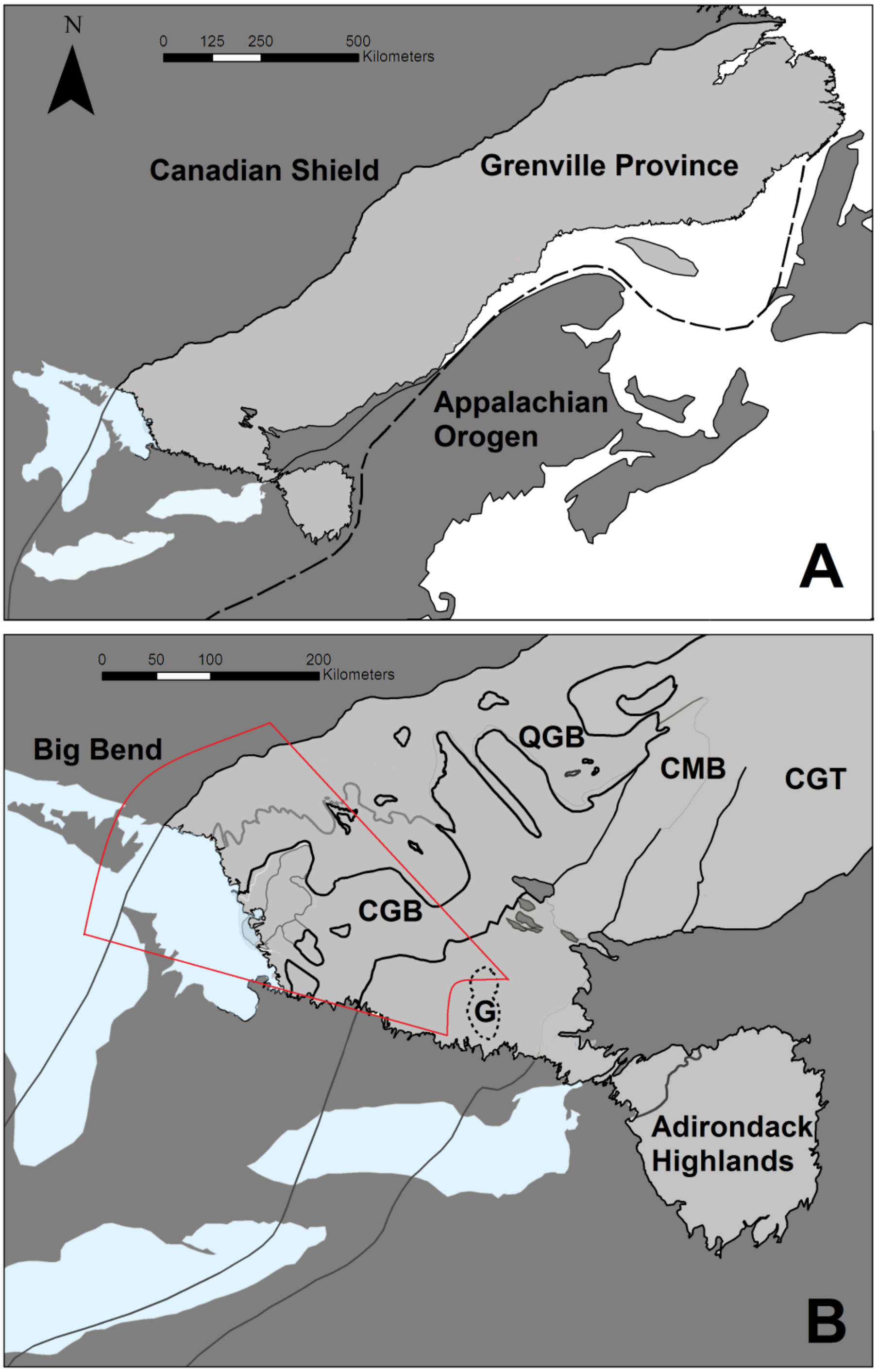

Figure 1.1: A) Map showing the extent of the Grenville Province in Canada. B) Map showing the major lithotectonic boundaries in the SW Grenville Province. The Big Bend is indicated by the area enclosed in the red line. Abbreviations; CGB- Central Gneiss Belt, QGB- Quebec Gneiss Belt, CMB- Central Metasedimentary Belt, CGT- Central Granulite Terrane, G- Grimsthorpe domain.

The first comprehensive/modern understanding of Grenvillian geology was published by Wynne-Edwards (1972) as a chapter in “Variations in Tectonic Styles in Canada” (Price and Douglas, eds, 1972). In his chapter, Wynne-Edwards (1972) subdivided the Grenville Province into a series of lithotectonic belts and drew the first orogen-scale cross-sections (Figure 1.2). These were the first major steps towards unravelling the so-called ‘Grenville Problem’ and applying the new paradigm of plate tectonics to this part of the Canadian Shield.

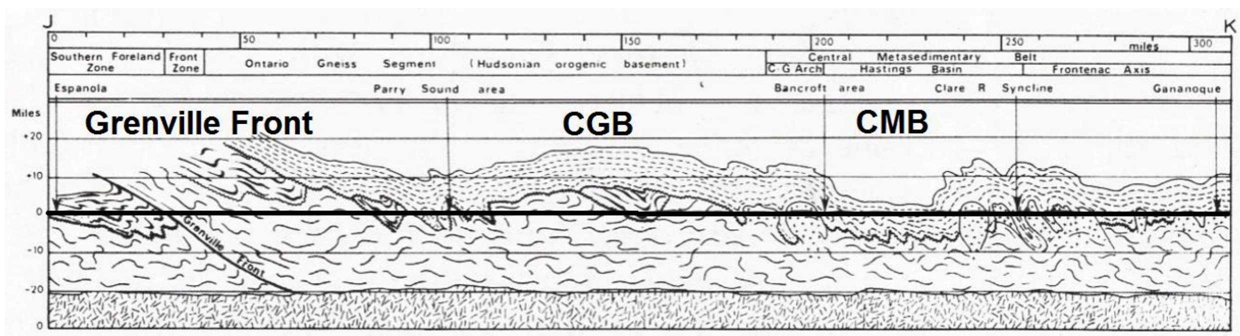

Figure 1.2: A cross-section drawn by Wynne-Edwards (1972) through the SW Grenville Province in Ontario. The solid black line in the center is the limit of erosion.

Detailed mapping and improvements in research techniques throughout the 1970s and 1980s eventually led to deep-crustal seismic surveys and tomography by the COCORP and Lithoprobe projects in the late 1980s and early 1990s. Hundreds of kilometers of seismic profiles revealed the structural framework of the Grenville Province and surrounding tectonic belts (Green et al., 1988; Kellet et al., 1991; White et al., 1994). These seismic projects aided immensely in the current understanding of Grenvillian geology. During this period geochronologists were beginning to uncover the details about the timing of the magmatic and metamorphic events in the SW Grenville Province (Marcantonio et al., 1990; Krogh, 1994). Nd isotope mapping was developed to refine the location of the major lithotectonic boundaries (Dickin et al., 1988; Dickin and McNutt, 1989; Dickin et al., 1990). And the structural geologists were identifying structural relationships between the major lithotectonic belts and lithologies that are restricted to and/or cross the major boundaries (Davidson, 1984; Rivers, 1989; Schwerdtner et al., 1987; Schwerdtner and van Berkel, 1991).

Analysis of the structural relationships between the major thrusts is usually done by mapping exposed rocks at the surface and cross-sectional analysis. This has led to the overuse of cross-sections which may not properly represent the seismic profiles. To overcome the limitations of 2D cross-sections it is now possible to explore the three-dimensional structure of the major thrusts in the SW Grenville Province using SketchUp (Strong, 2015). SketchUp is software that was developed to create objects in three-dimensional space with a user friendly interface. The application of SketchUp to the SW Grenville Province provides a new perspective of the large-scale structure and major structural trends between the thrust sheets (Chapter 2).

The largest structural trend is found in Ontario where all lithotectonic belts are deflected around Georgian Bay (Figure 1.1b). This was termed the Big Bend by Schwerdtner (1987) who demonstrated this region as a narrow domain of strong horizontal shortening. The Big Bend was first mapped by Lumbers (1975) and later Davidson (1984) who suggested it was a response to listric ductile thrusting. In contrast, Schwerdtner (1987) proposed that the large-scale cross folding and 'flow' in the SW Grenville Province was a consequence of the Big Bend rather than the Big Bend being a result of the style of thrusting. This has led to question the origin of the Big Bend which can be attributed to either; an embayment in the margin of SE Laurentia that governed subsequent ductile deformation of the orogenic crust; or that the thrust stack was flexed at this location during late Grenvillian deformation (Schwerdtner et al., 2010; Schwerdtner et al., 2016).

Dickin and North (2015) pointed out that the sharpness of structural bending is correlated with the metamorphic age of thrusting. The CMBBZ is Shawinigan (~1160Ma), the ABT is Ottawan (~1080Ma) and the Grenville Front is Rigolet (~980Ma) (Rivers et al., 1989). Dickin and North (2015) argued that the Elzevirian aged rift zone margin (Dickin and McNutt, 2007) was reactivated during the Shawinigan age which controlled the trajectory of the Ottawan-aged ABT and later the Rigolet-aged Grenville Front. This sequence of events produced the Big Bend in a top-down style of thrusting comparable to modern-day Himalayan thrust regimes (DeCelles et al., 2001).

In Chapter 2 a three-dimensional model of the major lithotectonic boundaries in the SW Grenville Province explores the structural geometry of thrusts, their relationships and how the superimposition of thrust geometry from the top-down produced the Big Bend. Then in Chapter 3 the tectonic model of Dickin and McNutt (2007) is tested using Sm-Nd isotope mapping of the Weslemkoon and Elzevir batholiths in the Grimsthorpe domain (Figure 1.1). The new isotope analyses identify domains with older crustal formation ages separated by thin salients with younger crustal formation ages inside the Weslemkoon batholith suggesting that the Laurentian basement was incorporated during the initial stages of rifting and subsequently broken up. The new evidence supports the conclusion that the Big Bend was produced by the geometry of the CMB continental rift, a crustal structure predating Grenvillian orogenesis (Dickin and McNutt, 2007; Dickin and North, 2015).

To develop the tectonic interpretation for the CMB the trace element signatures of the earliest mafic magmatism are explored. The trace element geochemistry of the Queensborough and Kaladar mafic-ultramafic complexes, should demonstrate back-arc trace element signatures based on the published interpretations. The earliest mafic magmatism should sample the mantle wedge of the subduction zone at the Laurentian margin during the onset of back-arc spreading. However, when the published trace element analyses are scrutinized plume-like trace element ratios are prevalent (Chapter 4). This question is raised to explore possible directions of future work in the CMB.

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Chapter 2:

Three-dimensional visualization of the major lithotectonic boundaries in the SW Grenville Province, Ontario

Introduction

Three-dimensional visualization of subsurface geologic boundaries can provide geologists with a new perspective of the crustal structure in orogenic belts. In the SW Grenville Province of Ontario and western Quebec, the three-dimensional subsurface structure of the major lithotectonic belts can be visualized using *SketchUp*. *SketchUp* is freeware that was developed to construct three-dimensional 1:1 real-world structures using lines and closed polygons to create surfaces (Trimble Navigation Limited, 2014). In *SketchUp* it is possible to manipulate polygons and surfaces in Cartesian xyz space. Surfaces can be uniquely textured so that 2D images, such as seismic transects, can be represented in three-dimensional space (Strong, 2015).

The SW Grenville Province in Canada consists of a series of thrust sheets that developed from collisional events during the Grenville orogeny (Rivers et al., 1989). The major lithotectonic boundaries in Ontario are the Grenville Front, Allochthon Boundary Thrust (ABT), the Algonquin duplex and the Central Metasedimentary Belt boundary (CMBb) (Figure 2.1). These boundaries were major deformation zones associated with NW directed crustal transport, separating the major lithotectonic belts. The lithotectonic belts have been defined as the Parautochthonous Belt, Allochthonous Polycyclic Belt and Allochthonous Monocyclic Belt (Rivers et al., 1989), of which the latter largely coincides with the Central Metasedimentary Belt (Wynne Edwards, 1972). These belts have distinct Sm-Nd TDM model age distributions which have been used to refine the locations of the major boundaries in Figure 2.1 (Guo and Dickin, 1996; Dickin, 2000; Dickin et al., 2010; Dickin et al, 2012; Dickin et al, 2014; Dickin and North, 2015; Dickin et al., 2017).

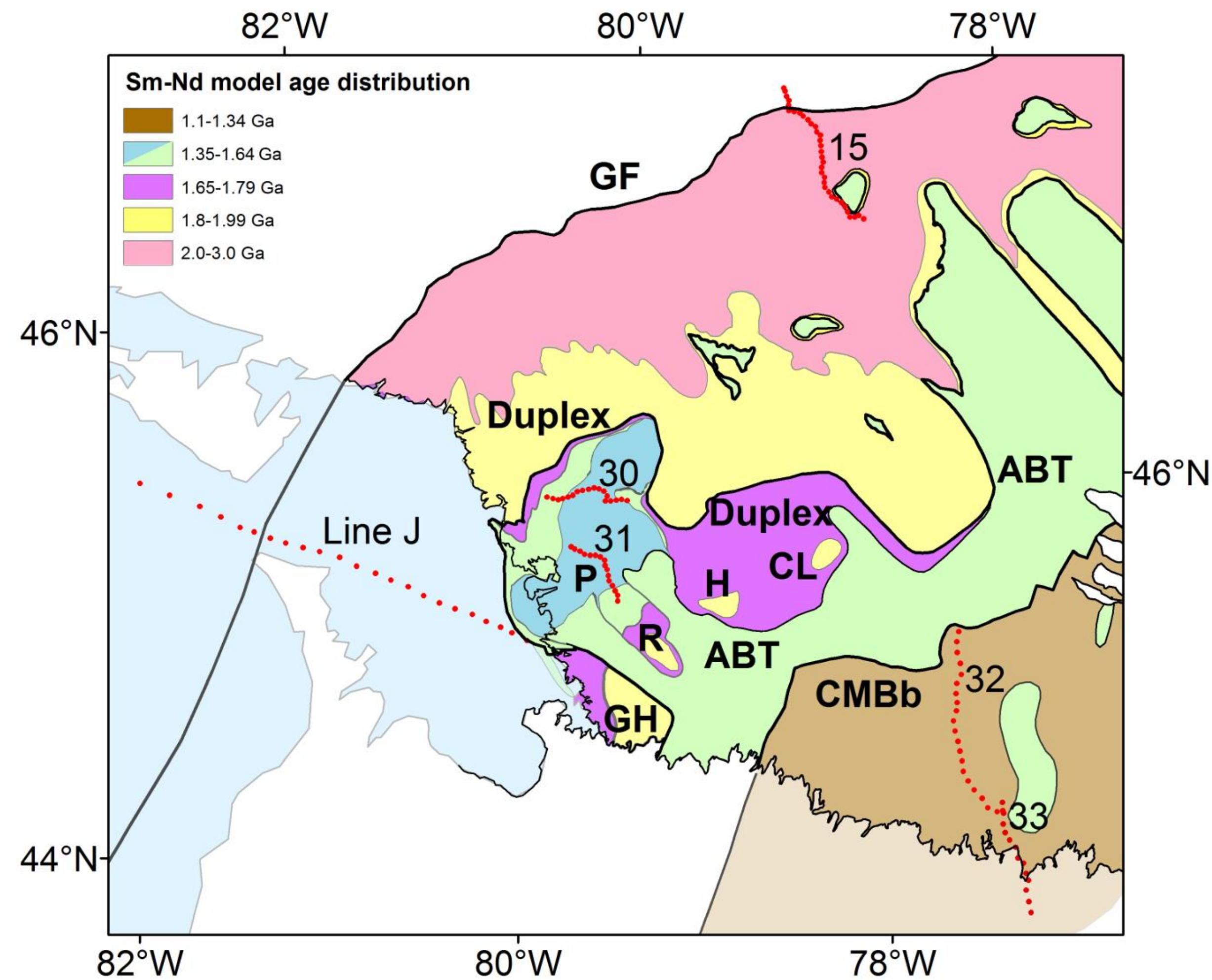

Figure 2.1: Summary map of the SW Grenville Province depicting the major tectonic boundaries and seismic transects in this study. The major tectonic boundaries are the Grenville Front (GF), Algonquin duplex (Duplex), Allochthon Boundary Thrust (ABT), Parry Sound Domain (P) and Central Metasedimentary Belt Boundary (CMBb). The major lithotectonic terranes are the Parautochthonous Belt (red-Archaean and yellow-Paleoproterozoic), Allochthonous Polycyclic Belt (purple-duplex and green-ABT) and Central Metasedimentary Belt (brown). The abbreviations indicate; GH- GoHome window, R- Rosseau window, H- Huntsville window and P- Parry Sound Domain.

Background

In the early 1970s and 80s geologic mapping in the SW Grenville Province began to delineate the major lithotectonic terranes and their bounding shear zones (Wynne-Edwards, 1972; Davidson, 1984, 1985). Davidson's (1984 and 1985) reviews helped to develop a general classification scheme of the SW Grenville Province domains, derived from mapping the three lithologically distinct belts and their bounding shear zones.

Seismic surveys in the SW Grenville Province began in the late 1980s as part of the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE), funded by the Canadian and United States governments. GLIMPCE produced several transects, one of which crossed Lake Huron and Georgian Bay, termed GLIMPCE line J (Green et al, 1988). GLIMPCE line J imaged the Grenville Front, Grenville Front Tectonic Zone and the Superior Province. In the 1990s the Lithoprobe program continued this work funded by the National Science and Engineering Research Council of Canada (NSERC). The Abitibi-Grenville seismic surveys include lines: 15, 30, 31, 32, 33, 52, and 53 (Figure 2.1). Line 15 imaged the Grenville Front (Kellet et al, 1994), line 30 and 31 imaged the Parry Sound Shear Zone and ABT, line 32-33 imaged a transect of the CMB and some of the ABT ramp (White et al, 1994), and lines 52-53 imaged all three major belts and their bounding shear zones, although published in low resolution (Martignole et al, 2000).

At a similar time in the late 1980s and early 1990s the location of the ABT was mapped on a province–wide basis using aeromagnetic evidence. It was interpreted to exhibit ramp-flat geometry in the eastern Grenville Province but the westernmost segment of the ABT in Ontario was more difficult to interpret (Rivers et al, 1993). The Parry Sound Shear Zone was originally inferred as the probable extent of the ABT on the northerwestern side of the Parry Sound Domain (Rivers, 1989). However, the Central Britt Shear Zone further north (Jamieson et al, 1994) was subsequently inferred as the local expression of the ABT after Lithoprobe line 31 revealed that the basal thrust of the Allochthonous polycyclic belt was more closely related to the structurally lower Central Britt Shear Zone (White et al, 1994). In turn, confirming a regional gravity study that interpreted the Parry Sound Domain as a distinct crustal block (Lindia et al, 1983). The various seismic transects helped to reveal the tectonic framework of the SW Grenville Province which was interpreted by Davidson (1995), shown in Figure 2.2.

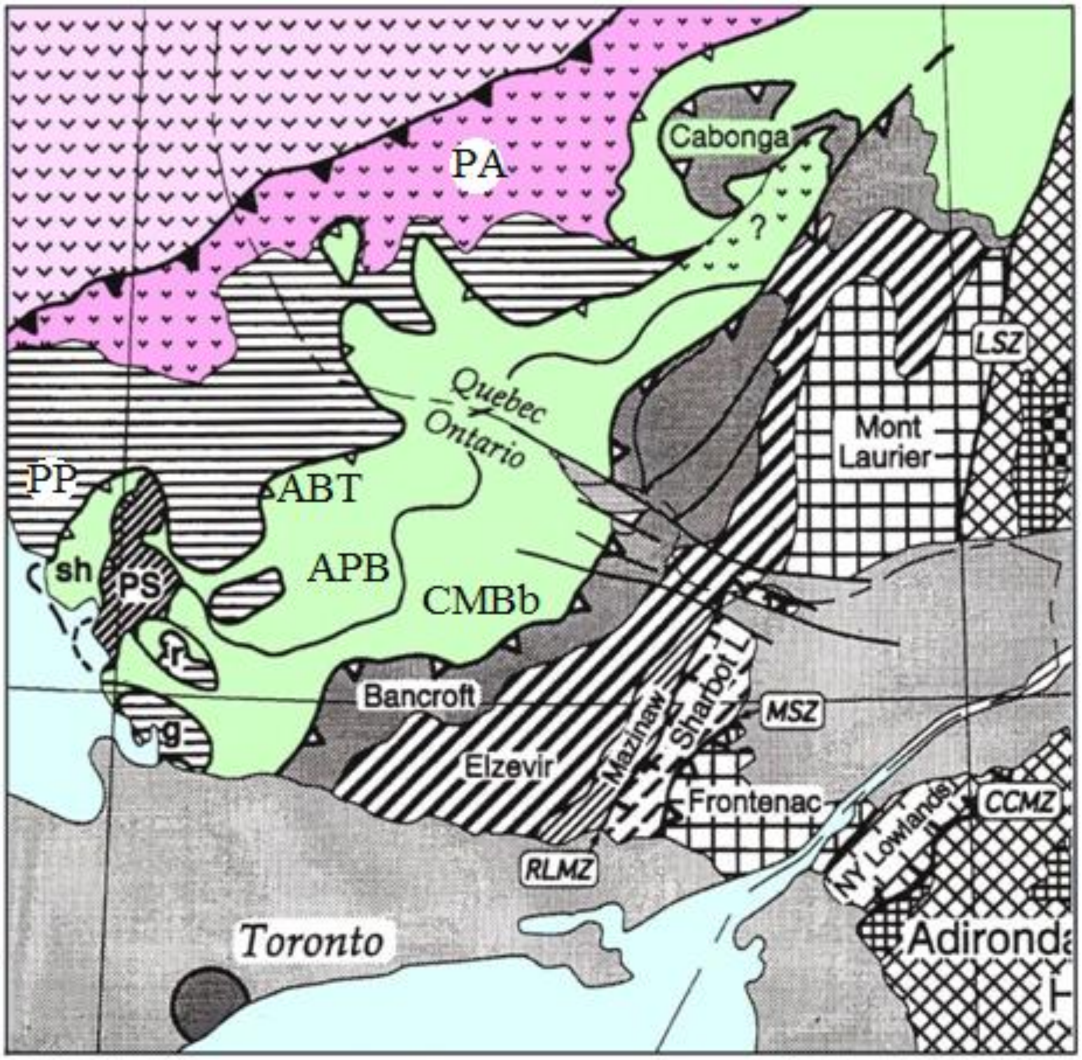

Figure 2.2: Map of the SW Grenville Province from Davidson (1995) with the postulated extent of the Allochthonous Polycyclic Belt, the Parautochthonous Archean (purple) and Parautochthonous Paleoproterozoic (horizontal ruling).

This model identified windows through the Allochthonous Polycyclic Belt to the Parautochthonous Belt on the basis of correlated lithologies in the regions of Go Home, Rosseau and Huntsville, in part predicted by Rivers et al (1989). It also recognized a tectonic outlier near Lac Boothe, Quebec, based on previous geologic mapping (Rive, 1981) and Lithoprobe line 15 (Kellet et al, 1994). The Allochthonous character of the Lac Boothe klippe was shown by Indares and Dunning (1997) who identified that the Lac Watson Shear Zone was synonymous to the Central Britt Shear Zone. The location of the Allochthon Boundary Thrust was first based on the location of Allochthonous Polycyclic rocks that exhibit pre-Grenvillian and/or Grenvillian metamorphic histories with no direct link to the Parautochthonous crust in the footwall (Rivers et al, 1989). The classification was modified to include the most northwesterly expression of retrogressed eclogite bodies and coronitic olivine metagabbros by Ketchum and Davidson (2000). This model redefined the windows as the lowest layer of the Allochthonous Polycyclic Belt. However, recent Nd isotope results suggest that Davidson's 1995 model in Figure 2.2 corresponds more closely with the Nd isotope map in Figure 2.3.

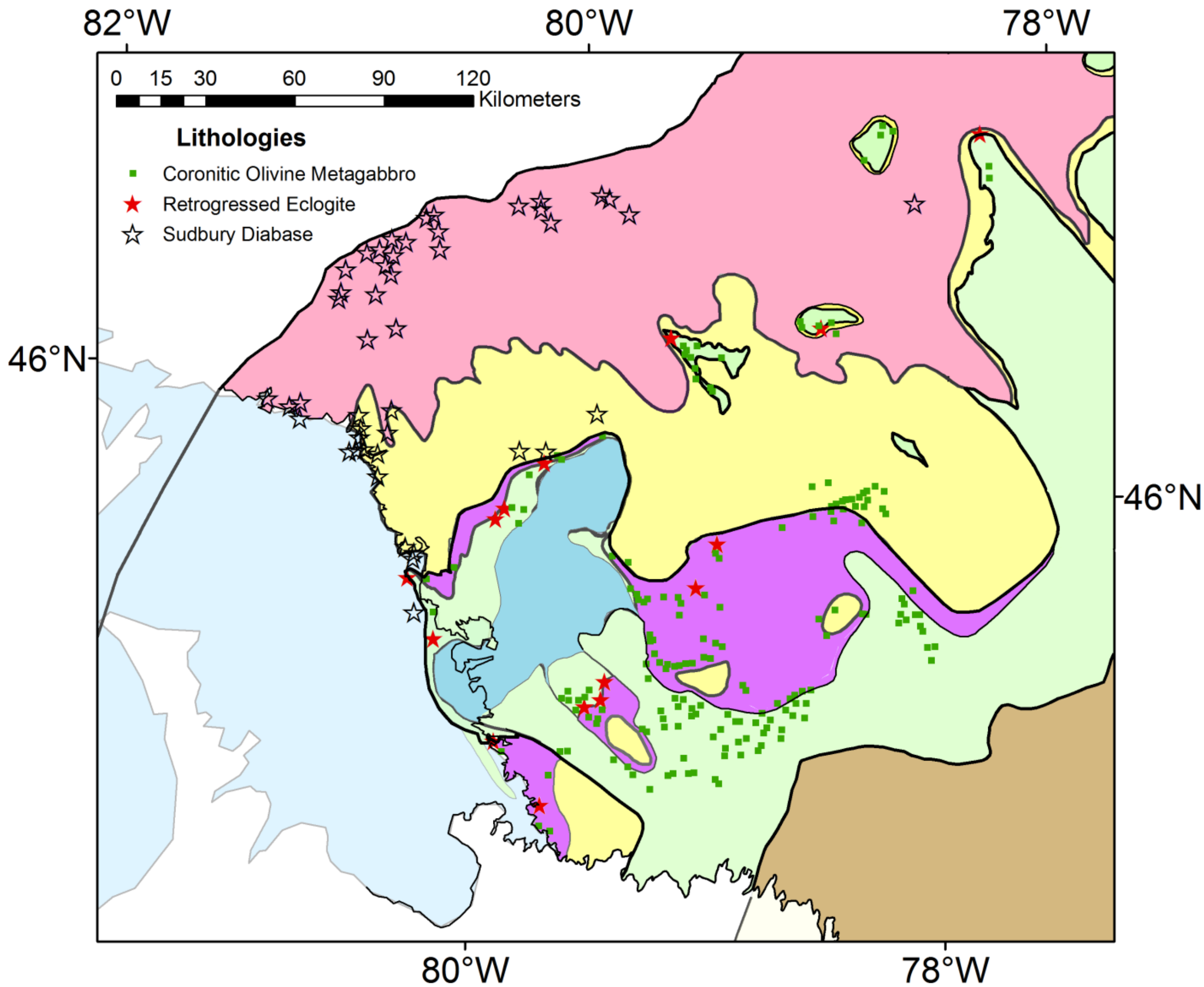

Figure 2.3: Map of the SW Grenville Province with coronitic olivine metagabbros (green squares), retrogressed eclogites (red stars) and Sudbury diabase (hollow black stars) approximate locations from Ketchum and Davidson (2000).

Isotope mapping subsequently identified the boundaries of the Lac Boothe klippe and the Lac Watson and Dumoine lobes (Dickin and Guo, 2001). Isotope mapping has identified several Allochthonous klippen, which exhibit Sm-Nd model ages averaging ~1.7Ga while the underlying Parautochthonous crust averages ~1.9Ga (Dickin and McNutt, 2003). For example, the North Bay klippe is correlated with the expression of coronitic olivine metagabbro and retrogressed eclogite bodies of Ketchum and Davidson (2000). The lateral discontinuity of the metagabbro and retrogressed eclogite bodies between Burks Falls and North Bay precludes tracing the ABT directly to North Bay. In addition, there is a lateral discontinuity of Allochthonous <1.8Ga TDM crust within the boundary of Ketchum and Davidson (2000) except at North Bay and Renzy. This was the first indication that the Sm-Nd isotope mapping directly related to the structure of the ABT allowing the structure of the North Bay klippe to be resolved (Dickin and McNutt, 2003).

The identification of the major belts and their boundaries was further refined by Dickin et al (2012) and Dickin et al, (2014). In these studies it was eventually concluded that prior interpretations of the seismic surveys had ignored important evidence (White et al, 1994). This led to a refinement of the tectonic framework and major structural divisions of the SW Grenville Province (Dickin et al, 2014). By reinterpreting Lithoprobe line 31 Dickin et al (2014) proposed a ramp-flat geometry of the ABT in the SW Grenville Province complete with various klippen and windows. Support for this model is provided from Sm-Nd isotope mapping, undulating fabrics recording anticlinal-synclinal structures SE of the Parry Sound Domain described by Schwerdtner and van Berkel (1991), mapped lithologies of Ketchum and Davidson (2000) and the Lithoprobe seismic surveys showing the Allochthonous Polycyclic Belt extending below the Parry Sound Domain in line 31 and the Lac Booth Klippe on the Parautochthonous Belt in line 15 (White et al, 1994; Kellet, Barnes and Rive, 1994). The dip directions of the ABT identified in Lithoprobe line 31 can be extrapolated to the surface, in the northwest (Shawanaga shear zone), and southeast (Upper Rosseau shear zone).

Methodology

The tectonic boundaries observed in the regional seismic transects of the SW Grenville Province are difficult to anchor to the surface without both isotope and structural constraints. Hence, a structural model explaining the isotope distribution of the lithotectonic units in the SW Grenville Province must be defined. The tectonic boundaries observed by the regional seismic transects can be easily anchored to the integrated geologic and Sm-Nd isotope boundaries using *SketchUp*.

First, seismic fences of the GLIMPCE and Lithoprobe surveys were constructed in three-dimensional space, located with the published central-mid-point coordinates. Following the setup of surface boundaries and seismic fences, subsurface tectonic boundaries in the seismic transects were correlated with the geologic and isotope derived surface boundaries. This approach was reiterated multiple times to account for recent developments. Using this approach it is possible to visualize the major tectonic boundaries of the SW Grenville Province in Canada for the first time in three-dimensions.

Results and Discussion

The results of this work are shown in the form of a series of snap shots of the 3D model. The discussion will walk through the structural understanding of the SW Grenville Province beginning with the Parry Sound Domain. The Parry Sound Domain has a well understood multi-lobed structure with an abundance of high-density mafic lithologies. These high density lithologies gave rise to well-defined basal reflectors on Lithoprobe line 31 (White et al., 1994), which can be coupled with gravity data (Lindia et al, 1983) to enable tracing of the basal shear zone in three dimensions. This structure was used as a test of the 3D visualization of crustal scale geologic structures using SketchUp (Strong, 2015). The three-dimensional visualization shows that the structure resembles a sedimentary 'load cast' caused by the gravitational sagging of the high density Parry Sound Domain on the lower density Allochthon.

The extent of the ABT in Ontario and western Quebec is defined as the NW limit between the Parautochthonous Belt which have recorded pre-Grenvillian metamorphic histories and the 'Allochthonous' terranes to the south which have recorded Grenvillian metamorphic events (Rivers et al, 1989). The location of the ABT was refined using the presence of retrogressed eclogite bodies in the hangingwall and Sudbury diabase in the footwall (Ketchum and Davidson, 2000). Dickin et al. (2014) showed that the ABT has a similar trajectory to the Parry Sound shear zone in Lithoprobe line 31, but 2-3 km deeper in the crust. The new visualization in Fig. 5 shows the revised three-dimensional structure (Dickin et al., 2017). The tectonic history of the Allochthonous Polycyclic Belt involved exhumation from depth on a crustal-scale ramp, followed by northwest directed transport as a sub-horizontal thrust sheet (Dickin et al, 2014). However, the Parry Sound Domain loaded down the Allochthonous belt during later stages of northwestward transport, forming an undulating thrust sheet that was subsequently perforated as a result of exhumation and erosion (Figure 2.4 and 2.5A-C).

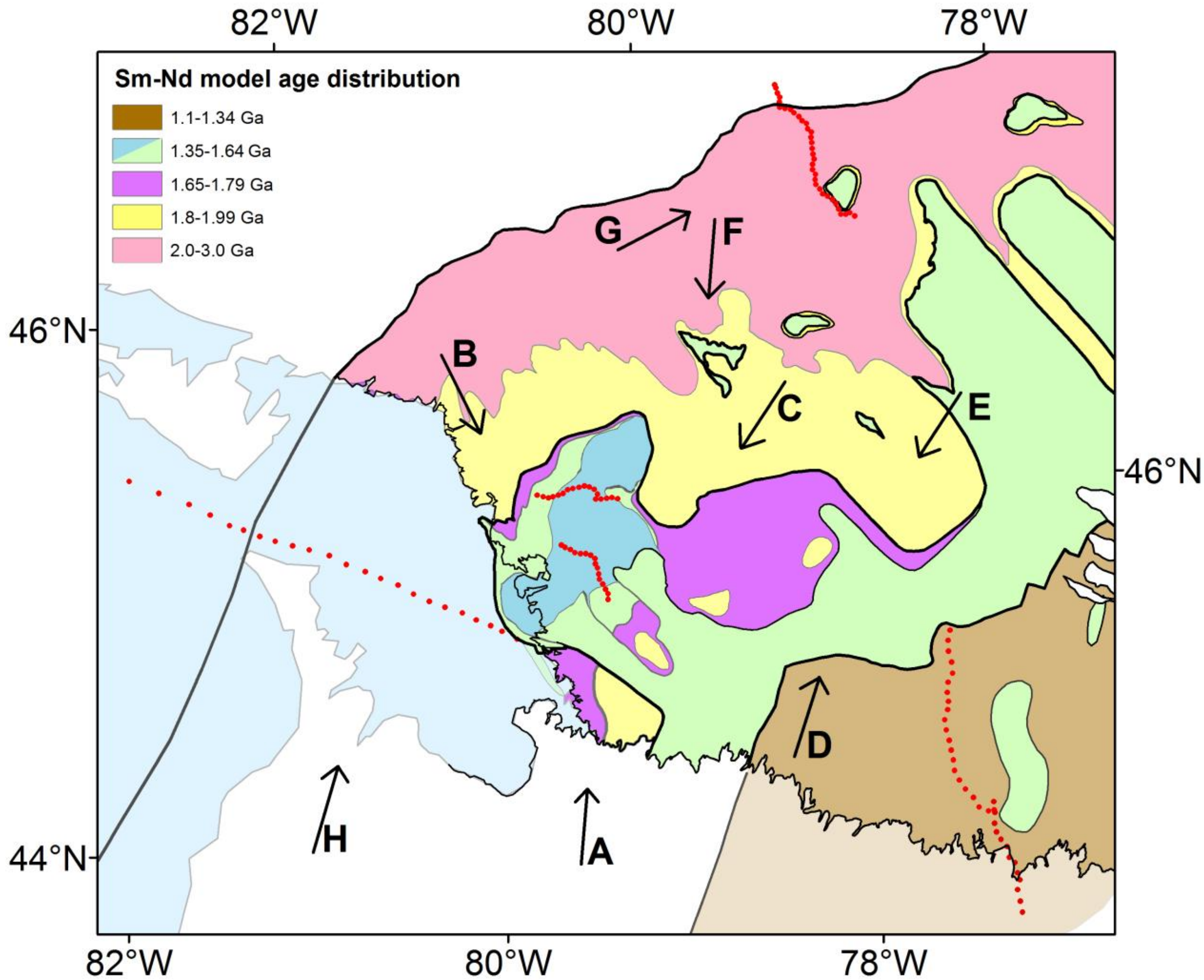

Figure 2.4: Map of the SW Grenville Province showing the viewing direction and location for Figures 2.5, 2.6 and 2.7.

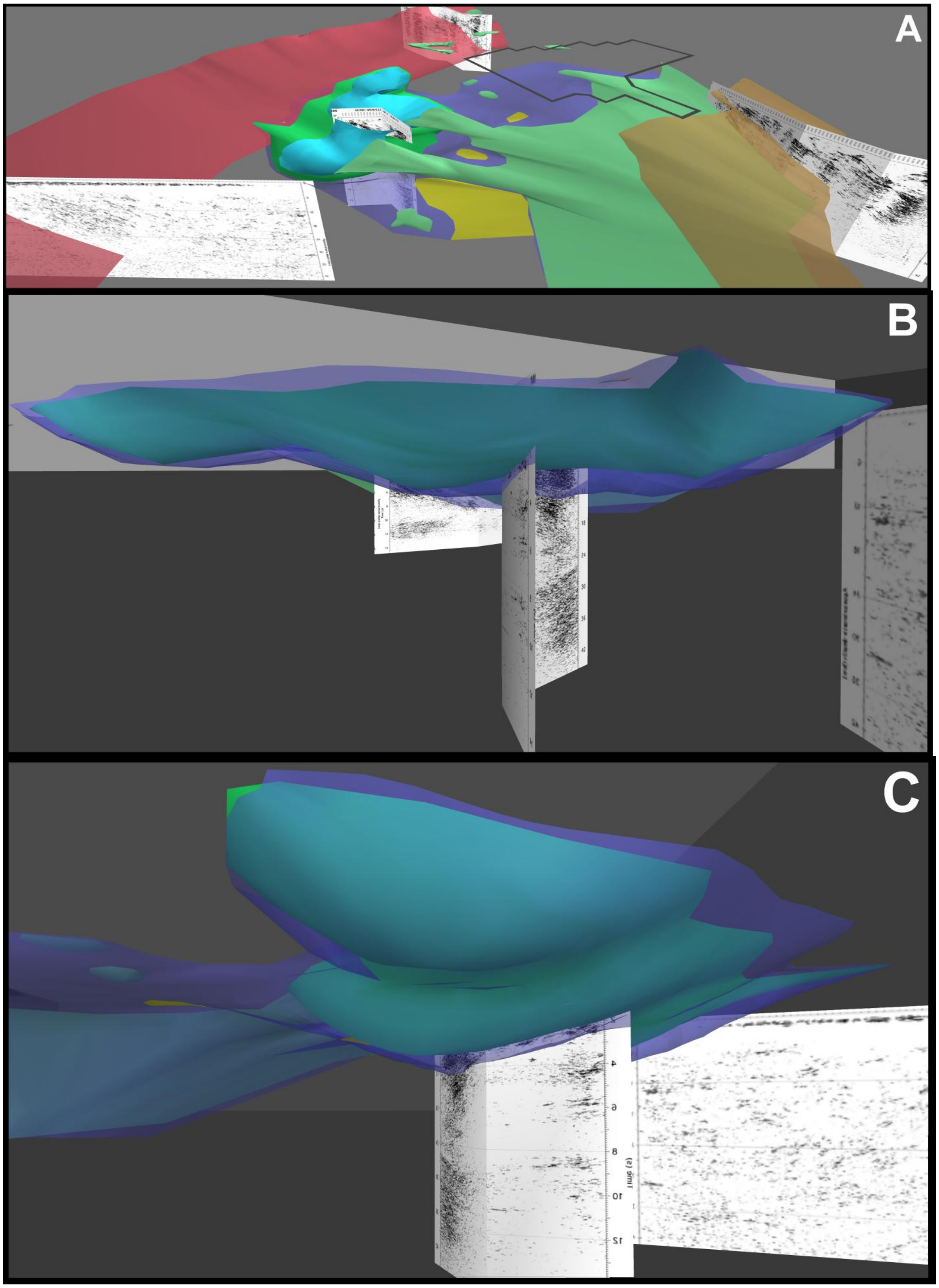

Figure 2.5: View of the Parry Sound Domain, windows through the Allochthon and the basal thrust of the ABT below the Parry Sound domain; A- from the south of Parry Sound above the surface, B- from the north of Parry Sound from below the surface, C- from the east of Parry Sound from below the surface. Colours are the same as Figure 2.1. See Figure 2.4 for viewing direction.

Key evidence from tectonic windows indicates the ramp of the ABT must be located SE of the windows and subparrallel with the CMBb (Figure 2.6D). The ABT ramp is observed in Lithoprobe line 32 as a strong band of SE dipping reflectors at ~14km depth (Figure 2.6E). These seismic reflectors anchor the angle of the ABT which correlates with the expression of several windows and klippen (Figure 2.6F). The windows expose crust with Sm-Nd model ages >1.8Ga, typical of the footwall to the Algonquin duplex whereas the klippen contain a distribution of younger model ages (1.35-1.65Ga) typical of the Muskoka domain while the duplex exhibits intermediate model ages with a tight distribution (1.65-1.79) (Dickin et al., 2017).

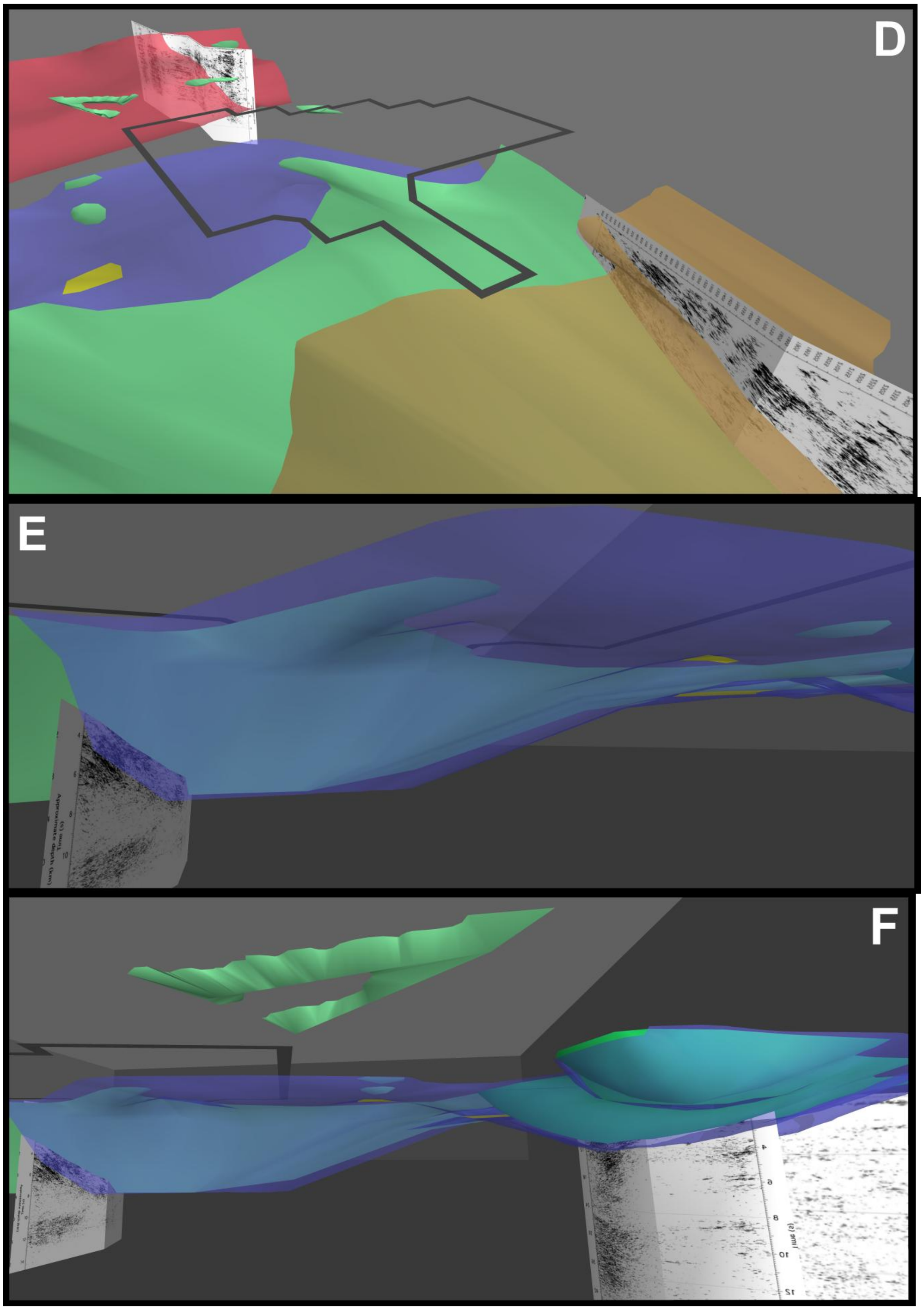

Figure 2.6: View of the Algonquin duplex and ABT; D- Algonquin Park from the SW and above the surface, E- Opeongo nappe from the NE and below the surface, F- North Bay klippe from the North and below the surface. Colours are the same as Figure 2.4. See Figure 2.4 for viewing direction.

The GF formed during the Rigolet phase (Rivers, 2008) implying it was influenced by tectonic structures that formed in earlier orogenic events such as the ABT and CMBbz. The location of these thrusts was controlled by an earlier crustal structure resulting from the Elzevirian-age back-arc rift zone (Dickin and McNutt, 2007) and reflects progressive northwestward migration of the locus of thrusting through the Shawinigan, Ottawan and Rigolet phases of the Grenville Orogenic Cycle (Rivers, 2008). This is observed by the ~130° dogleg of the GF, ABT and CMBb in the axial plane along the eastern coast of Georgian Bay as they continue below Paleozoic cover into the United States to the SW.

The GF exhibits linear dipping reflectors in GLIMPCE line J which transition at some point NW of North Bay to a truncated ramp-flat style in Lithoprobe line 15 (Figure 2.7, A and B). This structure reflects the Allochthonous crustal load which extends further north on the Parautochthon east of North Bay. The effect of this structure has been explored using whole rock Pb-Pb showing that the Archean Parautochthonous crust was more deeply exhumed to the West near Georgian Bay than in the East near the Ontario-Quebec border (Dickin, 1998).

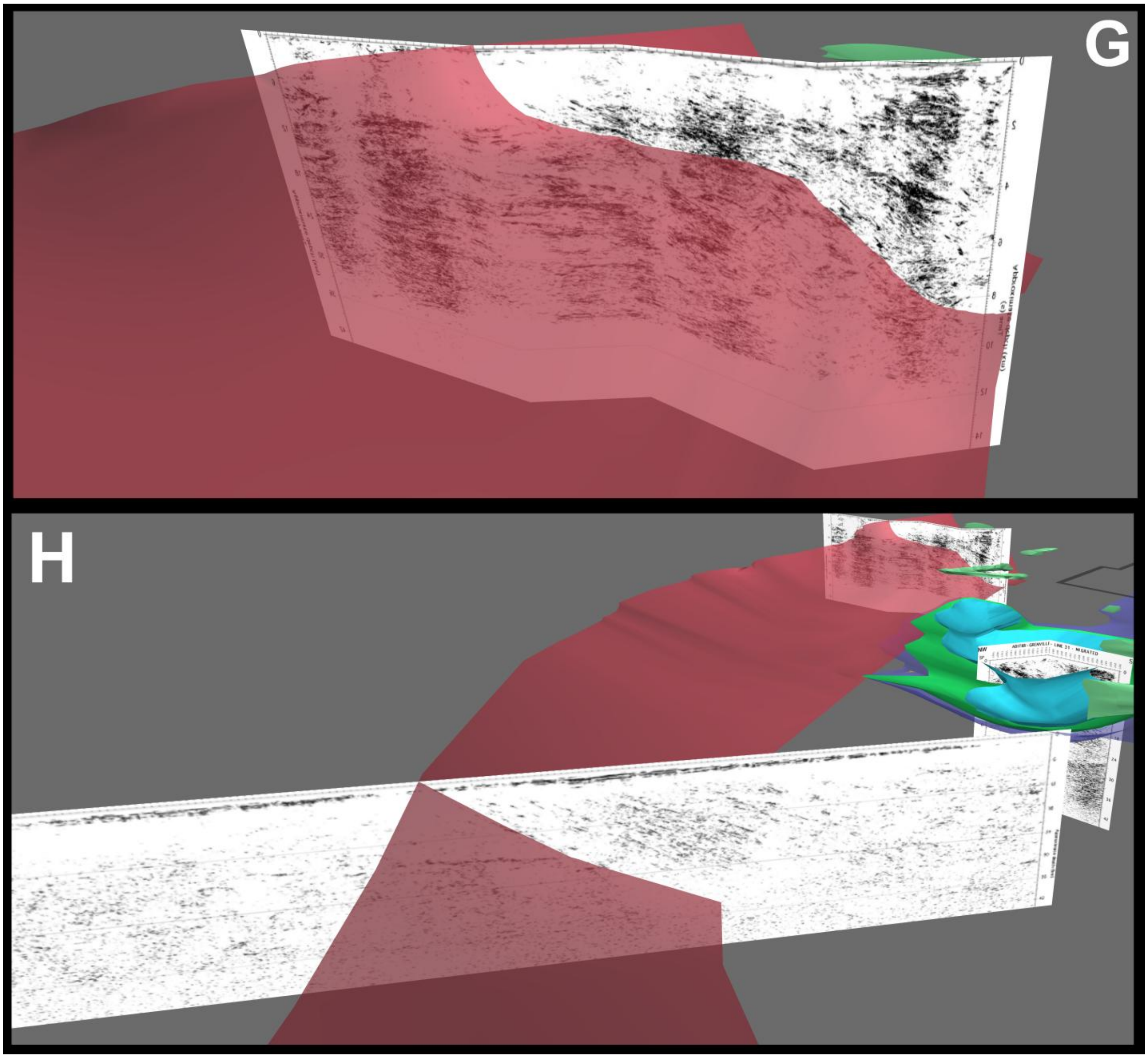

Figure 2.7: View of the Grenville Front; G- Lithoprobe line 15 from the West and above the surface, H- GLIMPCE line J from the South and above the surface.

Conclusions

The subsurface structure of the Grenville Front, Allochthon Boundary Thrust and Central Metasedimentary Belt boundary have been shown in three-dimensions to provide a new perspective of the tectonic structure in the SW Grenville Province. The GF transitions from linear dipping reflectors in GLIMPCE line J to a truncated ramp-flat style in Lithoprobe line 15 somewhere NW of North Bay. This appears to be caused by the extent of the Allochthonous crustal load which extends further towards Lithoprobe line 15. The ABT exhibits a ramp-flat geometry with an estimated thrust length of ~200km from ramp to klippe. The CMBb exhibits the tightest angle in the Big Bend which correlates with the oldest metamorphic age of thrusting and the superimposition of thrust geometry from the overlying thrusts onto the underlying younger thrusts supporting a top-down style of thrusting.

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Chapter 3:

Mesoproterozoic rifting in the Central Metasedimentary Belt, Grenville Province

Introduction

The Grenville Province of the SE Canadian Shield is a deeply exhumed orogenic belt with large areas of high grade gneisses. The high-grade gneisses are exposed in the Central Gneiss Belt (CGB) of Ontario, the Quebec Gneiss Belt (QGB) and Central Granulite Terrane (CGT) of Quebec (Figure 3.1). In contrast, the Central Metasedimentary Belt (CMB) is sandwiched between and structurally above these gneiss belts preserving relatively low-grade metavolcanic and supracrustal assemblages, notably marbles of the Grenville Supergroup (Wynne-Edwards, 1972). The CMB is comprised of a thick sequence of metavolcanic and metasupracrustal sequences locally intruded by, or uncomformably overlying granitic to gabbroic intrusions (Davidson, 1985). Using the extent of the dominant supracrustal assemblage it is possible to subdivide the CMB into the Marble, Quartzite and Morin domains, which was the original convention devised by Wynne-Edwards et al., (1966) and applied here (Figure 3.1; M, Q and Mo).

The preservation of low-grade metasedimentary rocks and the subparallel flanking gneiss belts led to the interpretation of the CMB as a back-arc aulacogen (Baer, 1976). In contrast to other tectonic models, such as the Composite Arc Belt (Brown et al, 1975) or the back-arc basin (Holm et al, 1985), the back-arc aulacogen can account for both the geometrical and geochemical characteristics of the region (Dickin and McNutt, 2007). The bimodal nature of the locally intercalated volcanic rocks (Bartlett, 1983), are suggestive of extensional tectonics particularly back-arc rifting. However, workers have interpreted the Marble domain of the CMB as accreted terranes of the Composite Arc Belt (Carr et al., 2000) or as a back-arc basin (Holm et al., 1986; Smith and Holm, 1990). The margins of the Marble domain equate with the extent of the aulacogen in the CMB which exhibits parallel-sided rift geometry, depicted by a series of enechelon segments ~50-200km apart (Figure 3.1c).

Nd isotope mapping was used to test these three models and has identified large areas of juvenile crust (1.1-1.34Ga) with discrete older blocks (1.35-1.6Ga) (Dickin and McNutt, 2007). The older crustal blocks (1.35-1.6Ga) are interpreted as melts generated from rifted basement in the thinned lithosphere of the propagating aulacogen. The older blocks have been termed Elzevir, Dysart and Douglas (Moretton and Dickin, 2013; Dickin et al., 2016).

Within the Grimsthorpe domain large tonalitic bodies have intruded some of the oldest gabbros in the CMB (Easton and Ford, 1994). The Weslemkoon batholith spans the majority of the Northern half of the Grimsthorpe domain and the Elzevir batholith is exposed as a large NE trending lobe in the Southern half. Northwest of the Elzevir lobe two smaller NE trending lobes of similar lithology outcrop on either side of Lingham Lake, termed the Lingham Lake intrusive complex (LL in Figure 3.2) (Easton, 1992). All of these tonalitic bodies represent some of the oldest and largest intrusives of the CMB which acted as rigid bodies during Grenvillian orogenesis (Schwerdtner and Yakovenko, 2004). The Weslemkoon batholith and Elzevir batholiths have unpublished U-Pb ages of 1276 and 1296Ma respectively quoted from a personal communication by Larry Heaman to McNutt and Dickin (2012). The western half of the Lingham Lake intrusive complex has published U-Pb ages of 1286±3Ma (Easton, 2008).

The Weslemkoon batholith was previously identified as a polygenetic stitching pluton by Dickin and McNutt (2007) with TDM ages >1.35Ga in the western half and <1.35Ga in the eastern side. Dickin et al, (2016) constrained the boundaries of the older portion which was restricted to a single block spanning the Grimsthorpe domain, termed the ‘Elzevir block’ (Figure 3.1b). Further sampling showed that thin salients of juvenile crust separate distinct older lobes of Nd model aged crust, discussed below.

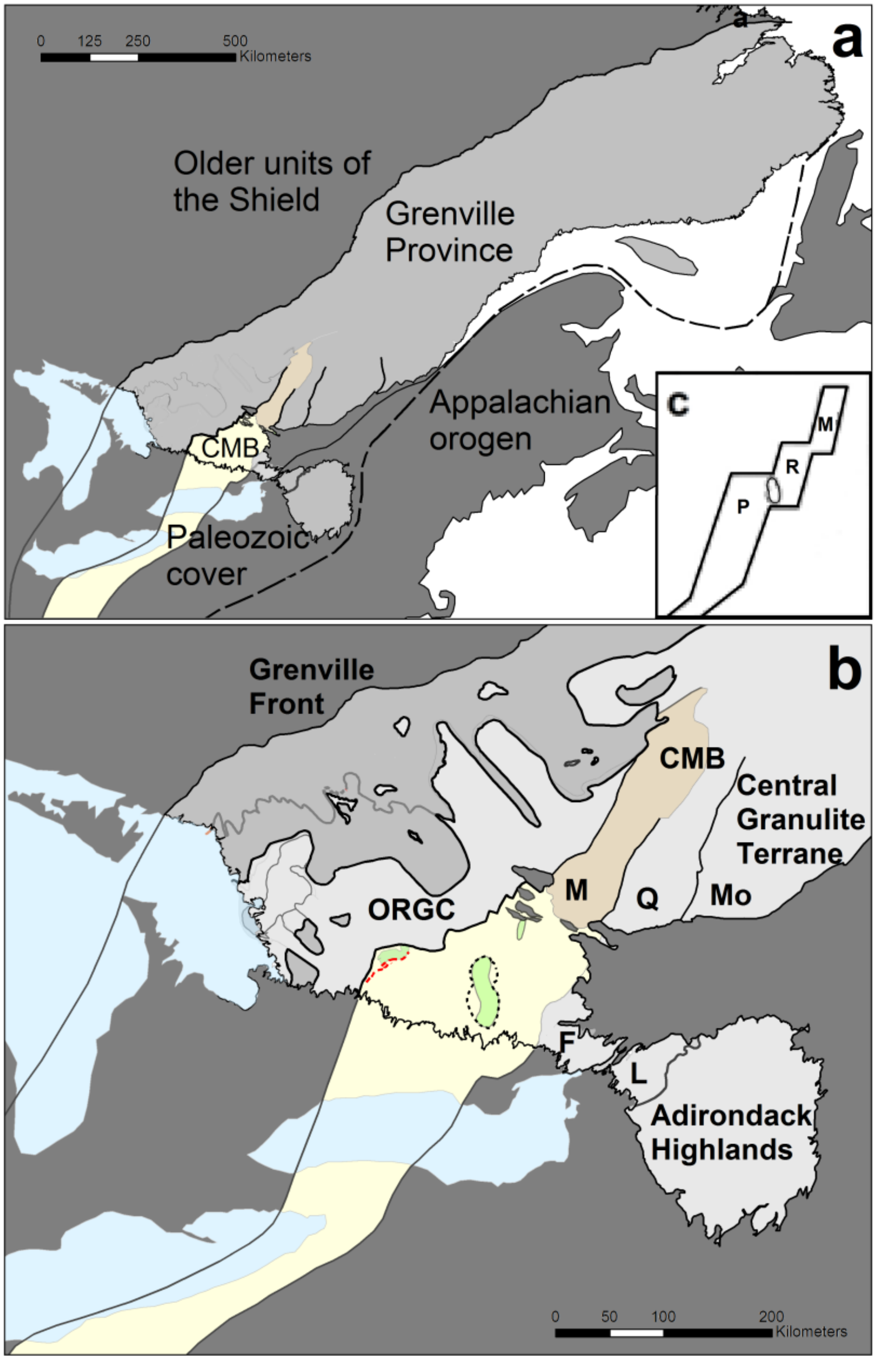

Figure 3.1: Summary maps of the Grenville Province to show (a) the location of the CMB within the Grenville Province and (b) the location of the CMB in regard to the flanking high-grade gneiss belts. Inset (c) shows tectonic interpretation of en-echelon rift segments; P-Peterborough, R- Renfrew, M- Maniwaki. The CMB is labeled according to lithological and regional subdivisions: F – Frontenac Terrane, L – Adirondack Lowlands, M – Marble domain, Q – Quartzite domain, Mo – Morin domain, ORGC – Ottawa River Gneiss Complex.

Sampling and analytical methods

The objective of this study was to characterize the protolith age boundaries of the previously identified rifted block in the Grimsthorpe domain by Dickin and McNutt (2007) and Dickin et al., (2016). Sampling was limited to granitoid orthogneisses which are recognized as forming the bulk continental crust. Previous studies have shown granitoids and granitoid orthogneisses have Nd isotope signatures that are consistent and predictable (McNutt and Dickin, 2012). Hence, the Sm-Nd depleted mantle model of DePaolo (1981) can be reliably applied to the Precambrian granitoids and orthogneisses in the CMB of the Grenville Province.

On average, 1 kg of rock was crushed, after the removal of any weathered, veined or migmatized material, and careful attention was given to obtain a fine powder that was representative of the whole rock. Sm–Nd analysis followed the established procedures. After four-day dissolution at 125 °C using HF and a small amount HNO3, samples were converted to the chloride form before splitting and spiking. Standard cation and reverse phase column separation methods were used. Nd isotope analyses were performed on a VG isomass 354 mass spectrometer at McMaster University using double filaments and a four-collector peak switching algorithm, normalized to a 146Nd/144Nd ratio of 0.7219. Average within-run precision on the samples was ± 0.000015 (2 sigma), and an average value of 0.51185 ± 20 (2 sigma population) was determined for the La Jolla Nd standard during this work. The reproducibility of 147Sm/144Nd and 143Nd/144Nd is estimated at 0.1% and 0.002% (1 sigma), respectively, leading to an analytical uncertainty on each model age of 20 Ma (2 sigma), based on empirical experience over multiple years of analyzing duplicate dissolutions.

Results

Nearly 60 new Nd isotope analyses are presented in Table 1, where they have been used to calculate TDM ages using the model of DePaolo (1981). Samples are grouped in Table 1 by age and location (Old/Juvenile, Weslemkoon/Elzevir). Samples are indicated in Figure 3.2 by colour coded symbols and in Figure 3.3 and 3.4 with numbered points according to Table 1. Published data are shown with similar symbolism but coloured black (Dickin and McNutt, 2007; Dickin et al., 2016).

The results of the new Nd isotope data are shown in Figure 3.2 revealing the existence of 4 NE trending lobes of older crust (>1.35Ga-blue triangles and squares) separated by younger salients (<1.35Ga-red open circles) within the Weslemkoon batholith. In Figure 3.3 the results of the Weslemkoon batholith are shown and in Figure 3.4 a sketch map from Lumbers (1968) shows extrapolated foliation directions and preliminary geologic mapping. In areas where bedrock is easily accessible such as on Weslemkoon Lake the petrological breaks identified by Lumbers (1968) roughly correlate with the identified Nd isotope boundaries. This suggests that the older lobes and younger salients represent different pulses of magma contributing to the Weslemkoon batholith during its formation.

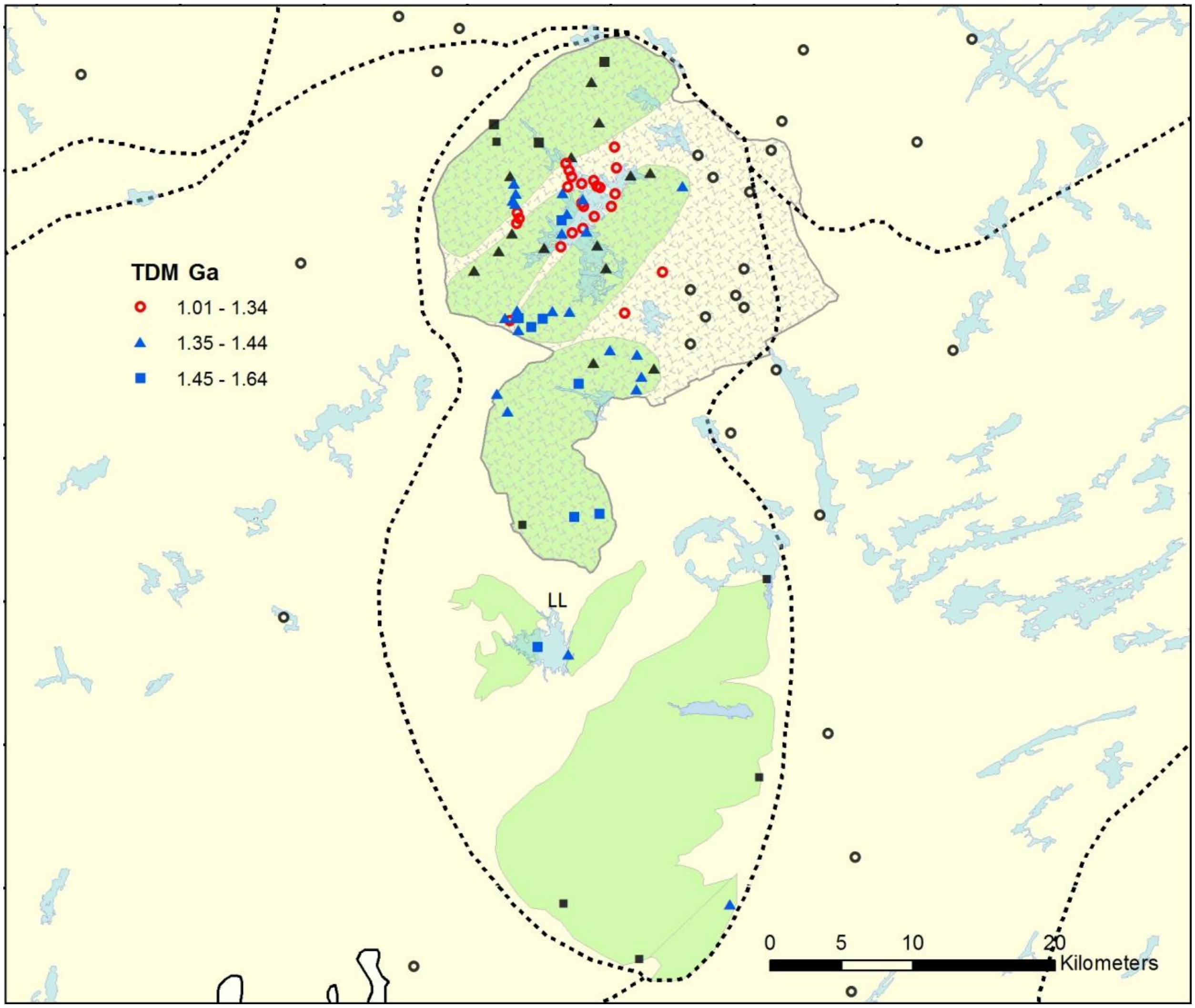

Figure 3.2: Map of the sample localities in the Grimsthorpe domain showing samples from the Weslemkoon batholith, Elzevir batholith and the Lingham Lake intrusive complex (LL). B) Sample localities of the Weslemkoon batholith showing samples around Weslemkoon Lake.

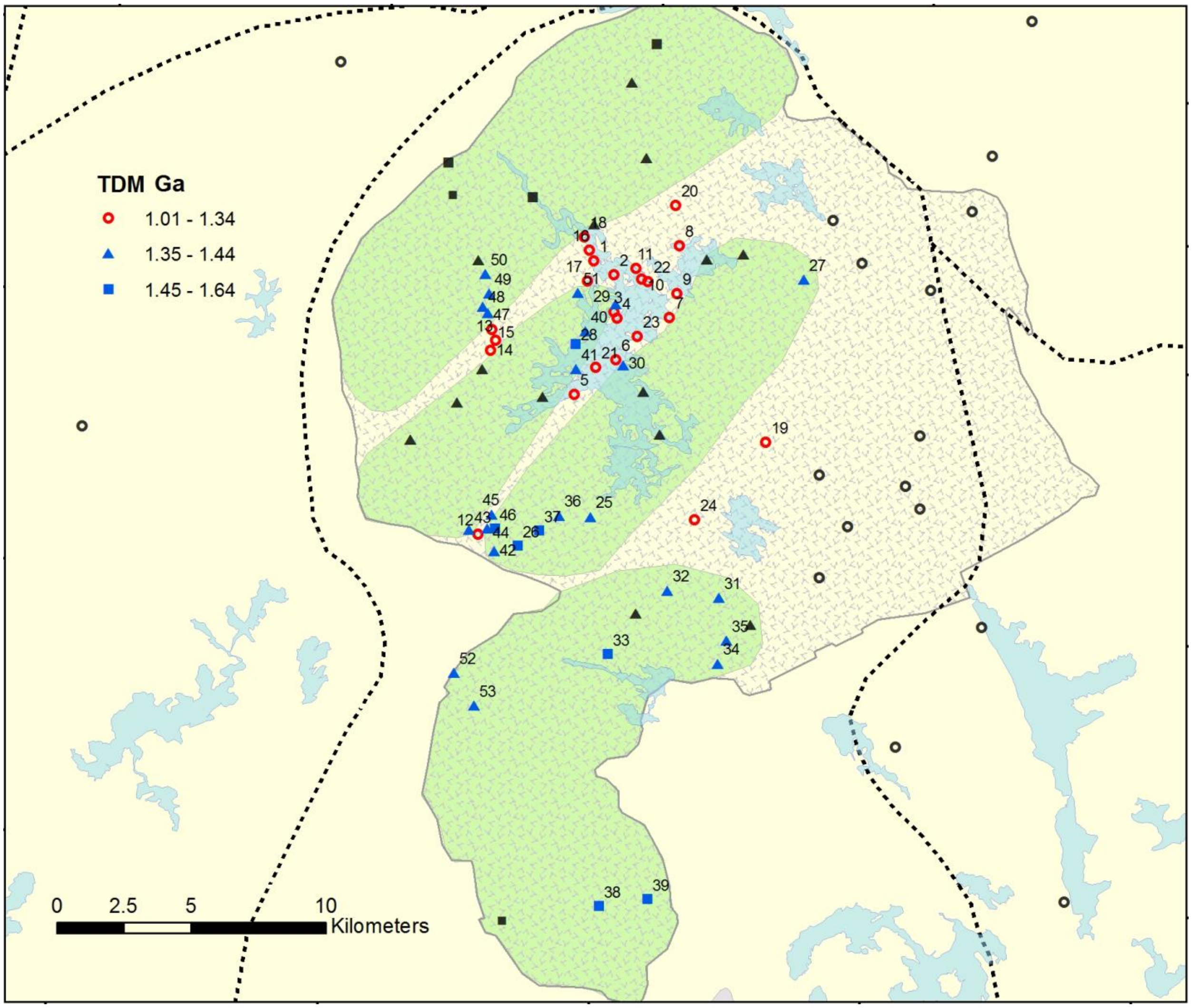

Figure 3.3: Map of the samples from the Weslemkoon batholith numbered according to Table 1.

Previous attempts to identify a systematic difference between the petrology/geochemistry of the 'old' and 'juvenile' Weslemkoon Nd suites found that on a whole rock scale their chemistry is too similar to differentiate (Dickin et al., 2016). Similar batholiths were used for comparison such as the Coast Mountains batholith from British Columbia (Girardi et al., 2012) and the Wooley Creek batholith in northern California (Coint et al., 2013) showing that a series of magma bodies with different crustal formation ages can amalgamate into a single, concentrically foliated pluton. The new data support the earlier model of the Weslemkoon batholith but refine the boundaries of the 'old' and 'juvenile' crust. As previously stated, the Nd isotope results appear to have some correlation with the 'visible' petrologic boundaries (Lumbers, 1968) inside the Weslemkoon batholith (Figure 3.4).

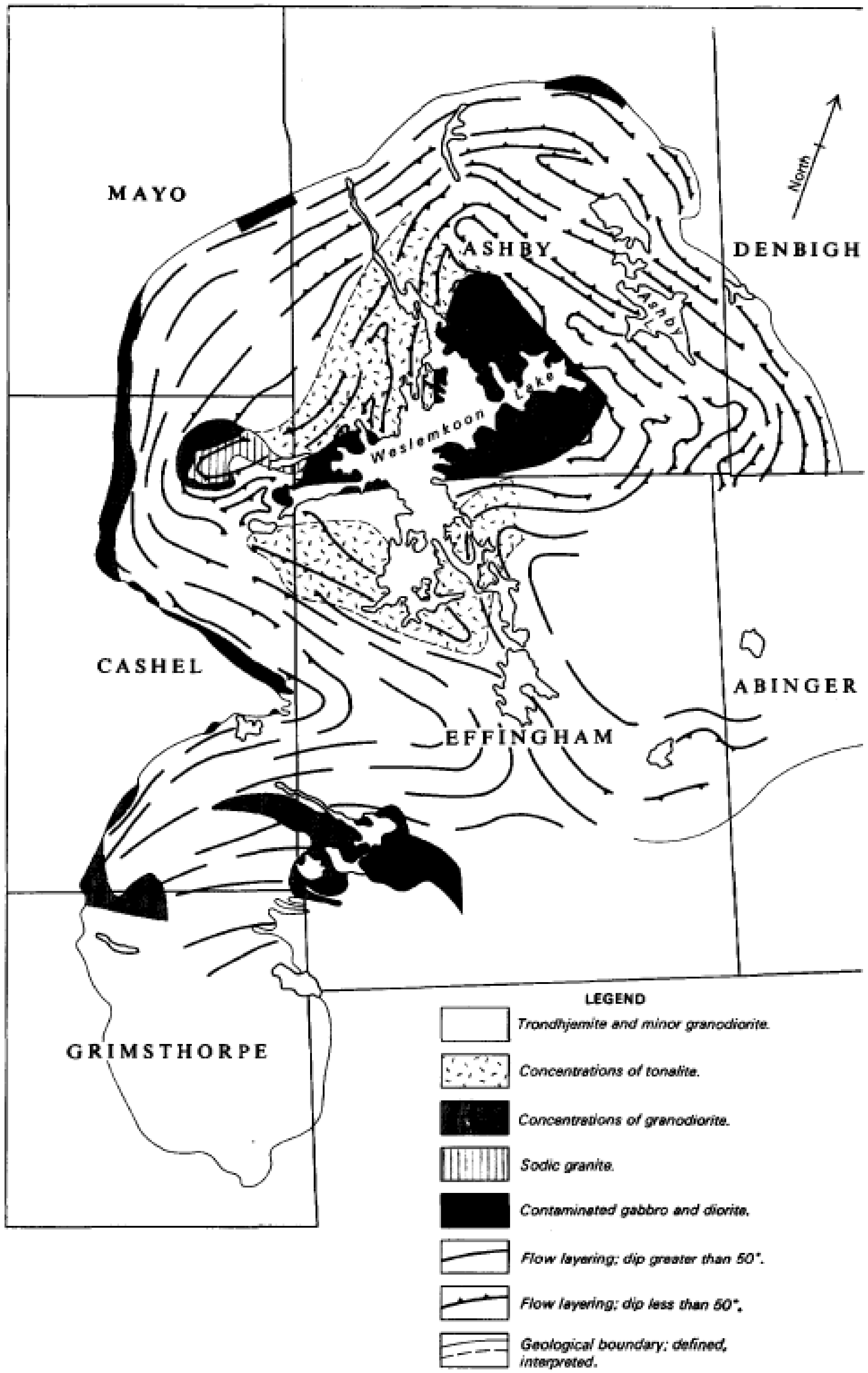

Figure 3.4: Sketch map from Lumbers (1968) showing foliation direction and intensity with some preliminary geologic mapping of the Weslemkoon batholith.

The Southern half of the Grimsthorpe domain contains the Elzevir batholith and Lingham Lake intrusive complex (LL) (Figure 3.5). Previous work showed that the Elzevir batholith was only comprised of the older Nd component unlike the polygenetic Weslemkoon batholith (Dickin and McNutt, 2007). However, the new data shows that the Elzevir batholith contains some of the moderate Nd component (1.35-1.44Ga) as a fault bounded block at the SE flank. In this region tectonized ultramafic rocks of the Queensborough complex can be found in the Moorton shear zone at the southeastern-most flank (Easton, 1992). In some ways, this feature is similar to the Eastern side of the LL which is flanked by the ultramafic Queensborough Complex and also exhibits the moderate Nd component.

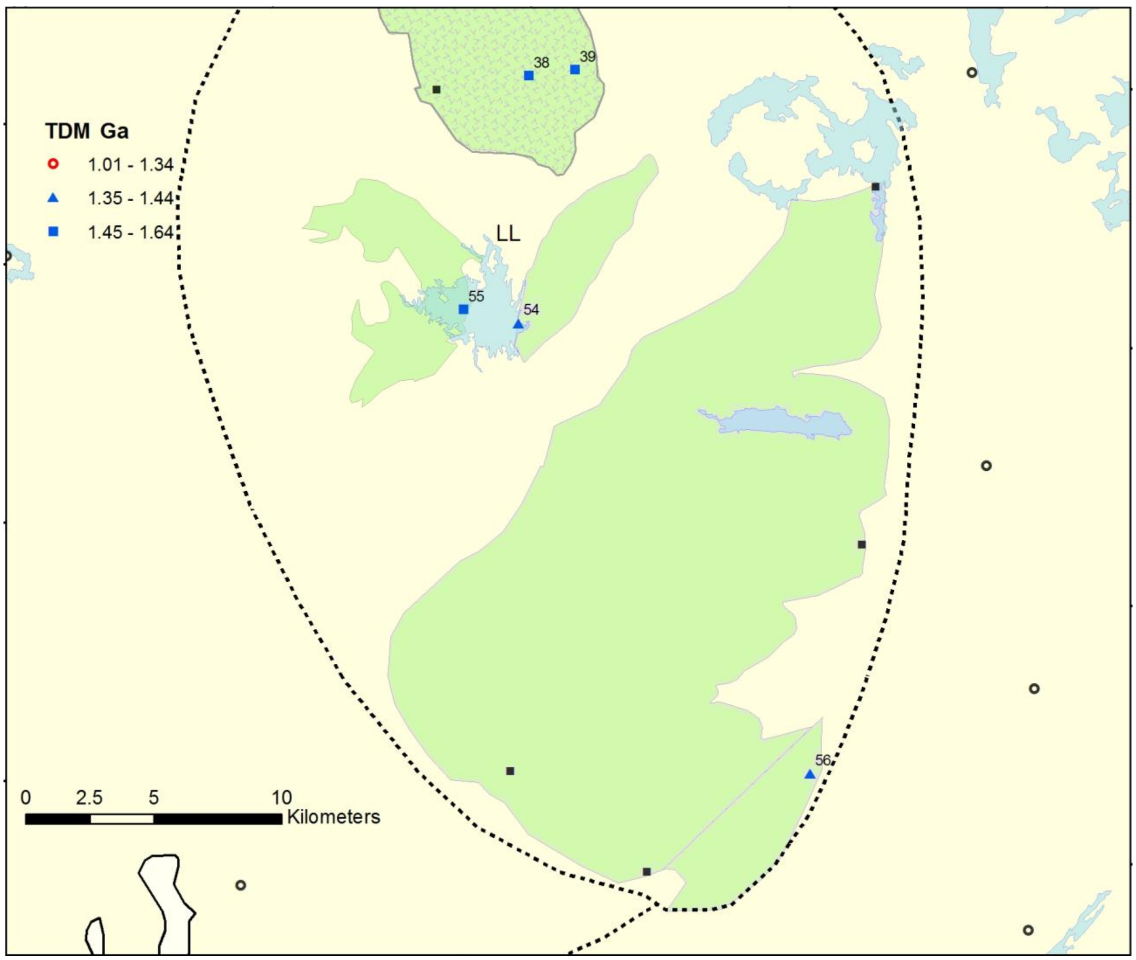

Figure 3.5: Map of the Southern Grimsthorpe domain showing samples from the Elzevir batholith and Lingham Lake intrusive complex (LL). Samples are numbered according to Table 3.1.

Table 3.1: Location and Sm-Nd data for samples from the Grimsthorpe domain.

Map#	Sample#	Y	X	Nd ppm	Sm ppm	147Sm/144	143/144Nd	TDM (Ga)
Young								
1	WJ1	4992548	308196	7.4	1.4	0.1145	0.512253	1.21
2	WJ2	4992102	308958	6.7	1.28	0.1151	0.512227	1.26
3	WJ3	4990735	309066	7.0	1.3	0.1117	0.512183	1.28
4	WJ4	4990516	309190	8.2	1.12	0.0825	0.511971	1.25
5	WJ9	4987570	307828	9.1	1.68	0.1122	0.512209	1.25
6	WJ10	4988979	309280	7.7	1.45	0.1145	0.512219	1.26
7	WJ14	4990665	311122	9.0	1.74	0.1168	0.512216	1.31
8	WJ16	4993360	311292	6.8	1	0.0899	0.512036	1.24
9	WJ17	4991569	311346	7.2	1.28	0.1078	0.512164	1.26
10	WJ18	4992009	309999	4.3	0.87	0.122	0.512249	1.32
11	WJ19	4992396	309763	7.1	1.3	0.1097	0.512193	1.24
12	WJ22	4982172	304661	9.3	1.74	0.1136	0.512244	1.22
13	WJ40	4989354	304787	8.3	1.72	0.1253	0.512287	1.3
14	WJ42	4988981	304624	10.3	1.84	0.1082	0.512136	1.32
15	WJ43	4989742	304607	7.5	1.59	0.1274	0.512294	1.32
16	WJ50	4992937	308004	10.6	2.36	0.1342	0.512368	1.29
17	WJ51	4991788	308004	10.8	1.93	0.1086	0.512125	1.33
18	WJ56	4993406	307764	15.0	2.17	0.0877	0.51196	1.31
19	WK7	4986351	315029	7.6	1.54	0.1224	0.512238	1.34
20	WK11	4994818	311053	7.8	1.56	0.1212	0.512282	1.23
21	WK24	4988631	308548	13.6	1.80	0.0801	0.511924	1.28
22	WK27	4991951	310242	5.6	1.00	0.1084	0.512150	1.29
23	WK29	4989884	309993	14.8	1.92	0.0788	0.511906	1.28
24	WK51	4983286	312624	17.4	3.01	0.1045	0.512101	1.31
Old								
25	WK1	4983100	308770	12.5	2.42	0.1165	0.512170	1.37
26	WK2	4981850	306160	12.0	2.06	0.1040	0.511978	1.48
27	WK9	4992436	315994	10.7	1.93	0.1094	0.512117	1.35

28	WK25	4989443	307746	5.1	1.47	0.1734	0.512653	1.46
29	WK26	4991021	309108	5.4	1.12	0.1249	0.512242	1.37
30	WK30	4988789	309560	10.6	1.83	0.1049	0.512069	1.36
31	WK52	4980470	313730	10.5	2.25	0.1302	0.512283	1.38
32	WK53	4980600	311800	20.6	3.66	0.1077	0.512039	1.44
33	WK55	4978100	309770	16.1	3.13	0.1177	0.512106	1.49
34	WK57	4978040	313870	15.4	2.87	0.1125	0.512101	1.42
35	WK58	4978920	314140	15.0	2.49	0.1007	0.512024	1.37
36	WK61	4983059	307606	3.2	0.49	0.0919	0.511891	1.44
37	wk63	4982459	306913	22.3	4.16	0.1130	0.512057	1.49
38	WK65	4968794	310134	14.9	2.68	0.1087	0.512013	1.49
39	wk67	4969176	311903	20.5	3.41	0.1006	0.511932	1.50
40	WJ5	4989925	308085	7.7	1.69	0.1324	0.51231	1.37
41	WJ7	4988513	307836	11.6	2.06	0.1075	0.512083	1.38
42	WJ20	4981567	305307	10.5	1.64	0.0946	0.51194	1.41
43	WJ21	4982306	304335	22.9	3.78	0.0996	0.511991	1.4
44	WJ31	4982394	305005	13.8	3.95	0.1335	0.51229	1.43
45	WJ32	4982927	305120	23.2	3.5	0.0909	0.511945	1.36
46	WJ34	4982412	305264	22.3	4.2	0.114	0.512049	1.52
47	WJ44	4990330	304439	14.0	1.8	0.0778	0.511839	1.35
48	WJ45	4990569	304220	5.7	1.28	0.1361	0.51233	1.4
49	WJ46	4991055	304423	7.7	1.52	0.1188	0.512179	1.4
50	WJ47	4991762	304220	13.3	2.39	0.1089	0.512103	1.37
51	WJ53	4991321	307699	11.6	2.15	0.1119	0.512099	1.41
52	WJ60	4976978	304164	15.0	2.48	0.0999	0.511981	1.42
53	WJ62	4975831	304994	10.3	1.83	0.1075	0.51206	1.41
54	JS31	4959163	310451	17.5	3	0.1038	0.512039	1.39
55	JS32	4959548	308267	18.6	3.53	0.1146	0.512027	1.56
56	EJ1	4942551	323046	11.9	2.3	0.1164	0.512144	1.41

Discussion

The Afar rift junction is the product of an upwelling mantle plume beneath the eastern African plate. The upwelling mantle plume has thinned the crustal lithosphere through domal extension facilitated by the emplacement of new magmatism (Falvey, 1974). The Afar rift junction will be used as one analogue for the CMB. Another example of continental rifting is the Gulf of California which began rift related activity following subduction break-off of the Farallon plate below North America ~30Ma (Menard, 1978). The Gulf of California rift propagated through oblique extension which is depicted by a series of short spreading centers and basins accommodated by long transform faults.

Rifted blocks or microplates are typically generated near propagating passive margins or continental rift settings (Vink et al., 1984). In the Afar junction the Danakil horst exposes Precambrian basement of the Danakil block. The Danakil block rifted from the Somalia plate and became stranded between the Red Sea and the Afar depression (Eagles et al., 2002). In the Gulf of California, there are several blocks of continental crust that are surrounded by thin oceanic crust. One of the rifted blocks of interest to this study is Isla Tiburon (IT) in Figure 3.6 (Gastil, 1999; Abera et al., 2016). These crustal fragments have been forced away from the main continental mass through ridge migration and/or complex wrench faulting (Abera et al., 2016; Nemcok et al., 2016).

Figure 3.6a shows the postulated rift propagation and the incorporation of the Elzevir block between the Peterborough and Mazinaw rift segments at ~1310Ma. Figure 3.6b shows complex wrench faulting and magmatic intrusions responsible for the rotation and fragmentation of the Danakil block in the Afar junction. Figure 3.6c shows complex wrench fault system in the Gulf of California rift. The two mechanisms of magmatic intrusion and wrench fault systems most likely contributed in tandem to the rifting of the 'Elzevir block'. Complex wrench faulting and shifting magmatic locus between the Peterborough and Renfrew rift segments (Dickin et al., 2016) probably promoted crustal melting of the region below the 'Elzevir block'. The NW trending older lobes are elongated parallel to the rift axis suggesting a transtensional mid-upper crustal setting.

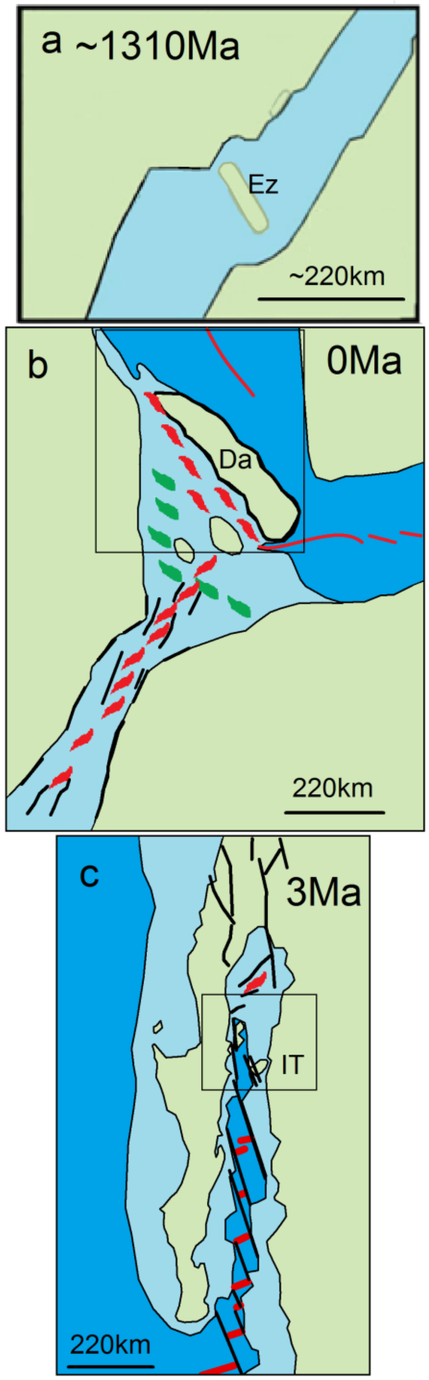

Figure 3.6: Schematic representation of extension and magmatism in the CMB and modern analogues; a) CMB, b) Afar rift, c) Baja California rift. Old and new spreading centers and magmatic intrusions are shown in green and red respectively. Old continental crust is light green, juvenile and thin continental crust is light blue and oceanic crust is dark blue. Approximate location of Figures 3.7 and 3.8 are indicated by the boxes in b and c respectively. Ez- Elzevir block, Da- Danakil block, IT- Isla Tiburon

The Nd isotope data shows that the Grimsthorpe domain contains a series of NE trending older lobes separated by thin salients of younger crust. The NE trending lobes are interpreted as melts generated from a larger block of rifted crustal basement within the aulacogen. The Elzevir and Weslemkoon batholiths sample the crustal basement of the rifted block and are elongated parallel to the proposed rift axis. The 1296-1276Ma ages for the Elzevir and Weslemkoon batholiths (McNutt and Dickin, 2012) prohibits elongation of the older NW trending lobes during the Grenville orogeny demonstrated by the lack of Grenvillian deformation on the interior the Weslemkoon and Elzevir batholiths (Lumbers, 1968). This finite structure is interpreted in terms of crustal-scale faulting. For example, this pattern is similar to the fault structure of the Danakil block which is breaking apart in the Afar depression. Epicenters and focal planes of the largest earthquakes for the Danakil depression in the period of 1973-2011, after Ogubasghi and Goitom, (2015), show how the Danakil block is currently being broken apart (Figure 3.7). Crustal melts generated from the Precambrian Danakil block would be isotopically distinct from the melts generated by the upper mantle. It is argued that melts generated from the juvenile mafic crust would be preferentially emplaced in the mid-crust along pre-existing structural features such as faults.

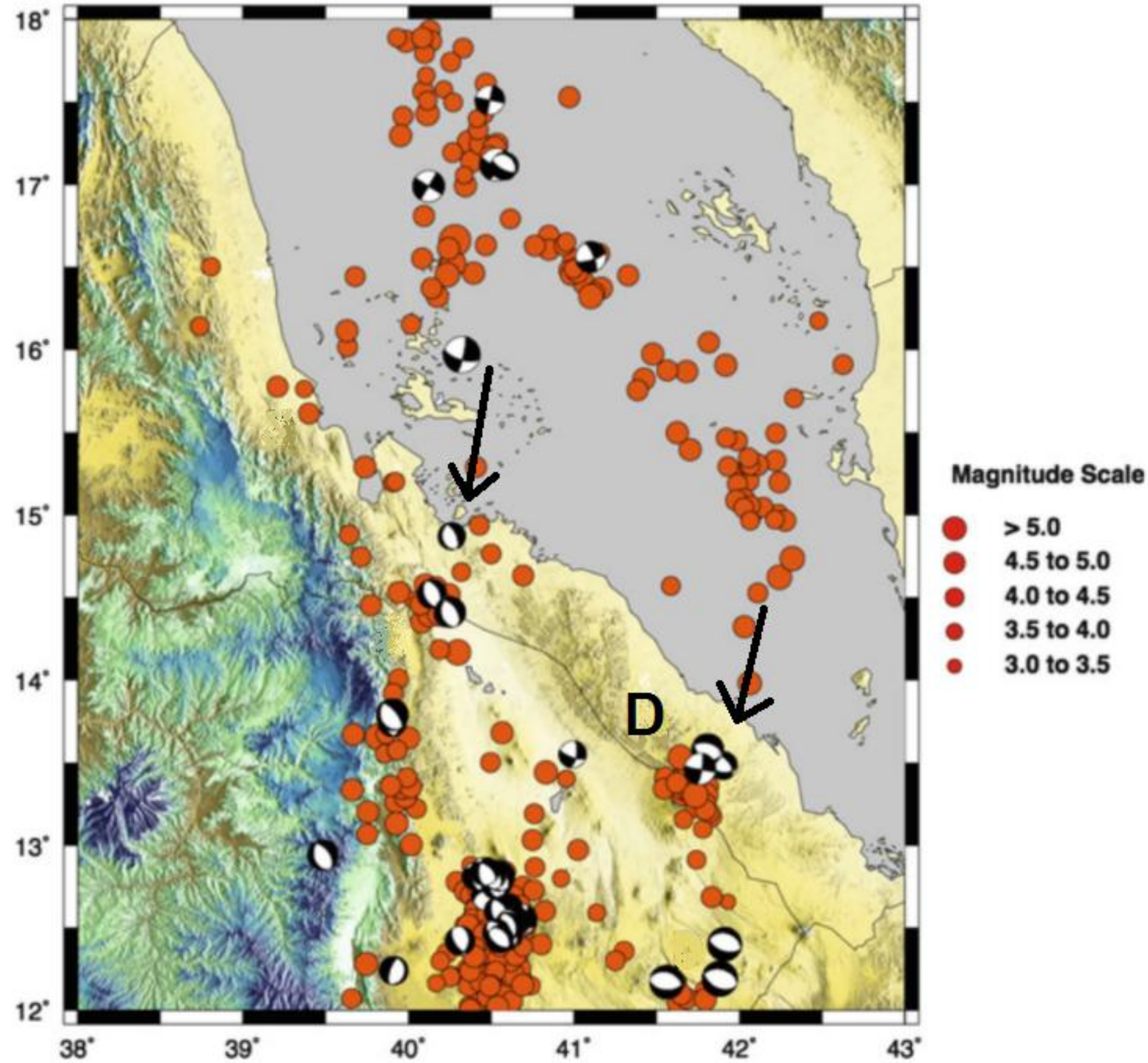

Figure 3.7: Map showing epicenters and focal planes during 1973-2011 after Ogubasghi and Goitom (2015). The Danakil block is identified by the letter D and arrows identify focal planes of seismic events that cross through the Danakil block.

Continental rift geometry is typically associated with a curvilinear pattern in map view with segments 50-200km apart separated by ‘accommodation zones’. These segments typically propagate as one or more arms normal to the regional stress field (Bosworth, 1985). The geometry of the CMB appears as a series of enechelon segments ~100-200km apart that propagated oblique to the SE Laurentian margin during the period 1300-1240Ma (Dickin and McNutt, 2007). The boundaries of the CMB suggest propagation in hot thin Mesoproterozoic back-arc crust to the SE and failure at cold thick Archean basement to the NE. This is similar to the geometry of the Gulf of California rift. Figure 3.8 shows a close-up of the complex wrench fault systems in the Gulf of California, after Bennett et al. (2016). This type of complex fault system has contributed to the geometry of continental rift observed in the Gulf of California and the transport/rifting of Isla Tiburon (Figure 3.8).

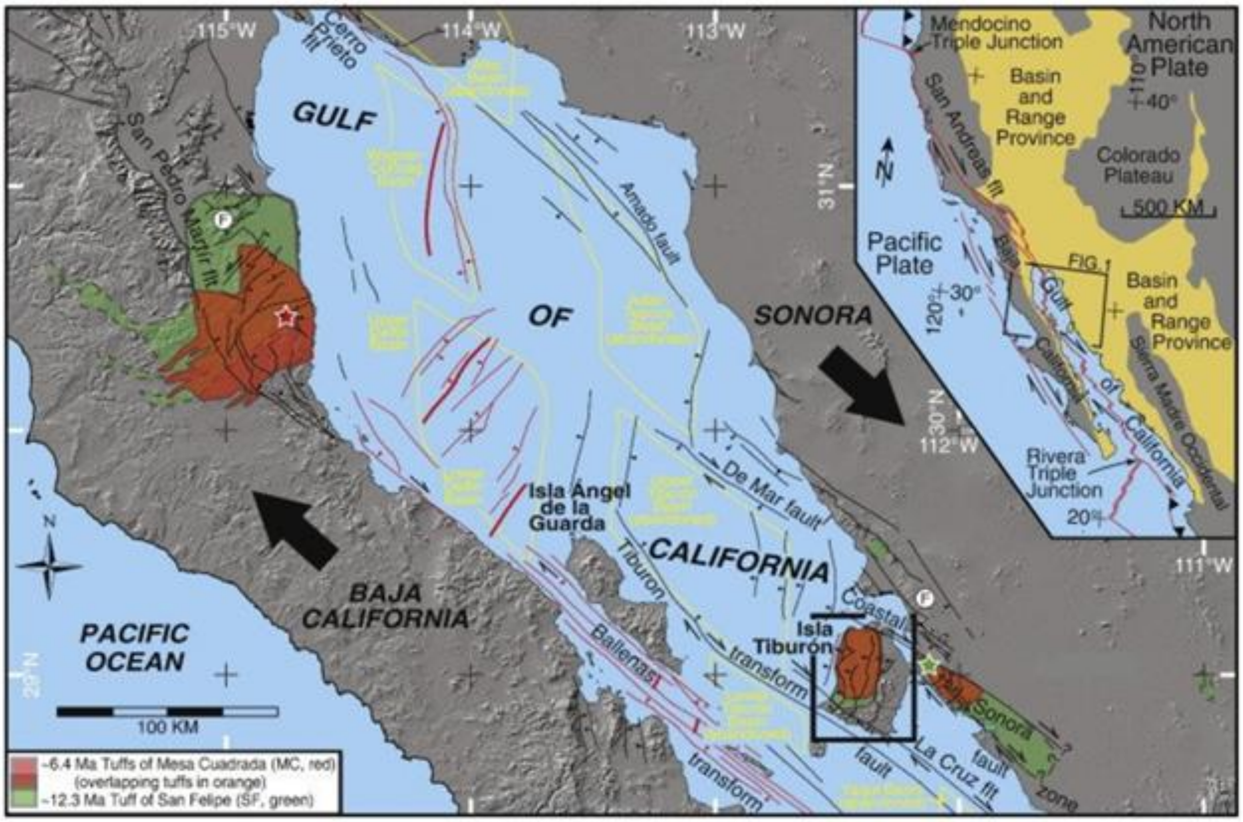

Figure 3.8: Map of the fault patterns and magmatic associations in the Gulf of California near the rifted continental block Isla Tiburon after Bennett et al. (2016).

Figure 3.9 depicts a schematic representation of the fragmentation and magmatic inclusion of the Elzevir block during the initial stages of rifting and later crustal melting in the CMB. The fault patterns are inferred from the current geometry of the domains with older crustal formation ages in the Elzevir and Weslemkoon batholiths. The Elzevir and Weslemkoon batholiths were emplaced at 1296Ma and 1276Ma which requires rift related fragmentation to occur around 1300Ma and the crustal melting could have occurred within that 30Ma window.

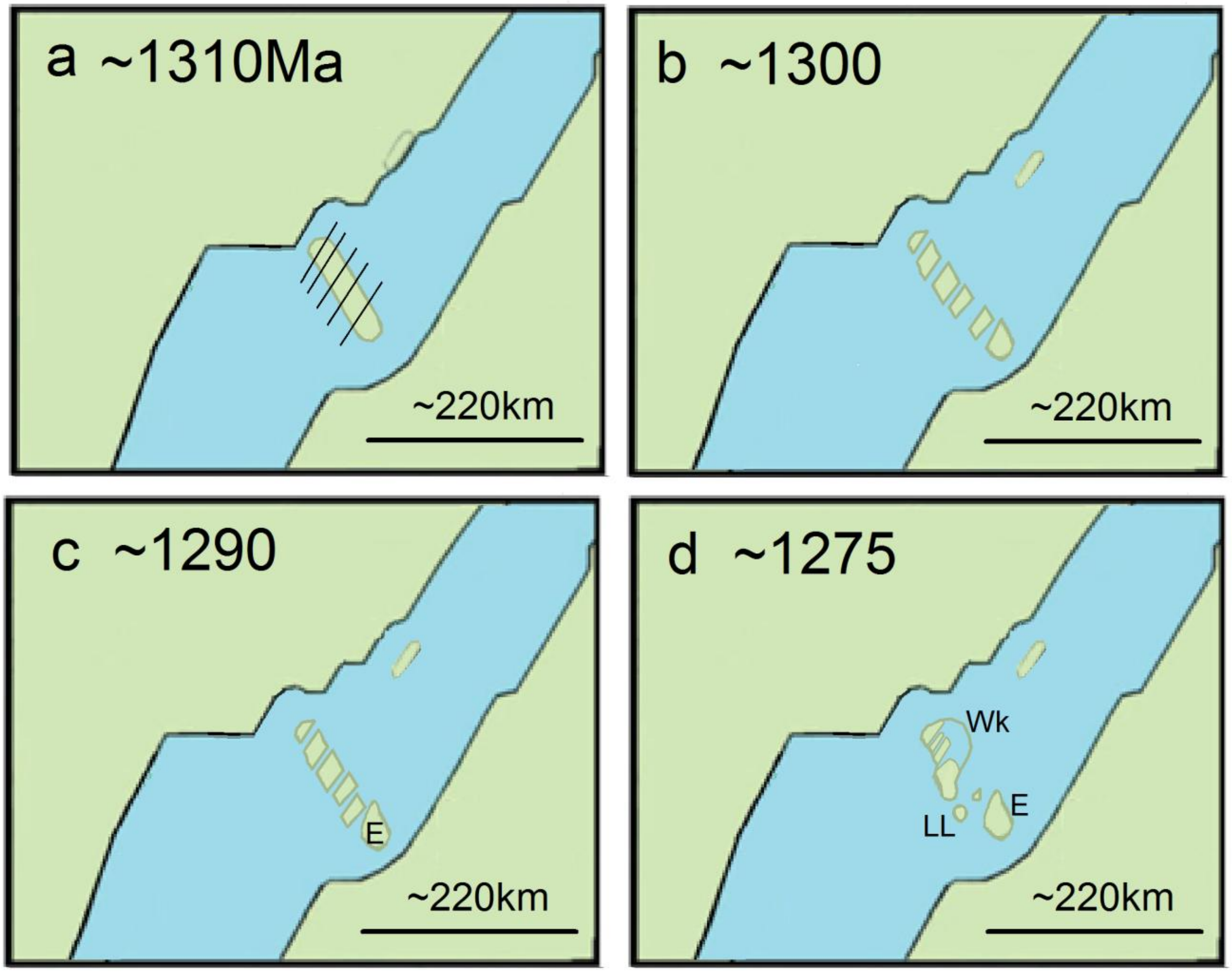

Figure 3.9: a) Schematic representation of possible fault patterns of the Elzevir block during rift propagation (~1310Ma). b) Orientation of the Elzevir block during fragmentation (~1300Ma). c) Partial melting and magma accumulation of the Elzevir batholith (~1290Ma). d) Partial melting and magma accumulation of the Weslemkoon batholith and Lingham Lake intrusive complex, completed by 1275Ma. Green colouration reflects the Laurentian continental crust and blue colouration represents juvenile rift related magmatism. Abbreviations; E-Elzevir batholith, LL-Lingham Lake intrusive complex, Wk-Weslemkoon batholith.

In the US a similar extensional event was identified in the Adirondack Lowlands. Termed the Trans Adirondack Basin (TAB), currently located ~150km to the SE of the CMB (Chiarenzelli, 2010). Sedimentation in the TAB likely began shortly after but at a similar time to the CMB evidenced by ~1280-1240Ma detrital zircon in several units of the Grenville Supergroup (Chiarenzelli et al., 2012; Chiarenzelli et al., 2015). The TAB, like the CMB, contains a sequence of ultramafic rocks but fewer <1.35Ga TDM ages exist suggesting some variability between ensimatic rifting and ensialic basin formation nearer the Laurentian marginal arc (Chiarenzelli et al., 2010; Chiarenzelli et al., 2011). This could be related to the thickening of continental crust nearer the marginal arc.

The bimodality of continental rifting can be identified from regional geochemical signatures. Temporal and spatial analysis of back-arc rift magmatism in Baja California depicts an average decrease in SiO_2 over time along with the intercalation of calc-alkaline and tholeiitic rocks throughout rift evolution (Bryan et al., 2016). In the CMB back-arc aulacogen the geochemical bimodality has been preserved by Elzevirian aged igneous rocks showing calc-alkaline and tholeitic trends. However, temporal analysis is more complicated in the CMB because many lithologies remain undated.

In Figure 3.10a the Elzevirian aged rocks from the CMB are plotted on a Jensen diagram with a data compilation of rocks from the Gulf of California rift spanning the Oligocene to present (Bartlett, 1983; Smith and Holm, 1990; Smith and Harris, 1996; Smith et al., 2001; Dickin et al., 2016; Batiza, 1979; Gastil, 1979; Desonie, 1992; Bellon et al., 1995; Castillo, 2002; Martin, 2000; Benoit, 2002; Calmus, 2003). In Figure 3.10b the same Elzevirian igneous rocks and Gulf of California data are plotted on a TAS diagram showing the typical bimodality of back-arc extension (Bryan et al., 2014). The preservation of bimodal geochemistry is indicative of rifting during the period of ~1300-1240Ma. It should be noted that the bimodality of the CMB is more pronounced than the Gulf of California. It is uncertain whether this is due to sampling bias or another related or unrelated subduction process.

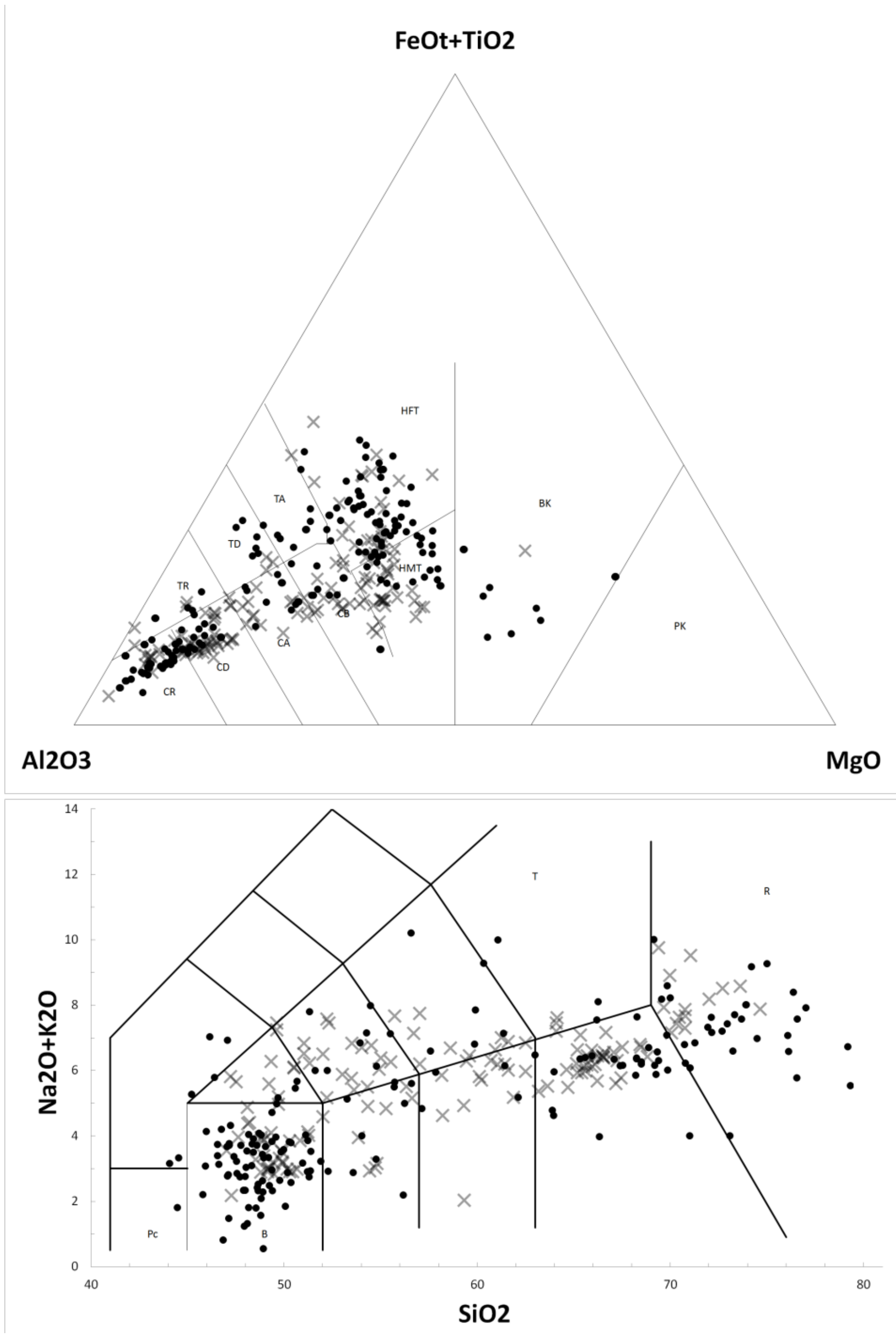

Figure 3.10: Jensen and TAS plot of Elzevirian aged 1300-1220Ma igneous rocks in the CMB (solid circles) with Oligocene to recent extrusives from the Gulf of California (crosses) (Jensen, 1974; Le Bas et al., 1986).

Conclusions

The Central Metasedimentary Belt of the SW Grenville Province is interpreted as an aulacogen that propagated oblique to the SE Laurentian margin during a period of crustal formation ~1300-1240Ma. The aulacogen is evidenced by;

1) Rifted basement identified by Nd isotope mapping as NE trending older lobes. The older NE trending lobes are interpreted as melts generated from continental basement. The emplacement ages of 1296-1276Ma for the Elzevir and Weslemkoon batholith suggest that elongation of the older lobes could be caused by rift transtension preceding closure of the rift and later Grenvillian orogenesis.
2) Rift geometry shown by the margins of the Marble domain in the CMB as a series of en-echelon segments separated by 50-200km.
3) Elzevirian magmatism (~1300-1240Ma) with bimodal calc-alkaline and tholeiitic suites typical of continental rifting throughout the Marble domain of the CMB.

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Chapter 4:

Plume in the SW Grenville Province ~1.4-1.2Ga?

Introduction

The Queensborough Complex (QC) is located in the Grimsthorpe domain of the Central Metasedimentary Belt (CMB), SW Grenville Province (Figure 4.1). Early mapping identified the QC as part of the surrounding metavolcanic units comprising some of the oldest lithologies in the CMB (Lumbers, 1967). The first detailed studies of the QC revealed that the small poorly exposed outcrops of ultramafic rocks show compositional layering (~1m) characterized by distinct mineral assemblages (LeBaron et al., 1987). The prevalent banding was interpreted as metamorphism and deformation of a sequence of coarse-grained ultramafic rocks. The foliations of the QC dip ~50-70 degrees away from the Elzevir batholith as the lenticular mafic-ultramafic sequence wraps around the Southern end of the batholith. This suggests that the Elzevir batholith intruded the mafic-ultramafic sequence (Easton, 1992). The intrusive event was at ~1296Ma which is the crystallization age of the Elzevir batholith (McNutt and Dickin, 2012). The mafic sequence of the QC is comprised of 'gabbros and their sheared derivatives' which are intruded by a few mafic dykes and in some outcrops pillow structures can be observed (Smith and Harris, 1996).

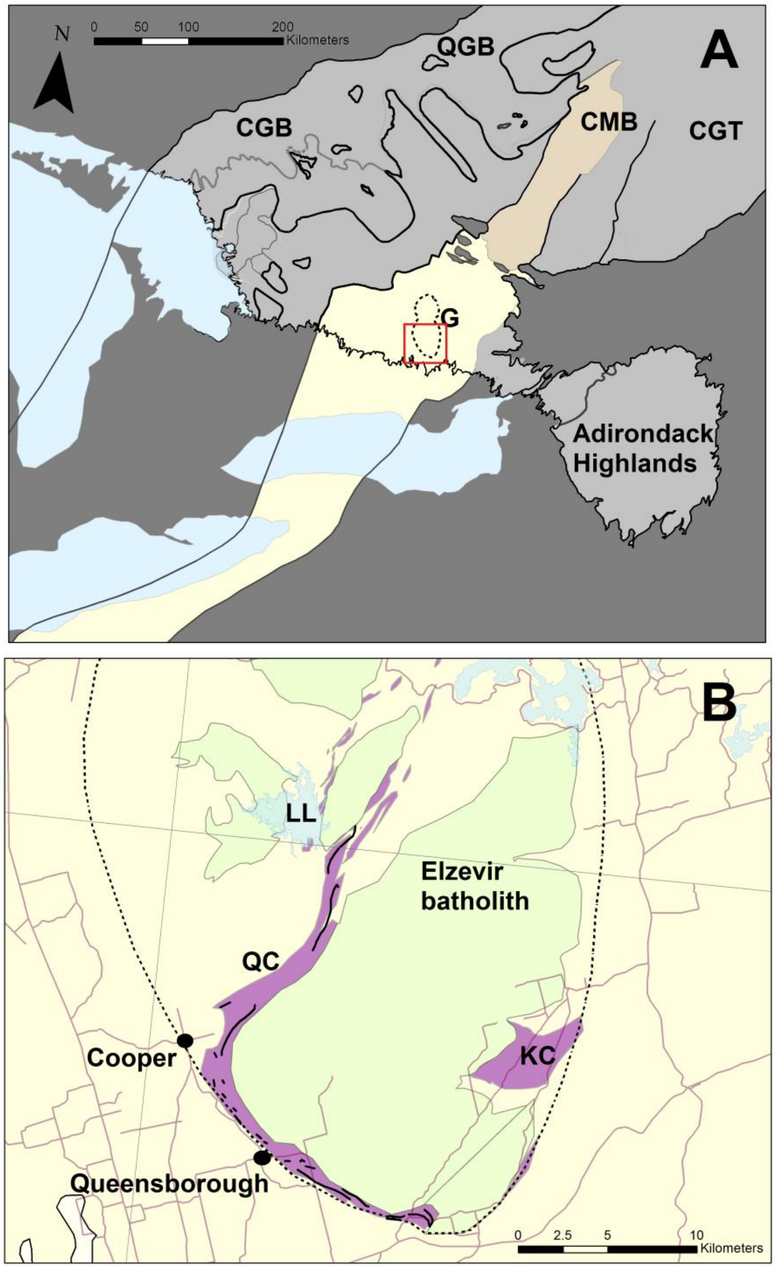

Figure 4.1: A) Map of the SW Grenville Province in Ontario and western Quebec. The red box indicates the extent of the second map. B) Map of the southern end of the Elzevir batholith and the Queensborough Complex (mafic- purple and ultramafic- black lines) showing major roads. Abbreviations: QGB- Quebec Gneiss Belt, CGB- Central Gneiss Belt, CMB- Central Metasedimentary Belt, CGT- Central Granulite Terrane, G- Grimsthorpe domain, QC- Queensborough Complex, KC- Kaladar Complex, LL- Lingham Lake intrusive complex.

Initially the QC was identified as a Mesoproterozoic meta-komatiite based on major element contents and compositional zoning of the sequence (LeBaron et al., 1987). Then it was suggested that the QC did not exhibit primary spinifex textures and was likely intrusive (Easton and Ford, 1990). Geochemical analyses of the QC and related mafic units built upon the prior mapping by showing their kinship to mantle rocks and proposed that the QC represented back-arc ophiolites (Harris, 1994; Smith and Harris, 1996). However, the geochemical studies did not properly constrain the trace element composition of the QC mafic-ultramafics, discussed below.

Another mafic-ultramafic complex in the Grimsthorpe domain is the Kaladar Complex (KC) (Figure 4.1b). A study of the KC was never published, but an unpublished PhD thesis has provided the necessary data for comparison with the QC (Chappell, 1977). Based on their composition it appears that the QC and KC are equivalent units and part of the same magmatic event that was later intruded by the Elzevir batholith at 1296Ma. The unpublished PhD thesis was supervised by R.L. Brown, who in 1975 published his interpretation of the CMB as a series of accreted island arc terranes. The accreted arc terrane model was partially based on the apparent change in chemistry within a 7km thick volcanic sequence from tholeiites at the base to calc-alkaline lavas at the top (Sethuraman and Moore, 1973). The term 'Composite Arc Belt' was eventually applied to describe the volcanic and plutonic rocks in the western part of the CMB (Carr et al., 2000).

An alternative model was proposed by Baer (1976) who interpreted the CMB as an aulacogen, which is a failed continental rift. The aulacogen model could account for the cul-de-sac geometry of the CMB and the concentration of volcanic and carbonate rocks between two major shear zones. Baer (1976) identified the Danokil depression at the southern end of the Red Sea as a modern analogue. The apparent weakness of this model is the presence of calc-alkaline magmatism that was thought to be a similar age to the rift-related units (Brown et al., 1975). However, the most abundant suite of rocks in the CMB are tholeiites which Holm et al. (1986) concluded involved rifting of continental crust in a back-arc setting, whereas Bartlett (1983) interpreted the chemistry of the tholeiites in the Belmont domain as ocean-floor basalts. These studies do not contain adequate trace element data to apply a tectonic setting to the tholeiite suite but it is well known that the tholeiite suite is preceded by the QC and KC. It is also known that the calc-alkaline magmatism (~1280-1240Ma) is younger than the earlier tholeiite suite in the

Grimsthorpe domain (~1300Ma) and ~30-40Ma younger than the QC and KC (Davis and Bartlett, 1988; Easton, 1992). The tholeiitic suites are associated with trondhjemitic plutonism in the Grimsthorpe domain which have been interpreted as crustal melts between 1296-1250Ma (Pride and Moore, 1983). Since adequate trace element data exists for the QC and barely adequate data for the KC it might be possible to uncover the tectonic affinity of the mafic-ultramafic suites comprising the initial magmatism responsible for the formation of the CMB.

To the SE in the United States a back-arc rift zone was recently identified, termed the Trans-Adirondack Basin (TAB) (Chiarenzelli et al., 2011). Within the TAB the Pyrites mafic-ultramafic complex was emplaced prior to the onset of Grenvillian orogenesis (Chiarenzelli et al., 2012). The Grenville Supergroup was also deposited prior to Grenvillian orogenesis in the TAB and CMB between 1280-1250Ma (Chiarenzelli et al., 2015). Therefore, if the two back-arc ophiolites were emplaced in the CMB and TAB prior to the onset of Grenvillian orogenesis they should possess similar back-arc ophiolite trace element geochemistry. What we find instead is that the QC and KC in the CMB possess less geochemical characteristics of back-arc ophiolites than expected. However, the Pyrites complex in the TAB does exhibit back-arc signatures suggesting that their interpretation is correct and that the TAB is the true back-arc of the Laurentian margin.

Although various tectonic settings have been attributed to the lithologies in the CMB the most prominent tectonic scenarios in the literature include a back-arc basin (Holm et al., 1985; Smith and Harris, 1996; Hanmer et al., 2000), accreted arc terranes (Brown et al., 1975; Carr et al., 2000) and more recently a back-arc rift zone (Dickin and McNutt, 2007; Dickin et al., 2016). However, these models are problematic because they do not account for the restricted geographic location and composition of the QC and KC. For example, an arc collision would have produced a sequence of ultramafics that span the CMB along the principle suture. On the other hand, the initial stages of back-arc spreading would produce a more scattered distribution of the mafic-ultramafic sequence and not a point source. Hence, the lack of petrologic indicators, restricted geographic distribution and composition of the QC requires some review to sort out the tectonic significance.

Results/Discussion

Various attempts to discern the tectonic setting of the Queensborough ultramafic-mafic sequence using field evidence, petrography and geochemistry have reached contrasting conclusions (LeBaron et al., 1987; Easton and Ford, 1990; Smith and Harris, 1996). Here the geochemistry of the QC is reviewed to re-evaluate the various prescribed tectonomagmatic settings. The major element patterns show a degree of scatter interpreted as alteration but the quantification of the alteration is not the aim of this study. Some discussion of the alteration is necessary background.

Major element variation diagrams for the QC are shown in Figure 4.2. The major element mobilization was attributed to regional metamorphism and deformation (Smith and Harris, 1996). The mobilization of major elements was never concretely established because they attributed mobilization to 'deformation and metamorphism' and their data was insufficient to quantify this alteration. A critical analysis of the major and trace element data using discrimination diagrams was not explored by Smith and Harris (1996) and represents a discrepancy.

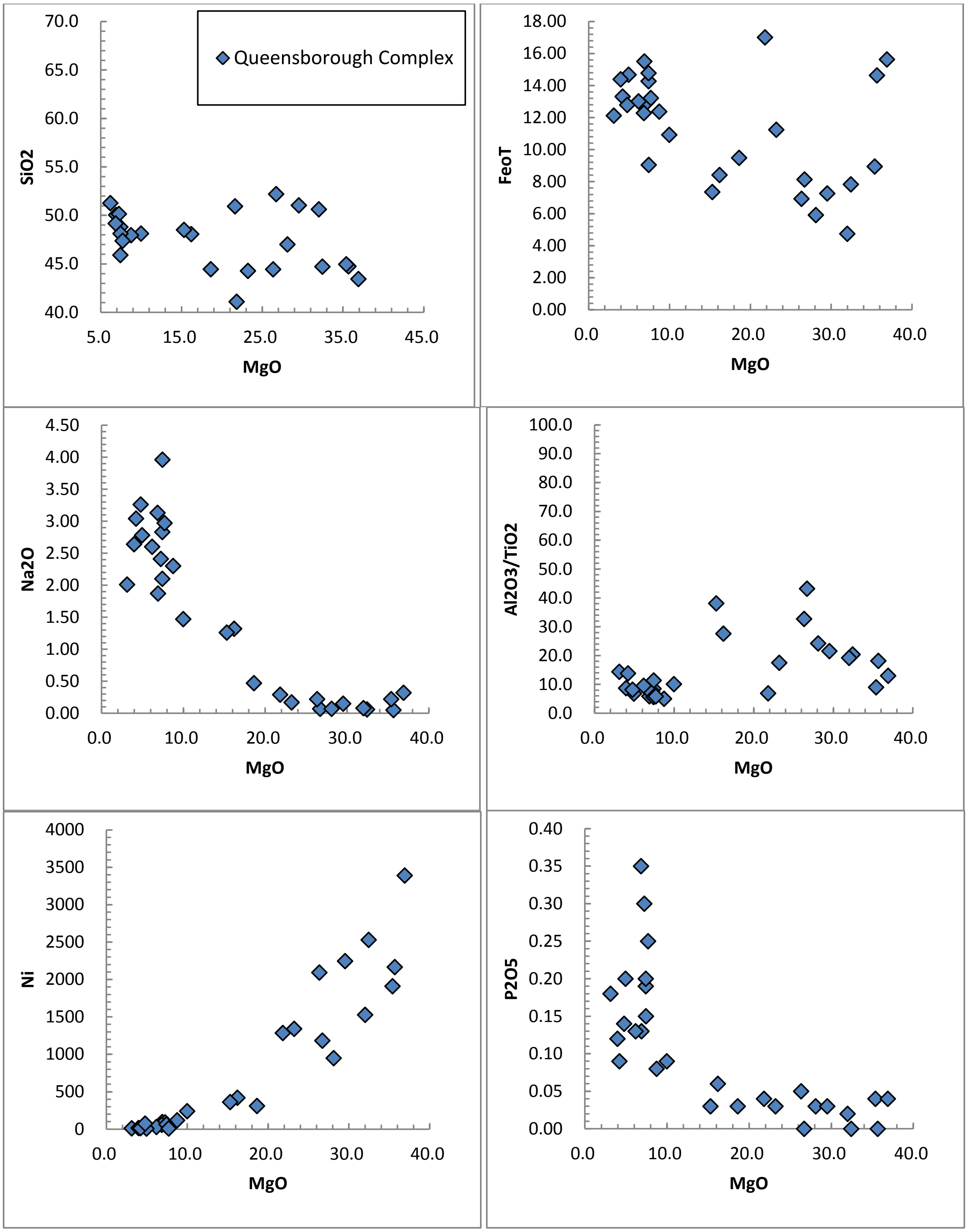

Figure 4.2: Geochemical variation diagrams showing analyses from the QC mafic-ultramafic sequence after Smith and Harris (1996).

Attention will be drawn to the immobile trace elements which were depicted in variation diagrams and elementally reduced spidergrams by Smith and Harris (1996). Smith and Harris (1996) concluded that, "all of the major elements and the majority of the trace elements with the exception of Y, Ti, Zr, and Nb were mobile during the metamorphism of the mafic and ultramafic rocks of the QC". It could be significant that on Y vs. Zr and Ti vs. Zr diagrams the QC and KC plot close to primitive mantle trendlines (Figure 4.3) (Rollingson, 1999). Smith and Harris (1996) attributed the co-linearity of the QC on these diagrams to olivine accumulation/fractionation but did not recognize the slopes of the sequence which could indicate a Primitive Mantle source. It should be noted that the geochemical data for the QC is derived from XRF. The Niobium data has ±10% reproducibility and the other trace elements have ±1% reproducibility for the rocks of the QC (Smith and Harris, 1996). A larger degree of scatter is associated with the few samples that have lower concentrations and are nearer the detection limits.

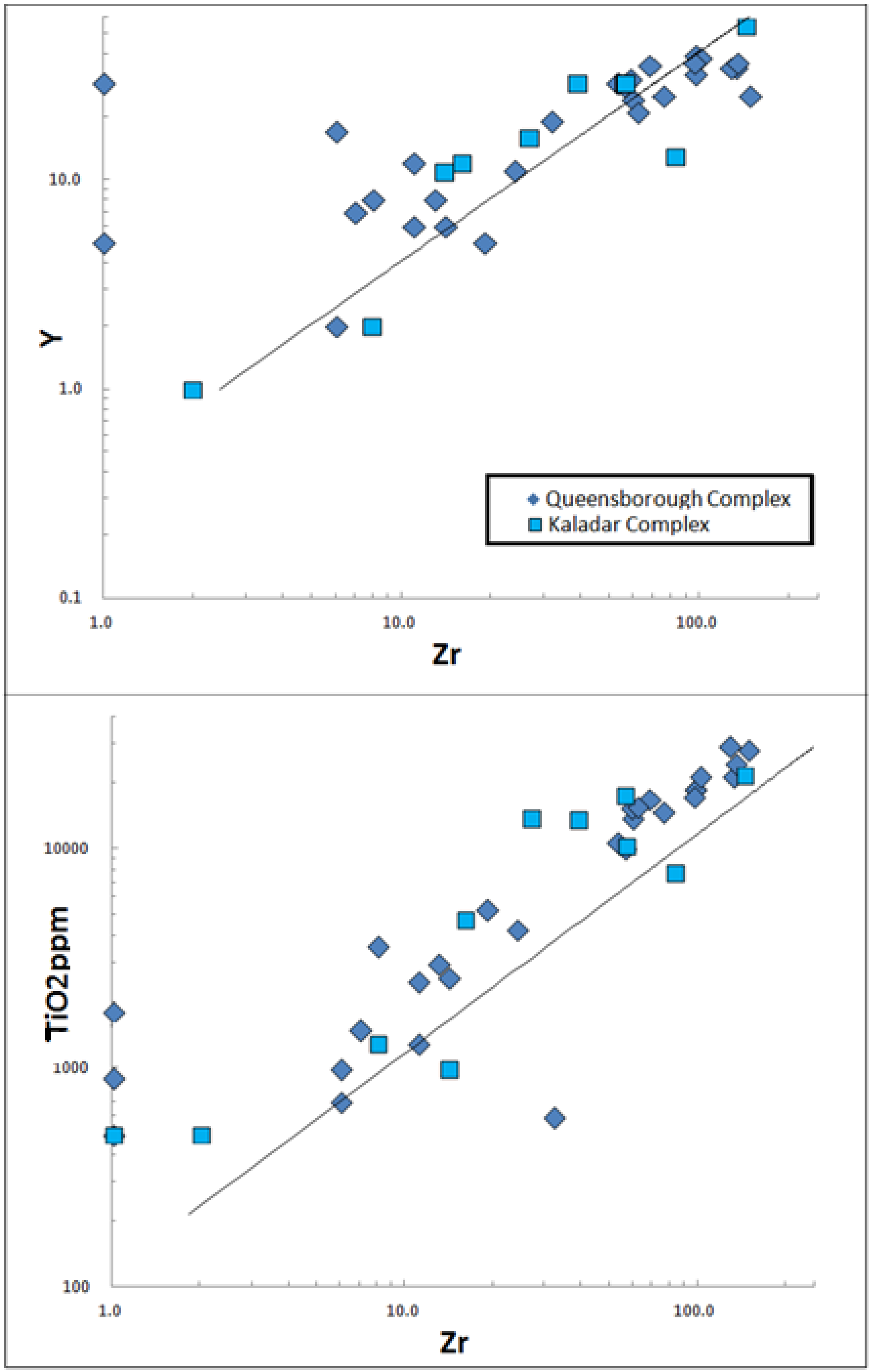

Figure 4.3: Y-Zr and Ti-Zr diagrams showing the Queensborough Complex and Kaladar Complex mafic-ultramafics after Smith and Harris (1996). The trend lines correspond with Primitive Mantle ratios of Ti/Zr= 116 and Zr/Y= 2.46 (Sun and Mcdonough, 1989).

The various tectonic settings prescribed to the CMB have relied upon major element geochemistry, structural mapping and isotope geology. However, it will be demonstrated that the currently prescribed tectonic settings do not account for the entirety of magmatism in the CMB. A couple discrimination diagrams have been constructed using the elements Y, Ti, Zr and Nb to show the lithologic and tectonic affinity of the mafic rocks of the QC and KC. On Zr/Ti vs Nb/Y diagram the QC and KC mainly plot within the Subalkaline Basalt field with a few samples in the Alkali Basalt field (Winchester and Floyd, 1977). However, in contrast to the conclusions of Smith and Harris (1996) the mafic rocks from the QC and KC mostly plot in the field of within plate basalts on a Zr/Y vs Ti/Y diagram (Pearce and Gale, 1977). Figure 4.4 prompts some review of the trace element composition of the QC and KC to understand this irregularity in more detail.

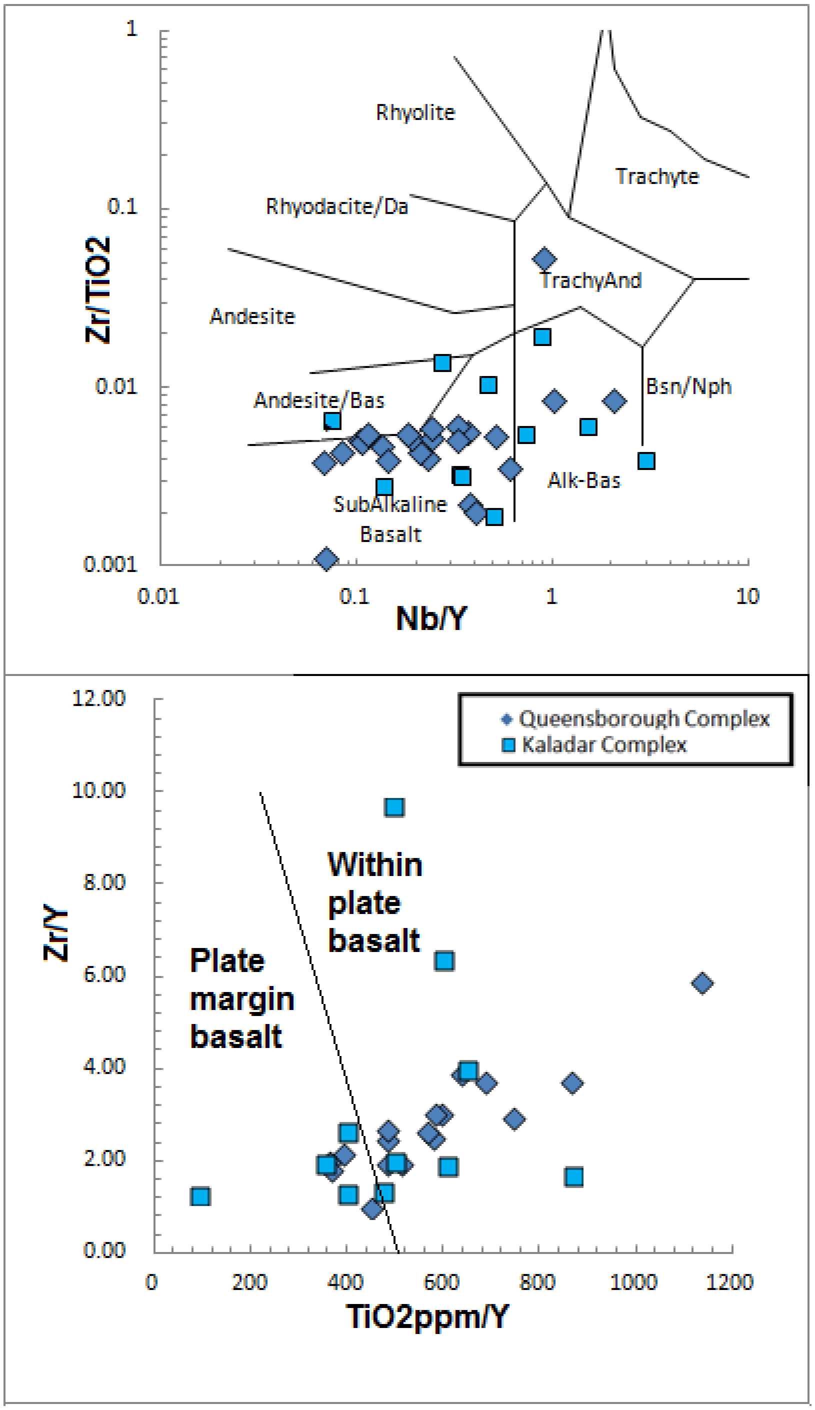

Figure 4.4: Discrimination diagrams showing the lithologic and tectonic affinity of the Queensborough Complex and Kaladar Complex (Winchester and Floyd, 1977; Pearce and Gale, 1977). Only the mafic rocks of the Queensborough Complex are plotted on the tectonic discrimination diagram.

The elements Y, Nb and Zr are particularly important because they can distinguish between plume and non-plume sources on Nb/Y vs. Zr/Y diagrams (Fitton, 1997; Condie, 2005). Fitton (1997) was the first to identify a correlation between plume and non-plume sources using the Nb/Y vs Zr/Y diagram and Icelandic basalts. Fitton (1997) defined the delta Nb line which was used to distinguish between N-MORB basalts and Icelandic plume basalts. Subsequent work led Condie (2005) to recognize that the Nb/Y vs Zr/Y diagram could be coupled with a Zr/Nb vs Nb/Th diagram to help distinguish between the mantle source regions. For reference in Figure 4.5, the diagrams from Condie (2005) show the mantle sources, the Iceland basalt array and the Kerguelen plume track (plume head, plume tail and En- contaminated basalts).

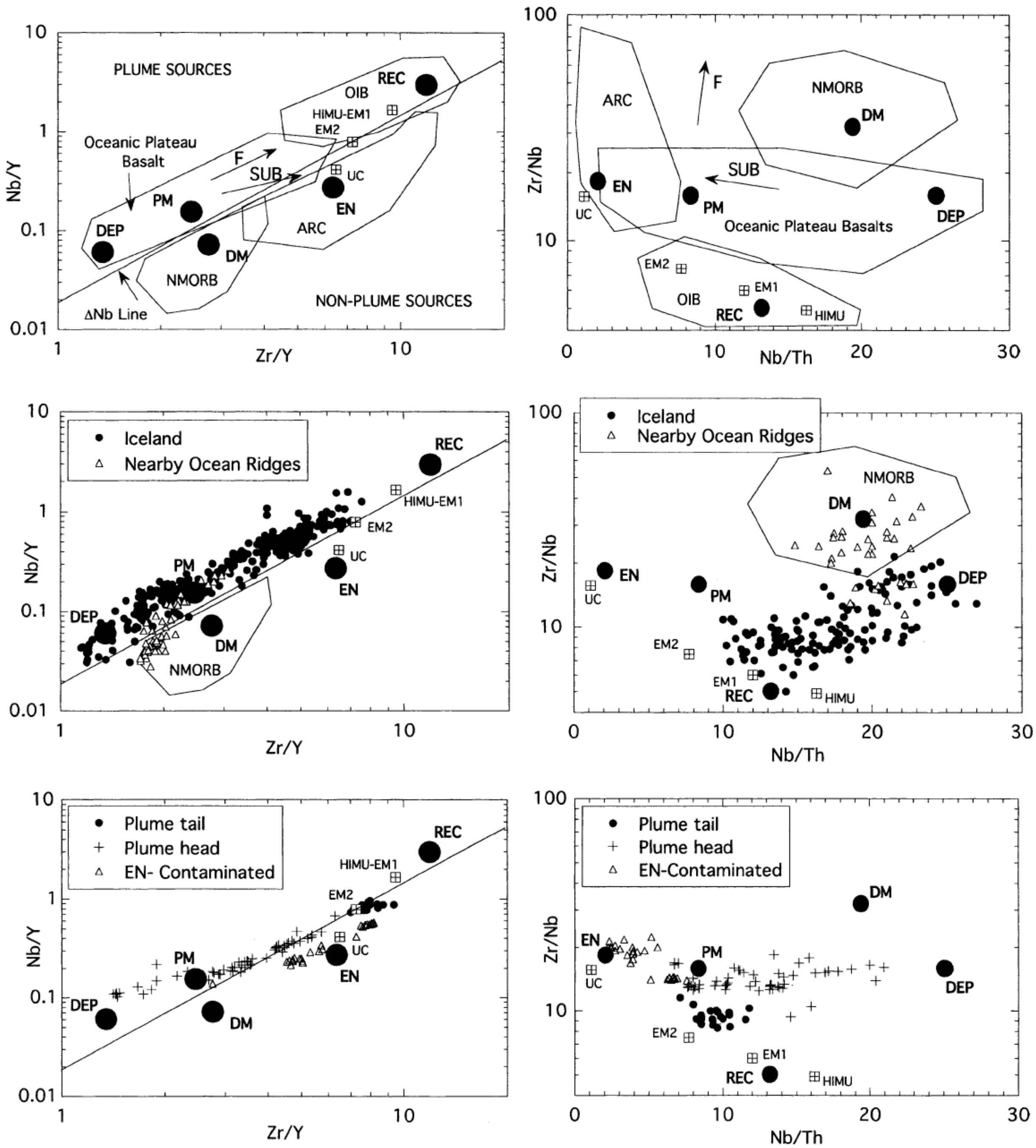

Figure 4.5: Nb/Y vs Zr/Y and Zr/Nb vs Nb/Th reference plots showing mantle components and vectors for batch melting (F) and subduction fractionation (SUB) derived from Condie (2005). In addition, the Icelandic basalts are shown in one set of diagrams and the last set of diagrams shows basalts from the Kerguelen plume track (Condie, 2005).

Smith and Harris (1996) specifically discussed the Nb/Y ratio of the QC and showed that the Nb/Y ratios averaged 0.19 for the mafic rocks which is higher than DM and the back-arc basalts they used for comparison. In addition, the Zr/Y ratio averages 2.64 which means on the Nb/Y vs. Zr/Y diagram the QC average (excluding low concentration samples) plots above the delta Nb line in the plume field. The Nb/Y vs Zr/Y plot in Figure 4.6 includes the QC mafic-ultramafic rocks (Smith and Harris, 1996), the KC mafic-ultramafic rocks (Chappell, 1978 PhD thesis), Elzevirian intrusives in the CMB (Smith and Holm, 1990), the Pyrites Complex (Chiarenzelli et al., 2011) and the Sudbury diabase (Shellnutt and MacRae, 2012). A large spread of the datasets from the CMB is apparent but there is a cluster around the PM with most of the samples inside the Iceland basalt field. The KC almost exclusively plots above the delta Nb line and above the Iceland basalt field with a few samples trending towards the enriched component. The Sudbury diabase plot above the enriched component and just on/below the delta Nb line. This suggests that a plume/primitive mantle source may have contributed to these suites of mafic and ultramafic units. On the other hand, the Pyrites Complex from the Trans Adirondack Basin plots exclusively in the non-plume field which corresponds with its interpretation as a back-arc ophiolite sampling the depleted mantle with substantial subduction enrichment (Chiarenzelli et al., 2011).

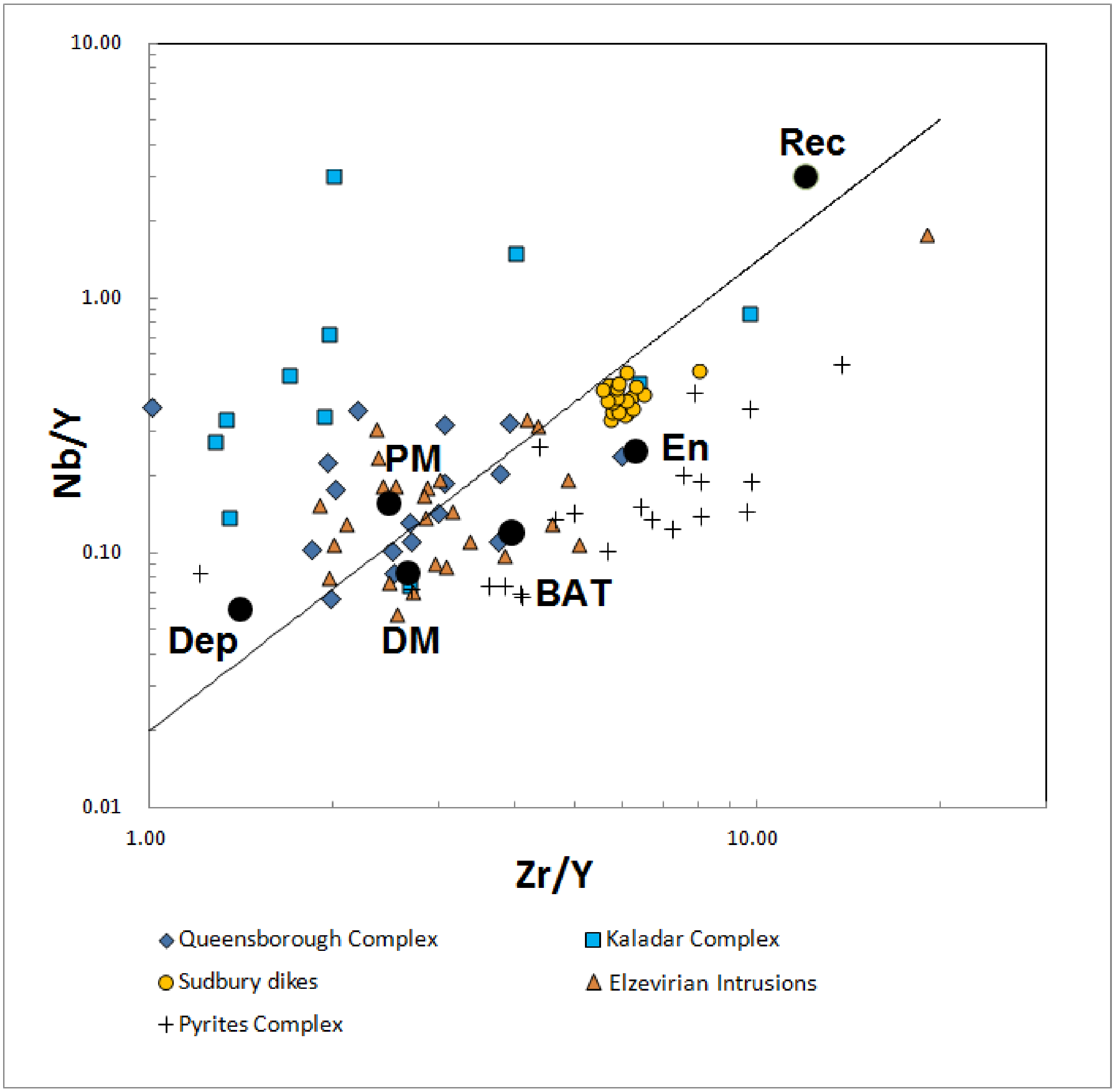

Figure 4.6: Nb/Y vs. Zr/Y plot of the Queensborough Complex, Kaladar Complex, Elzevirian mafic intrusions in the CMB, the Sudbury diabase and the Pyrites Complex. Abbreviations: Dep- deep depleted mantle; DM- shallow depleted mantle; PM- primitive mantle; En- enriched component, Rec- recycled component after Condie (2005) and BAT- back arc tholeiites after Smith and Harris (1996).

The samples from the QC and KC do not have complete trace element analyses. However, it is possible to plot some of the suites from Figure 4.6 on a Zr/Nb vs Nb/Th diagram. The Zr/Nb vs Nb/Th diagram can also distinguish between the different mantle sources (Condie, 2005). In Figure 4.7 the Elzevirian mafic intrusions, Sudbury diabase and Pyrites Complex are plotted with a field for Icelandic basalts. There is a slight trend towards arc enrichment of the Elzevirian intrusions and Sudbury diabase but also a trend towards the Recycled component (Rec) and Deep Depleted Mantle (Dep). The trend towards Rec and Dep is unexpected for the prescribed back-arc tectonic setting for magmatism in the CMB. It should be noted that the Pyrites Complex lies above the Enriched component in this diagram which is typical of arc related basalts or back-arc basalts.

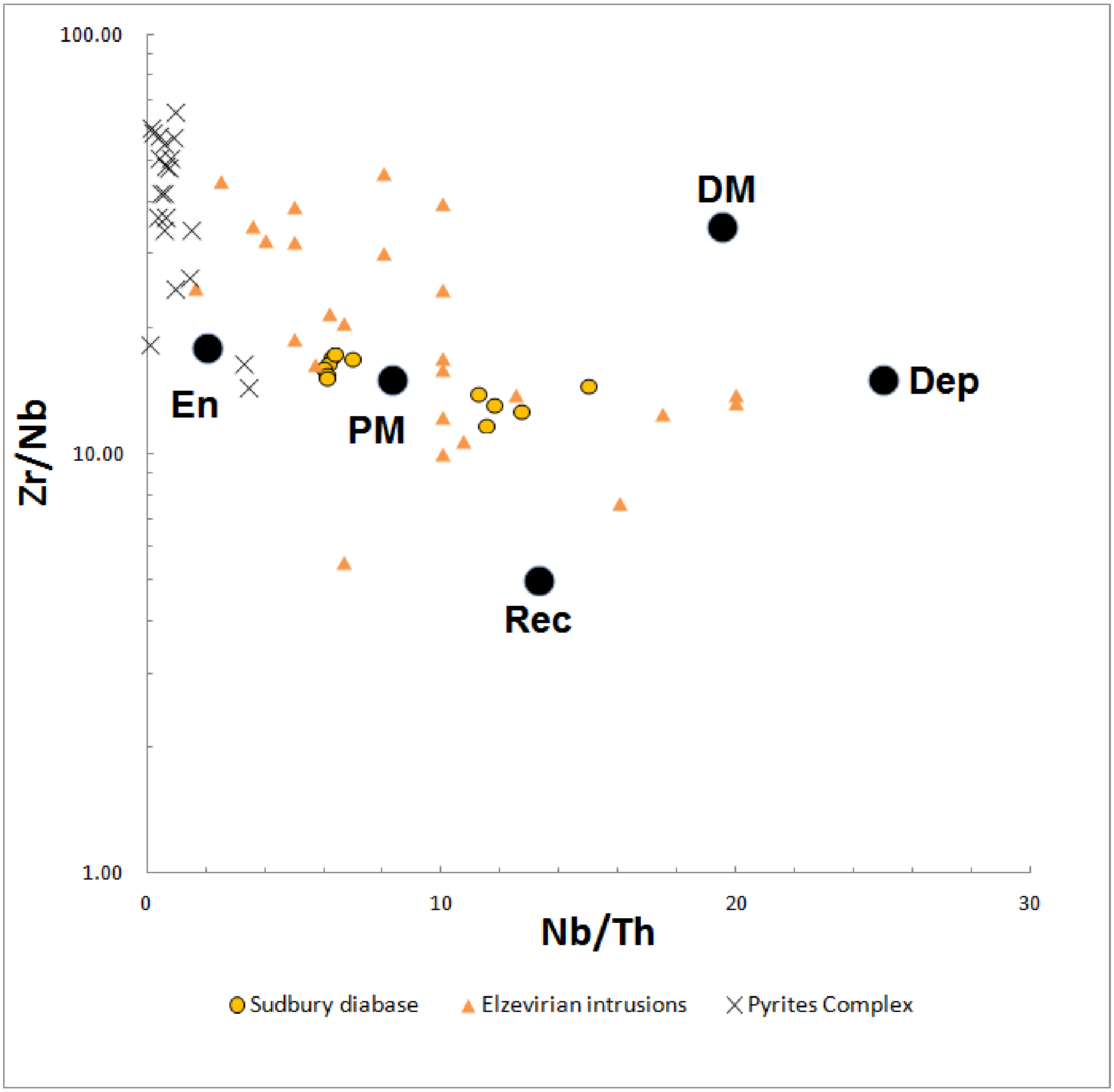

Figure 4.7: Zr/Nb vs Nb/Th plot of the Sudbury diabase, Elzevirian mafic intrusions and Pyrites Complex. Labels are the same as in Figure 4.5 (Condie, 2005).

The establishment of the QC and KC as back-arc ophiolites led to a series of tectonic interpretations for the CMB such as a back-arc basin and accreted arc terranes (Carr et al., 2000; Hanmer et al., 2000). These models were superseded by a model involving back-arc rifting to explain Sm-Nd isotope distributions and the geometry of the CMB by Dickin and McNutt (2007) and Dickin et al., (2016). In addition, various rifted arc sequences surrounding the proposed rift have been identified and grouped as part of the 1400-1350Ma Dysart-Mt. Holly arc (Hanmer et al., 2000; Rivers and Corrigan, 2000; McLelland et al., 2010). The downside of a back-arc rift model for the tectonic evolution of the CMB is that the trace element signature of the QC and KC and some of the pre-metamorphic intrusions do not appear to reflect back-arc trace element ratios (Figure 4.6 and 4.7).

The controls on crustal formation in the CMB have been typically attributed to subduction related arc and back-arc systems. The data presented suggests that a primitive mantle or plume source was also involved in the tectonomagmatic evolution of this part of Mesoproterozoic Laurentia around ~1.3Ga and possibly earlier. The pre-Elzevirian arc, known as the Dysart-Mt.Holly suite (1400-1350Ma) evidently began to rift before 1300Ma (McLelland et al., 2010). At a similar time as rifting initiated in the CMB, the Trans Adirondack Basin began to form in the true back-arc of the Laurentian continental margin. The Grenville Supergroup was subsequently deposited in the rifts and basins between 1280-1250Ma (Chiarenzelli et al., 2015). Then the Grenville Supergroup was intruded by Elzevirian diabase prior to deformation in the CMB (Smith and Holm, 1990). Around this time (1235Ma) the Sudbury diabase intruded the Parautochthon of the Grenville Province and the adjacent Superior Province trending NW (Krogh et al., 1987). The Elzevirian culminated with the docking of Amazonia and closure of Laurentian continental rifts and basins, such as the CMB and TAB before 1.2Ga (Chiarenzelli et al., 2011). This correlates with the emplacement of the Pyrites ophiolite along the major deformation zone identified as the Carthage Colton Shear Zone in the Trans Adirondack Basin (Chiarenzelli et al., 2011).

Shellnutt and Macrae (2013) concluded that the Sudbury diabase are not likely related to a mantle plume or the break-up of a supercontinent. Based on the published data their conclusion could be partially incorrect. To be fair, almost all tectono-magmatic interpretations regarding the CMB and in turn the SW Grenville Province are problematic because they cannot explain the primitive mantle or plume composition found in the mafic rocks. Shellnutt and Macrae (2013) attributed the 'OIB-like' signatures of the Sudbury diabase to partial melting of the Sub-Continental Lithospheric Mantle (SCLM). Shellnutt and Macrae (2013) suggested that the SCLM was partially melted after crustal unloading in the foreland basin during the closure of the Elzevir basin at 1235Ma. The model of Shellnutt and Macrae (2013) is partly based on the ~180Ma Karoo basalts which are part of a recognized LIP in South Africa. For the low-Ti Karoo basalts the mantle source is inferred to be the SCLM (Jourdan et al., 2009). However, more recent results suggest it is unclear if the source for some of the high-Ti basalts resides in SCLM, the convecting mantle or 'deep plumes' (Kamenetsky et al., 2017). In addition, the Karoo basalts are associated with the continental rifting of Gondwanaland in the early Jurassic and the formation of the South Atlantic rift in the Jurassic and early Cretaceous (White and McKenzie 1989; Cox, 1992). With these variables concerning the source of the Karoo basalts it becomes unclear if the model for the Sudbury diabase of Shellnutt and Macrae (2013) can account for the characteristics of magmatic events in the SW Grenville Province.

Other researchers in the Grenville Province of Ontario and western Quebec have identified various mafic gneisses which generally contain some 'OIB-like' signatures. In fact, OIB-like signatures have been found in most mafic gneisses dated between 1.4-1.2Ga in the SW Grenville Province. These mafic gneisses include the Renzy, Bondy and Armer Bay gneiss associations (Montreuil and Constantin, 2010; Blein et al., 2003; Culshaw et al., 2013). In Figure 4.8 and 4.9 all mafic gneisses, dated between 1.4-1.2Ga in the SW Grenville Province, are plotted on the diagrams from Condie (2005) exhibiting trace element ratios typical of plume related magmatism with contributions from subduction processes.

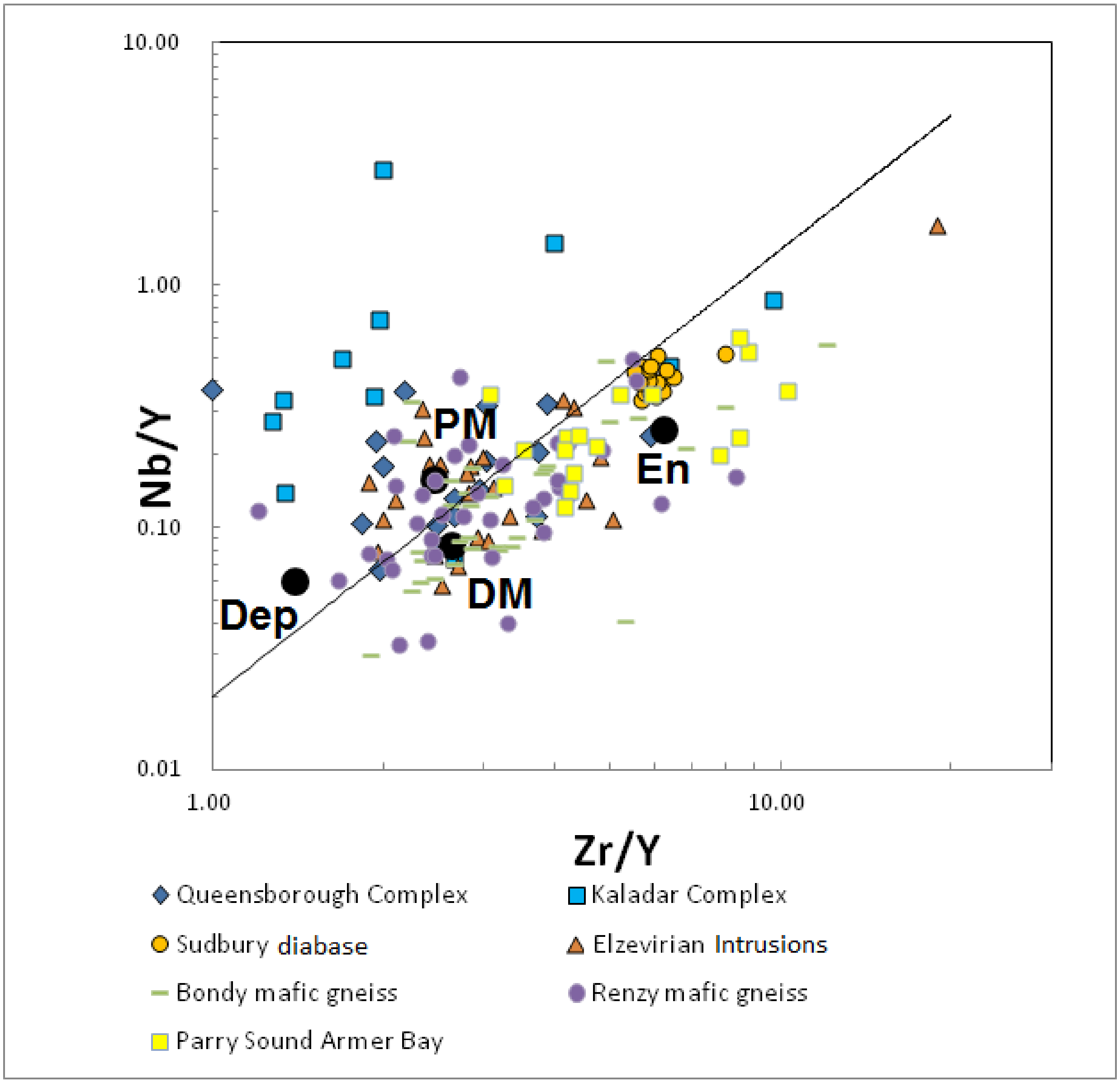

Figure 4.8: Nb/Y vs. Zr/Y plot of the mafic magmatism in the SW Grenville Province dated between 1.4-1.2Ga.

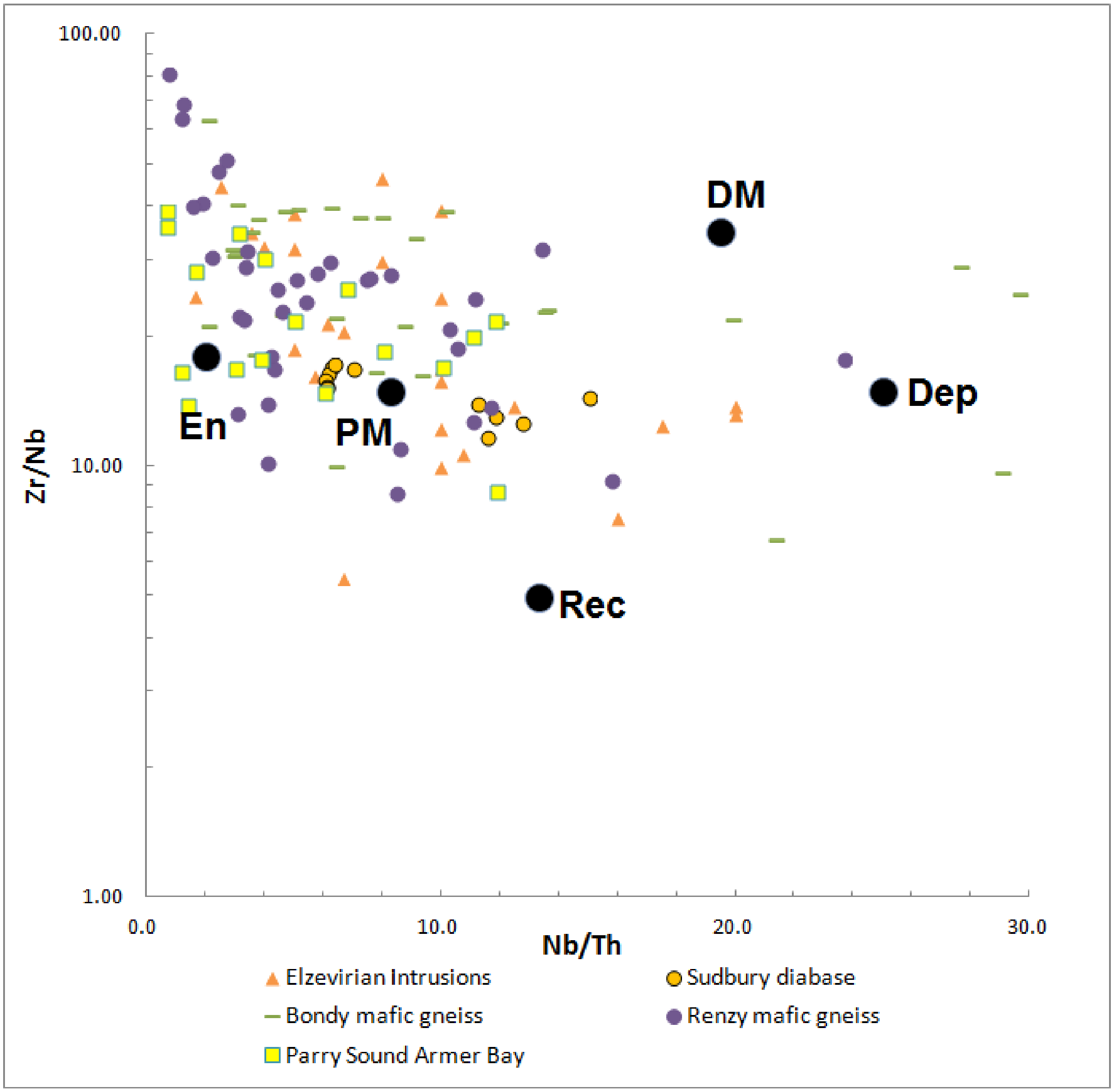

Figure 4.9: Zr/Nb vs Nb/Th plot of the mafic magmatism in the SW Grenville Province dated between 1.4-1.2Ga.

Further support is drawn from Th/Yb vs. Nb/Yb and Ti/Yb vs. Nb/Yb diagrams. These diagrams were developed by Pearce (2007) to aid in the characterization of mafic rocks with known and unknown tectonic affinities. Th-Nb is a proxy for crustal contamination and Ti-Yb is a proxy for melting depth (Pearce, 2007). When oceanic basalts are plotted on Th/Yb vs. Nb/Yb they typically plot along the diagonal MORB-OIB array. Basalts erupted at continental margins and subduction zones are commonly elevated above the MORB-OIB array and lie oblique to the array. This is caused by crustal interaction during magma generation (Pearce, 2007). The Ti/Yb vs. Nb/Yb diagram allows discrimination between low Ti/Yb MORB and high Ti/Yb OIB sources. High Ti/Yb reflects the generation of magmas from partial melting at depths greater than 1gPa which is caused by less partial melting within garnet facies (Pearce, 2007). For reference, the discrimination diagrams from Pearce (2007) are shown in Figure 4.10 along with diagrams for Icelandic basalts and the Mariana arc-basin system.

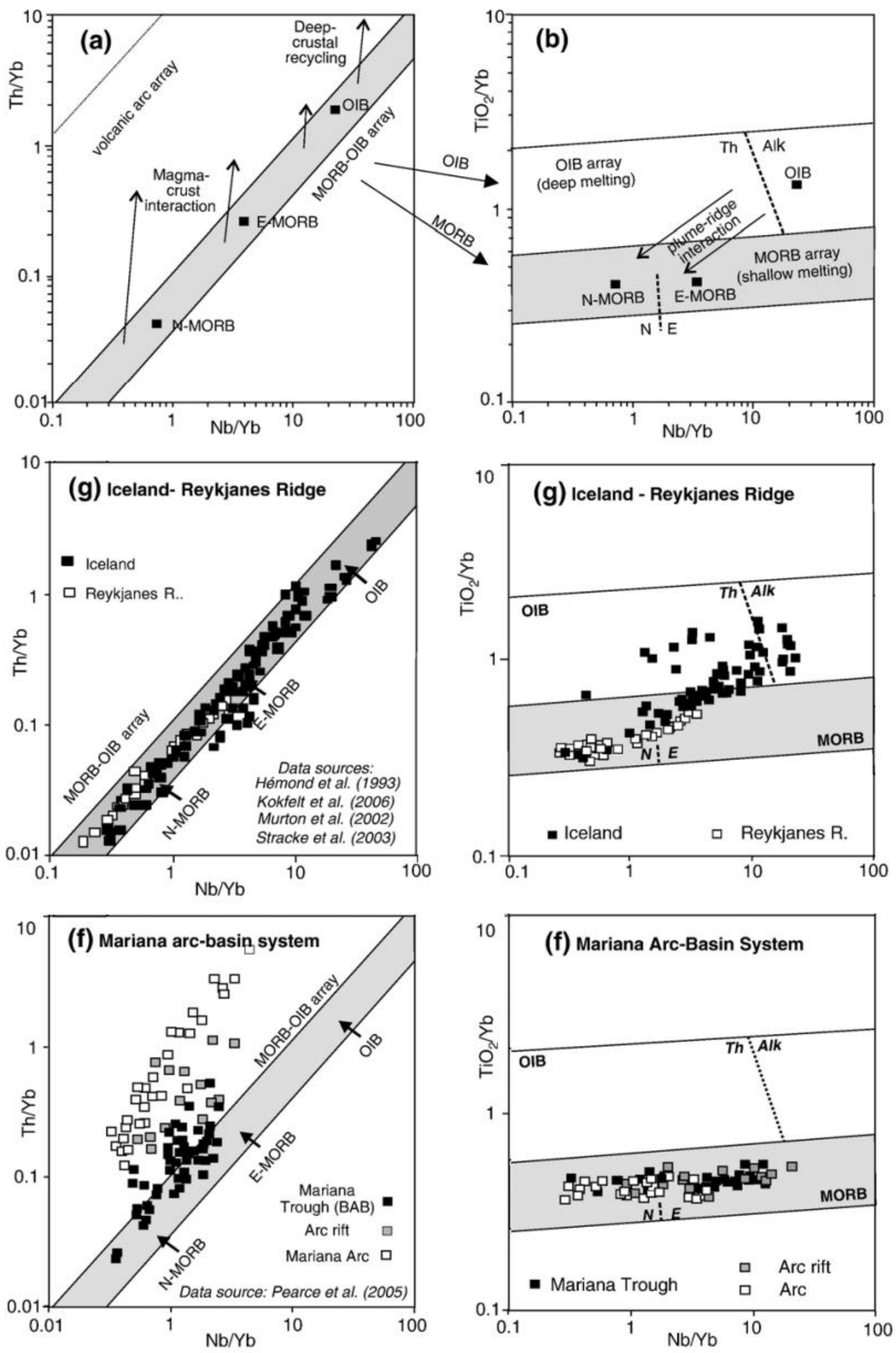

Figure 4.10: Reference plots of the Th-Yb and Ti-Yb discrimination diagrams reproduced after Pearce (2007).

In Figure 4.11 and 4.12 the mafic magmatism from the SW Grenville Province dated between 1.4-1.2Ga is shown on Th/Yb vs Nb/Yb and TiO2/Yb vs Nb/Yb diagrams. In these diagrams not all the mafic suites can be included due to the lack of analyses and in some cases only partial trace element compositions were acquired (probably due to cost). Figure 4.11 shows the Sudbury diabase, Elzevirian intrusions, Pyrites complex, Bondy gneiss complex, Renzy mafic gneiss and Armer Bay / Parry Sound mafic gneiss on a Th/Yb vs Nb/Yb diagram. All of the mafic gneisses exhibit subduction enrichment and generally plot nearer to the E-MORB mantle component than N-MORB. However, the Sudbury diabase, Renzy and Bondy mafic suites plot above the E-MORB and towards the OIB component.

Figure 4.12 is the TiO2/Yb vs Nb/Yb diagram showing the same mafic suites from Figure 4.11 but also including some analyses from the QC. The Sudbury diabase, Elzevirian intrusives, Renzy, Pyrites and Queensborough mafic complex exhibit deep mantle partial melt signatures, plotting above the discriminate. Other mafic suites exhibit this deep mantle signature but are not dated and cannot be included in this study. However, the correlation between the mafic suites included in this chapter is indicative of magmatism influenced by plume and subduction characteristics.

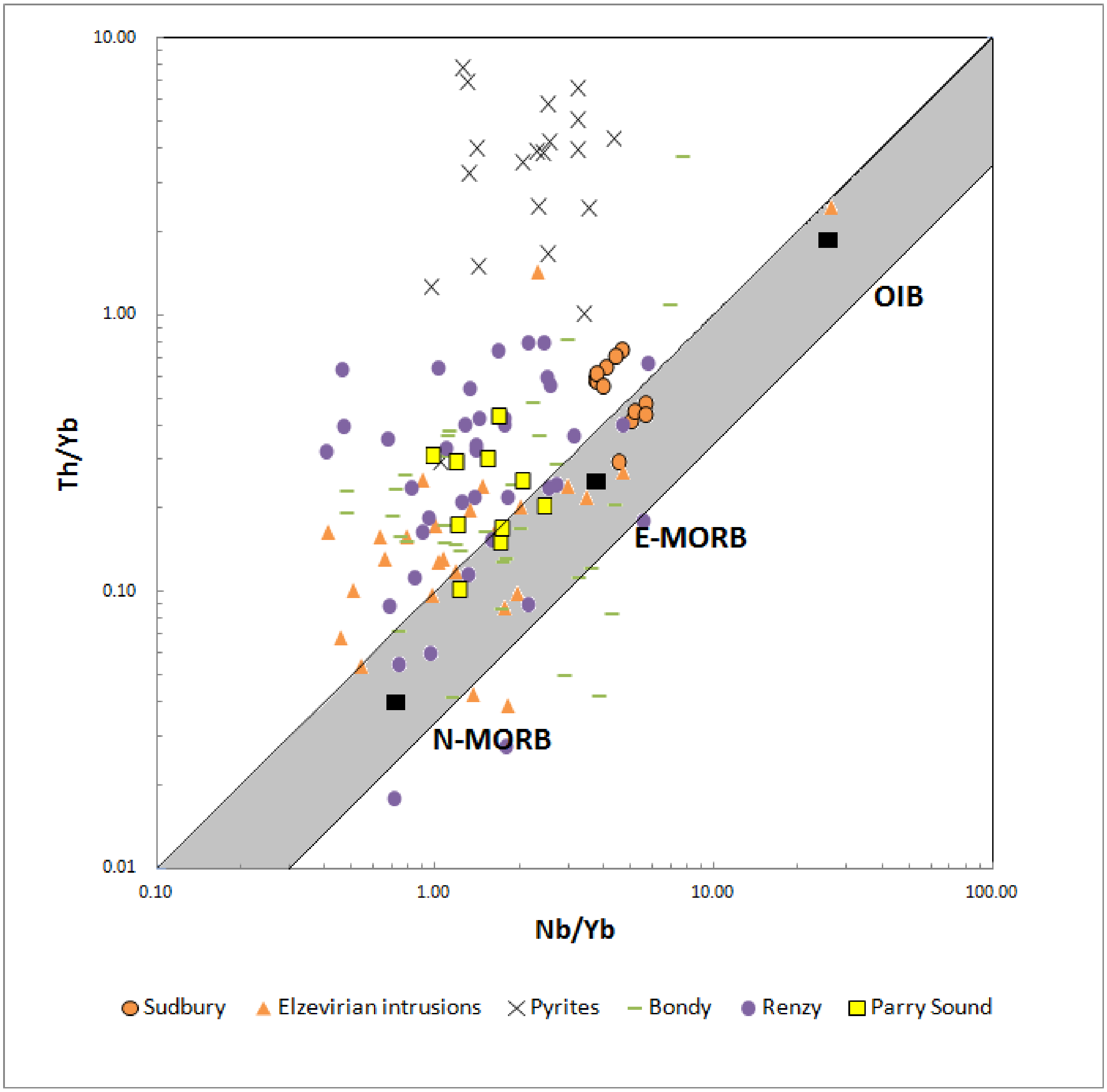

Figure 4.11: Th/Yb vs Nb/Yb plot of the mafic magmatism in the SW Grenville Province dated between 1.4-1.2Ga.

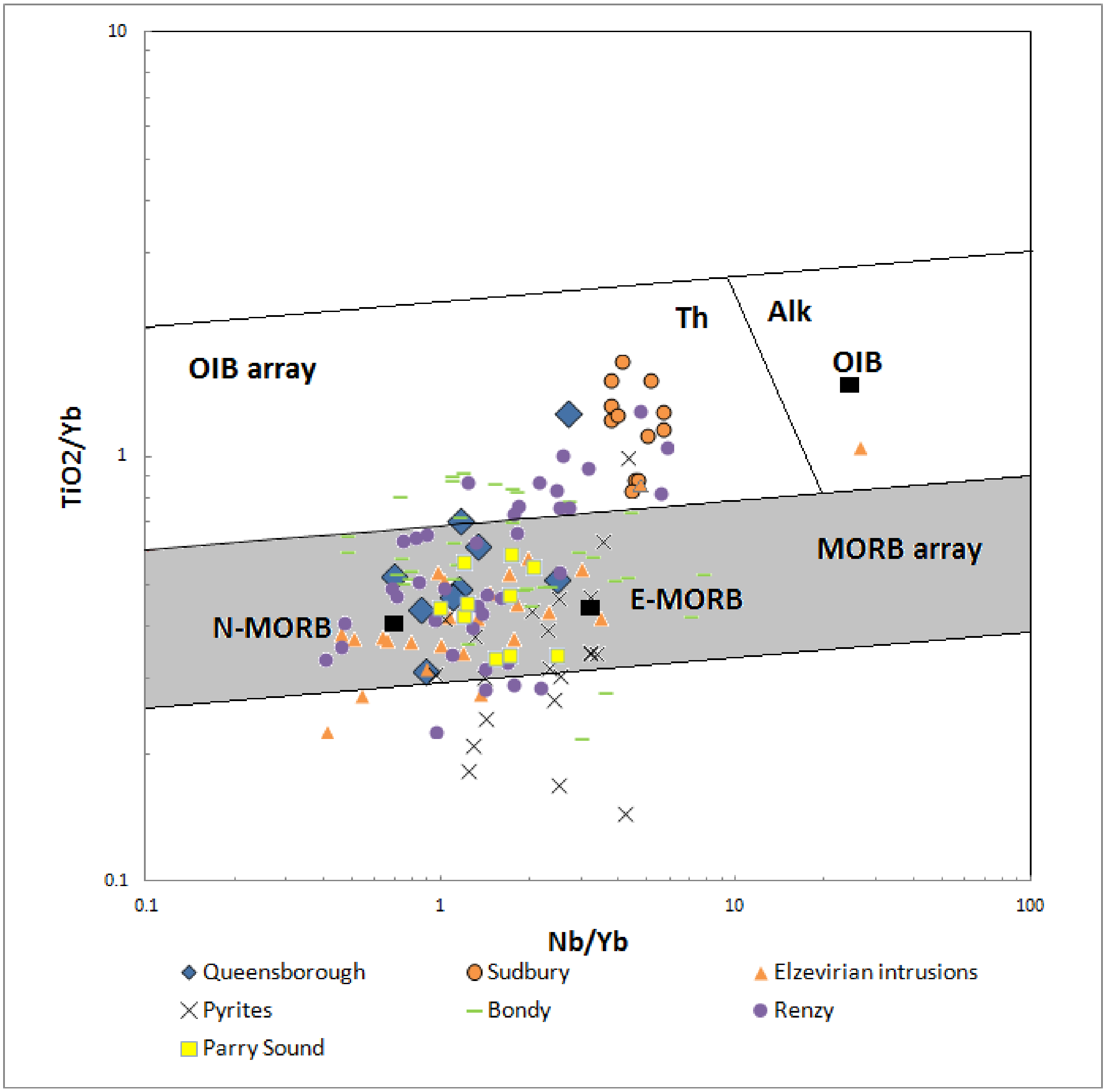

Figure 4.12: TiO2/Yb vs Nb/Yb plot of the mafic magmatism in the SW Grenville Province dated between 1.4-1.2Ga.

The basis for the QC and KC as an ophiolite or a type of komatiite/plume related sequence required the identification of a sheeted dyke complex or spinifex textures. However, neither of these characteristics were ever identified which concealed the true nature of the QC and KC for decades. In Chapter 3 the rifting process is detailed using geometrical arguments derived from Nd isotope mapping. These arguments do not depend on any trace element constraints of the magmatism in the Grimsthorpe domain and do not depend whether back-arc or plume related mantle upwelling caused rifting. However, in order to have a definitive model for rifting, it is necessary to identify the sources contributing to the magmatism in the Grimsthorpe domain and the timing of these events. In the future, defining these sources geochemically and geochronologically should complement the proposed geometrical arguments in Chapter 3. This will require more trace element analyses and geochronological studies in the Grimsthorpe domain of the CMB.

The discrimination diagrams featured in this chapter have not been applied to the mafic suites in the SW Grenville Province prior to this work. It is not totally clear where the plume was located due to the lack of high quality geochemical data in the CMB. The published geochemical evidence presented in this chapter has begun to shed light on some of the major discrepancies concerning the formation of the CMB and the tectonomagmatic evolution of the SW Grenville Province.

Conclusion

The trace element ratios of the QC suggest it could be a misidentified plume related sequence. A review of the published geochemistry for mafic-ultramafic sequences in the SW Grenville Province dated between 1.4-1.2Ga suggests that a plume is a possible source contributing to crustal formation. The suspected ~1.4-1.2Ma plume should be properly constrained with new isotope analyses and high precision trace element analyses of the various rock suites in the CMB such as the QC and KC but also other mafic suites in the SW Grenville Province. If the oldest igneous rocks in the CMB are not properly constrained then the formation of the CMB will continue to resist consensus within the Grenville community.

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Chapter 5:

Conclusion

Chapter Summary

The Big Bend is the largest structural feature of the major lithotectonic boundaries in the Grenville Province. This thesis has attempted to address some of the major questions related to this structural feature. The three-dimensional structure of the major lithotectonic boundaries in the SW Grenville Province was explored using SketchUp. The three-dimensional model of the Grenville Front, Allochthon Boundary Thrust and Central Metasedimentary Belt boundary was developed using Nd isotope results, detailed geologic mapping and geophysical observations. This has provided a new perspective on the structure of the mid-crust in orogenic belts. The three-dimensional visualization depicts the top-down superimposition of thrust geometry involving the, CMBb, ABT and GF which also coincides with the metamorphic age of the thrusts. The CMBb Elzevirian continental rift margins were reactivated during the Shawinigan and the geometry of the CMBb was superimposed on the ABT during the Ottawan which then became superimposed on the GF in the Rigolet phase.

The CMB has been identified as a back-arc aulacogen by Nd isotope mapping with blocks of rifted crustal basement (>1.35Ga) surrounded by juvenile crust (<1.35Ga). New Nd isotope results identify several older NE trending blocks in the Grimsthorpe domain. This thesis has identified older NE trending blocks separated by thin salients of juvenile crust inside the Weslemkoon batholith. The domains with older crustal formation ages are interpreted in terms of crustal-scale faulting of a rifted block and incorporation of depleted mantle along the pre-existing structure. Modern analogues show that the pattern is similar to the Danakil block breaking apart in the Afar depression and the transtensional faulting of Isla Tiburon in the Gulf of California. In addition, bimodal magmatism typical of continental rifting is found in the CMB the Gulf of California and the Danakil depression.

Last, the trace element signatures of mafic magmatism in the CMB and SW Grenville Province are explored to develop the interpretation for the formation of the Central Metasedimentary Belt. The Queensborough complex (QC) comprises the oldest formation in the CMB of Ontario. The trace element composition of the QC is suggestive of within plate plume-like magmatism. The published geochemical evidence presented here has identified some of the major discrepancies concerning the formation of the CMB and the tectonic evolution of the SW Grenville Province.

Future work

The suspected ~1.4-1.2Ma plume should be properly constrained with new isotope analyses and high precision trace element analyses of the various mafic rock suites in the CMB such as the QC and KC. Approximately 20 samples will need to be collected from the QC and KC and analyzed for their trace elements. The results should complement the published geochemistry of the QC and allow for a more detailed understanding of the mechanisms and sources responsible for the formation of the CMB. After the completion of more detailed geochemistry of the QC it may be necessary to revisit the trace element composition of other mafic rocks in the CMB and surrounding SW Grenville Province.