AGE AND GEOCHEMICAL CHARACTER OF GRANITE AND SYENITE
PLUTONS IN THE GRENVILLE PROVINCE OF SOUTHEASTERN
ONTARIO; INSIGHTS INTO MAGMATISM DURING THE OTTAWAN
OROGENY AND EVIDENCE OF THE FRONTENAC INTRUSIVE SUITE
IN THE SHARBOT LAKE DOMAIN

By

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ABSTRACT

Seven plutons in the Composite Arc Belt and Frontenac terrane of the Grenville Province are herein determined to be part of the Kensington-Skootamatta intrusive suite. The monzonite-syenite plutons and granite-monzogranite plutons have crystallization ages of ca. 1086-1072 Ma and ca 1077-1067 Ma, respectively. In general, the plutons are shoshonitic, metaluminous to weakly peraluminous, and alkalic to calc-alkalic. The plutons have conflicting trace element geochemical signatures that suggest a within-plate tectonic setting with a weak remnant suprasubduction zone signature and a depleted mantle isotopic signature of ϵNd 2-5. This geochemistry points to derivation of these melts through fractionation of an alkaline basalt and, or, partial melting of quartzofeldspathic crust. Melt generation was perhaps initiated by crustal delamination, and further heated though insulation by overthickened crust and the Midcontinent Rift magmatic system. Two other plutons that were studied have ca. 1180-1160 Ma crystallization ages and geochemical characteristics similar to the Frontenac intrusive suite.

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Appendix A – MRD 311: CD-ROM

Miscellaneous Release-Data 311: Release blurb

MRD311_release blurb.doc

Miscellaneous Release-Data 311: Readme file

MRD311_readme.doc: Contains a list and description of all files included in

MRD311 appendix.

CHAPTER 1 – INTRODUCTION

During the ca. 1090-980 Ma Grenville Orogeny, the ca. 1090-1060 Ma Kensington-Skootamatta ultrapotassic, alkaline intrusive suite was emplaced throughout the constituent terranes and domains of the Composite Arc Belt (CAB) and the Frontenac-Adirondack Belt (FAB; *figure 1.1a, b*). Circa 1090-1060, much of the Composite Arc Belt and Frontenac-Adirondack Belt were at mid- to upper-crustal levels and remained sheltered from the penetrative compressional deformation and metamorphism experienced by rocks near the Laurentian margin and at deeper crustal levels (e.g., Mazinaw terrane; cf. Rivers 2012). Rather, the terranes of the Composite Arc Belt and Frontenac-Adirondack Belt experienced late-stage extension through crustal-scale normal faults (Carr et al. 2000).

Corriveau et al. (1990) and Corriveau (1990) first introduced the term Kensington suite for 10 ultrapotassic, undeformed plutons in the Grenville Province in the Mont-Laurier region of Québec (*figure 1.1b*). Easton (1992) subsequently introduced the Skootamatta suite for plutons of this composition and general age in the Grenville Province of Ontario. The two suites together have since been referred to as the Kensington-Skootamatta suite.

The regionally extensive ca. 1090-1060 Ma Kensington-Skootamatta suite comprises undeformed and unmetamorphosed alkalic, shoshonitic to ultrapotassic syenite to monzonite plutons. The roughly 30 sub-circular intrusive bodies are aligned along a 400 km northeast-southwest trending, structure

parallel belt stretching in the northeast from Mont-Laurier in Quebec to Bancroft in the southwest. They are associated with aeromagnetic highs (*figure 1.1b*; Corriveau et al. 1990; Easton 1992). Easton (2008) suggested that the Kensington-Skootamatta suite may in fact be composed of two different suites of different ages and compositions; a ca. 1080 syenite-monzonite suite and a younger ca. 1070 Ma granite-monzogranite suite. Alternatively, the younger granite-monzogranite suite may be associated with the ca. 1070-1060 Catchacoma suite (Easton and Kamo 2011).

Nine plutons were selected for field, petrographic, geochemistry, isotope geochemistry and geochronology studies based on a number of factors, including: representation from a variety of lithotectonic domains, terranes and crustal levels; ease of accessibility; inclusion of a range of rock-types; and to infill and complement existing data sets for the suite based on limited previous work on other plutons. The plutons that were selected include the Skootamatta and Westport area plutons (Wolfe Lake, Foley Mountain, and Rideau Lake) which are believed to be part of the syenite-monzonite suite (*figure 1.2*), and the Elphin, Barber's Lake, McLean, Leggat Lake and Cranberry Lake plutons, which are believed to be part of the granite-monzogranite suite (*figure 1.3*). To avoid confusion, the three plutons in Westport, Ontario are referred to as 'the Westport area plutons' and the former 'Westport pluton' will be referred to as 'the Foley Mountain pluton'. The plutons in this study are located within the Grimsthorpe domain, Sharbot Lake domain, and Frontenac terrane (*figure 1.1a,b*).

The majority of the Kensington-Skootamatta plutons have a roughly round map pattern; in part, suggesting that they are undeformed. The Cranberry Lake pluton is of particular interest because firstly, it lies adjacent to the Robertson Lake shear zone (RLSZ); a major tectonic boundary between the Mazinaw terrane and Sharbot Lake domain, and secondly, the pluton has a complex map pattern that cross-cuts regional folds, thought to have formed prior to circa 1180 Ma. As a result, Easton (2001a) suggested that it may be a syn-tectonic intrusion during a stage of displacement along the Robertson Lake shear zone.

1.1 Previous work

The major element geochemistry of the Kensington-Skootamatta suite was characterised by Corriveau et al. (1990) as having low to moderate silica contents, $\text{TiO}_2 > 0.8\text{wt}\%$, and $\text{P}_2\text{O}_5 > 0.21\text{wt}\%$. Note that Corriveau's research was concentrated on the syenites of the Kensington-Skootamatta suite and there has been limited previous work on the granitoids. There have been few subsequent geochemical studies on the Kensington-Skootamatta suite. Preliminary sampling and geochemical analysis of the Barbers Lake, McLean, Leggat Lake and Elphin plutons was carried out by Davidson and van Breemen (2000b). Similarly, Easton (2001a) studied the Cranberry Lake pluton. More extensive sampling and analysis for major, and trace elements (excluding the rare earth elements (REEs)) of the Skootamatta syenite was carried out by Easton and Ford (1994).

A variety of tectonic settings and source region scenarios have been proposed for Kensington-Skootamatta plutons based on major, trace element,

radiogenic isotope (Sr, Sm-Nd) and stable isotope (O) geochemistry. Corriveau (1990) and Corriveau et al. (1990) suggested a subduction zone model, whereas others have suggested an anorogenic, within-plate tectonic setting (Corrigan and Hanmer 1997).

Stable isotope (O) and radiogenic isotope (Sr, Nd) geochemistry studies were conducted on the Westport area, Elphin and Barber's Lake plutons, and revealed ΔO^{18} values of 8.0-11.5, ϵNd values of 2.7-3.4 and ϵSr values of 7.6-38.9 (Marcantonio et al. 1990; Shieh 1985; Wu and Kerrich 1986). These isotopic values were interpreted as a remnant signature of an already enriched mafic igneous source, with some contamination from the surrounding marble and metasedimentary rocks.

Previous published geochronology work on the plutons of this study include crystallisation ages for the Westport (Foley Mountain) pluton of 1076 ± 2 (Corriveau et al. 1990; sometimes reported as 1077 ± 4 Ma based on Marcantonio et al. 1988), and crystallisation ages for the Barbers Lake and McLean plutons of $1066^{+3/-4}$ Ma and 1070 ± 3 Ma, respectively (Davidson and van Breemen 2000b). There are unpublished geochronology data for the Skootamatta pluton at ca. 1083 Ma (Carr and Easton 1995, *unpublished data*). See *table 1.2* for geochronology data for all ca. 1090-1060 Ma plutons in the map area.

1.2 Purpose

Several questions will be addressed herein based on a synthesis of previous work integrated with new petrology, geochemistry and geochronology data from plutons of the Kensington-Skootamatta suite: First-order questions are (i) what are the major and trace element geochemical signatures and isotopic geochemical character of the plutons selected for study?; (ii) what is the crystallization age of the Skootamatta, Rideau Lake, Wolfe Lake, Elphin, Leggat Lake and Cranberry Lake plutons? Second-order questions are (iii) based on the conclusions from (i) and (ii), are the granites and syenites part of the same igneous suite, or do they represent more than one distinct suite with different tectonic associations? (iv) if the rocks are one co-genetic suite, did they originate from a single source or multiple sources? (v) are there terrane specific sources that could account for the formation of the granite versus syenite plutons and/or local differences between intrusions? (vi) what melt sources or tectonic settings could account for the geochemistry data and does this agree with current tectonic models for Grenville orogenesis? (vii) and, why is the Mazinaw terrane apparently devoid of plutons of the Kensington-Skootamatta suite?

1.3 Sampling Rational

In total, 79 samples were collected for petrography and geochemical analysis. Five of these locales were also sampled for U-Pb zircon geochronology studies. Sampling of the plutons was based on obtaining different mineralogical and textural phases of each of the plutons, and where possible, along transects across the plutons from core to rim. Sampling was limited due to difficulty in

accessing private property; hence there was a focus on collecting from road cut exposures and in the case of the Barbers Lake pluton, using previously collected sample powders from Ken Ford.

1.4 Preliminary Results

Preliminary results related to this study have been presented in Ontario Geological Survey Open File Reports 6270 and 6280, and at the Geological Association of Canada—Mineralogical Association of Canada annual meeting 2013 (Cutts et al. 2011, 2012, 2013). Raw geochemistry data, isotope geochemistry and U-Pb geochronology sample preparation and chemistry procedures, outcrop photographs, hand sample photographs, photomicrographs, and scanning electron microscope cathodoluminescence images have been published in Ontario Geological Survey Miscellaneous Release—MRD311 (appendix A).

Table 1.1 - General stratigraphy, age, metamorphic character and tectonic setting of the Grimsthorpe, Sharbot Lake and Frontenac terranes.

Terrain/ Domain	Stratigraphy	Age	Metamorphism	Basement Assemblage Tectonic Setting
Grimsthorpe domain ^{1,2}	Kensington-Skootamatta syenite-monzonite plutons	ca. 1088 Ma	None	
	Mafic and felsic plutonic rocks preserving primary features	ca. 1267 Ma	<1267 Ma upper greenschist to mid-amphibolite facies	
	Deformed tholeiitic intrusive, volcanic and volcanoclastic rocks	>1267 Ma		Primitive Arc
Sharbot Lake domain ^{3,4}	Kensington-Skootamatta granite-monzogranite plutons	ca. 1067 Ma	None	
	Deformed gabbro and tonalite plutons	ca. 1168 Ma	ca. 1160 Ma mid-amphibolite to granulite facies	
	Deformed marble, tholeiitic metavolcanic, and siliciclastic metasedimentary rocks	>1224 Ma		Rifted arc
Frontenac terrane ^{3,5,6}	Kensington-Skootamatta syenite-monzonite plutons	ca. 1076 Ma	None	
	Syn-deformational monzonite to granite plutons	ca. 1190-1160 Ma	ca. 1160 granulite facies	
	Quartzofeldspathic gneiss, monzonite to granite orthogneiss, quartzite and marble	>1190 Ma (detrital zircon age from quartzites of 1306 and 1400 Ma)		Platform/ ocean basin

¹Easton and Ford 1994; ²Carr and Easton, unpublished age; ³Corfu and Easton 1997;

⁴Davidson and van Breemen 2000b; ⁵Davidson and van Breemen 2000a; ⁶Corriveau et al. 1990

Table 1.2: Published zircon geochronology data on ca. 1090-1060 Ma felsic plutons

Pluton	Rock Type	Age (Ma)	Reference
Calabogie	syenite	1088 ± 2	Corriveau et al. (1990)
Gawley Creek	syenite	1088	Lumbers et al. (1990) unpublished data
Loon Lake	monzonite	1090 ± 2	Corriveau et al. (1990)
Mount Moriah	syenite	1088	Lumbers et al. (1990) unpublished data
Skootamatta	syenite, monzonite	1083	Carr and Easton (2005) unpublished data
Umfraville	syenite	1088	Lumbers et al. (1990) unpublished data
Belmont Lake	granite	1088 +3/-2	Davis and Bartlett (1988)
Kensington	syenite	1083 ± 2	Corriveau et al. (1990)
Lac Rouge	syenite	1081 ± 2	Corriveau et al. (1990)
Loranger	syenite	1076 +3/-1	Corriveau et al. (1990)
Westport (Foley Mountain)	monzonite	1077 ± 4 or 1076 ± 2	Marcantonio et al. 1988; Corriveau et al. (1990)
Barber's Lake	granite, monzogranite	1066 +7/-4	Davidson and van Breemen 2000b
Cavendish Township	monzogranite	1067 ± 4	Easton and Kamo (2008)
McLean	monzogranite	1070 ± 3	Davidson and van Breemen 2000b

Figure 1.1: a) 1:100 000 scale geological map of the Grenville Province of eastern Ontario showing approximate domain and terrane locations with major shear zones. Map is modified from Ontario Geological Survey (2011) b) Schematic figure of the Grenville Province of eastern Ontario and southeastern Québec showing approximate domain and terrane locations, major shear zones and the extent of the ca. 1090-1060 Ma Kensington-Skootamatta ultrapotassic intrusive suite (modified after Carr et al. 2000; Corriveau and van Breemen 2000) with pluton locations from Corriveau and van Breemen (2000) and Easton (2008). Inset delineates the extent of the Grenville Province in North America, and the black rectangle indicates the location of *figures 1.1a*, and b and the cross-section profile in *figure 2.1*. Locations of *figures 1.2a* to *1.3c* delineated. See *table 1.1* for details of the individual domains shown in the figure. Granite-monzogranite plutons are numbered 1-10 and syenite-monzonite plutons are numbered 11-29. 1-Cranberry Lake; 2-McLean; 3-Leggat Lake; 4-Elphin; 5-Barbers Lake; 6- Belmont Lake; 7-Coe Hill; 8- Burns Lake; 9 – Bob’s Lake, 10-Catchacoma; 11-Rideau Lake; 12-Foley Mountain; 13-Wolfe Lake; 14-Skootamatta; 15-Mount Moriah; 16-Gawley Creek; 17-Loon Lake; 18-Mount St. Patrick; 19-Calabogie; 20-Gracefield; 21-Cameron; 22-Satellite; 23-Kensington; 24-Baskatong; 25-Piscatosine; 26-Lac Rouge; 27-Sainte Véronique; 28-Loranger; 29-unnamed. CMBbtz-Central Metasedimentary Belt boundary thrust zone; MMSZ-Mooroton Shear Zone; MSZ-Maberly Shear Zone; RLF-Rideau Lake Fault; RLSZ-Robertson Lake Shear Zone.

Figure 1.2: Detailed 1:50 000 scale geological maps of syenite-monzonite plutons from this study showing the geochemistry and geochronology sample locations from this study and sample locations from Easton and Ford (1994). a) The Skootamatta pluton and the Grimsthorpe domain (modified from Easton 2001d); b) The Westport Area plutons and the western Frontenac terrane (modified from Hewitt 1964). Locations of these maps are shown on figure 1.1b. MMSZ - Mooroton shear zone; RLF - Rideau Lake Fault

Figure 1.3: Detailed 1:50 000 scale geological maps of granite-monzogranite plutons from this study showing the geochemistry and geochronology sample locations. a) the Cranberry Lake Granite and the southwestern Sharbot Lake domain (modified from Easton 2001b); b) Elphin and Barbers Lake granite and the central Sharbot Lake domain (modified from Easton 2001b).; c) McLean and Leggat Lake and the southeastern Sharbot Lake domain (modified from Easton 2001c). Locations of these maps are shown on figure 1.1b. RLSZ - Robertson Lake shear zone.

CHAPTER 2 - GEOLOGICAL SETTING

2.1 Regional Geological Setting of the Ontario Grenville Province

The Grenville Province was constructed in multiple stages between ca. 1300-980 Ma. The predominant orogenic event, the Ottawa orogeny, resulted in construction of the main architecture of the large, hot, Himalayan-style (Beaumont et al. 2006) orogeny by ca. 1060 Ma. There were protracted orogenesis and extensional events as young as ca. 980 Ma (e.g. Rigolet orogenic phase). Significant tracts of rock exposed in southeastern Ontario preserve evidence of the ca. 1240 Ma Elzevirian Orogeny and the ca. 1190-1140 Ma Shawinigan orogeny, which were overprinted during the Ottawa orogeny. The present day erosional level in Ontario exposes some of the rocks that were in the core zone or infrastructure during Grenville orogenesis (e.g. Laurentia and near the pre-Grenvillian Laurentian margin, Mazinaw terrane) as well as tracts of rocks that were at upper crustal levels or in the superstructure (c.f. orogenic lid: Rivers 2012) during Grenville orogenesis (e.g. parts of the Composite Arc Belt (CAB) and the Frontenac-Adirondack Belt (FAB); *figures 1.1, 2.1*: Carr et al. 2000; Culshaw et al. 2006).

This study focuses on post-tectonic plutons that are located in the Grimsthorpe and Sharbot Lake domains of the Composite Arc Belt, and the Frontenac terrane of the Frontenac-Adirondack Belt (*figures 1.1, 2.1*). See *table 1.1* for further details of the geology of the constituent terranes. The volcanic arcs that comprise the Composite Arc Belt formed outboard of Laurentia at ca. 1280-

1270 Ma and their formation was approximately coeval with that of related sedimentary basins. These arcs were amalgamated between 1245-1230 Ma, during the Elzevirian orogeny, to form the Composite Arc Belt (Carr et al. 2000). There may be a north-south difference in the timing of Elzevirian magmatism. Elzevirian plutonic complexes in the northern-Composite Arc Belt are ca. 1240-1230 (Pehrsson et al. 1996; Easton 1992) whereas, those in the southern-Composite Arc Belt have ages of ca. 1270-1250 Ma (Corfu and Easton 1997; Easton 1992). The Frontenac- Adirondack belt, although younger than the Composite Arc belt, is similar in that there are a number of components that are interpreted to have formed in a regime outboard of Laurentia at ca. 1300 Ma (*figure 1.1*; Carr et al. 2000).

An alternate view on Elzevir orogenesis is based on geochronology and geochemistry from the Central Gneiss Belt and the Adirondack highlands and lowlands. This model states that the Elzevirian Orogeny was a ca. 1350-1185 Ma protracted event that involved continental-arc Andean-type magmatism on the Laurentian margin (c.f. Hanmer et al. 2000; McLelland et al. 1996). These arcs were subsequently rifted from the margin and re-accreted during a ca. 1200 Ma continent-continent collision (Hanmer et al. 2000). For the purposes of this thesis, the Carr et al. (2000) model will be used.

The Composite Arc Belt and Frontenac-Adirondack Belt were subsequently amalgamated to each other by ca. 1190-1140 Ma during the Shawinigan Orogeny and stitched together by the Frontenac intrusive suite (Carr et al. 2000; Corfu and Easton 1997). According to the model proposed by Carr et al. (2000),

following this amalgamation, these combined terranes were accreted to, and in some cases obducted onto the Laurentian margin. The accreted terranes together with the Laurentian margin underwent Himalayan-style orogenesis at ca. 1090-1020 Ma during the Ottawa phase of the Grenville Orogeny (Carr et al. 2000; Rivers 2008; Rivers 2012). Circa 1090-1020 Ma Ottawa orogenesis culminated at ca. 1060 Ma and evidence is preserved mainly in rocks, now exposed, that were in the infrastructure of the Grenville Orogen (e.g. Laurentian margin, Central Gneiss Belt and Central Metasedimentary Belt boundary thrust zone (CMBbtz: *figure 1.1*)). In contrast, the superstructure (eastern Composite Arc Belt and parts of the Frontenac-Adirondack Belt) remained relatively unaffected by deformation and metamorphism (Culshaw et al. 1997; Rivers 2008; Rivers 2012).

2.2 Regional setting and plutonism at ca. 1190-1140 Ma

The ca. 1190-1140 Ma Shawinigan Orogeny involved the amalgamation of the Composite Arc Belt and Frontenac-Adirondack Belt by ca. 1160 (Carr et al. 2000; Corfu and Easton 1997; Hanmer and McEachern 1992; McEachern and van Breemen 1993). There was coincident extensional magmatism resulting in the emplacement of ca. 1180-1160 Ma 'A-type' monzonites, granites and syenites of the Frontenac intrusive suite, anorthosite-mangerite-charnockite-granite complexes, and associated mafic to alkali intrusive rocks in both the Sharbot Lake domain of the Composite Arc Belt and in the Frontenac terrane. Some of the Frontenac suite plutons span the boundary zone between these two domains, thus acting as stitching plutons that post-dated and constrain the age of

the end of this tectonic event (Corfu and Easton 1997; Carr et al. 2000; Davidson and van Breemen 200a)

2.3 Regional setting and plutonism at ca. 1090-1060 Ma

The Ottawa orogeny involved ca. 1090-1030 Ma Himalayan-style orogenesis in a continent-continent collision with crustal thickening and shortening. From ca. 1090-1060 Ma most of the deformation and metamorphism was focussed on the voluminous infrastructure at deep- to mid-crustal levels, along the Grenville Front Tectonic Zone (GFTZ) and the Central Metasedimentary Belt boundary thrust zone (CMBbtz; Carr et al. 2000).

Meanwhile, parts of the Composite Arc Belt and Frontenac terrane were located at shallow crustal levels (<12 km: Busch et al. 1996) and escaped much of the penetrative Ottawa regional deformation and metamorphism (Carr et al. 2000). The Mazinaw terrane, however, is an exception in that it experienced ca. 1050-1000 Ma high-grade orogenesis at deep crustal levels (~20-25 km: Busch et al. 1996; Corfu and Easton 1995). The Kensington-Skootamatta suite was emplaced in the Frontenac-Adirondack Belt and much of the Composite Arc Belt during this time interval (Carr et al. 2000; Rivers 2012).

2.4 The Kensington-Skootamatta suite

The Kensington-Skootamatta suite is a syn- to post-tectonic, post-metamorphic intrusive suite that occurs in a linear belt that strikes northeast-southwest for 400 km within the Composite Arc Belt and Frontenac terrane (and equivalents in Quebec). The plutons of the Kensington-Skootamatta suite were emplaced at ca. 1090-1060 Ma during the Ottawa-stage of the Grenville

Orogeny (Carr et al. 2000) and do not occur in the Mazinaw domain. The Calabogie syenite is a possible exception (*figure 1.1*); however, it is located in an area where the terrane boundaries are not well defined. Granite pegmatite dikes were emplaced into higher metamorphic grade portions of the Composite Arc Belt between 1080 and 1030 Ma (cf. Easton 1986, 1992), for example at ca. 1080 Ma in northern Mazinaw domain (Corfu and Easton 1995). The relationship of these late granite pegmatite dikes to the Kensington-Skootamatta suite is unknown, and is beyond the scope of the thesis.

In general, the plutons are medium- to coarse-grained, unmetamorphosed and undeformed, locally displaying a weak biotite foliation at the margins, and cut across foliations, folds and regional structures in the country rock. There is lack of evidence for contact aureoles surrounding the plutons. The syenite-monzonite plutons can further be distinguished geophysically by their moderate eU and eTh contents and typically intense aeromagnetic highs, whereas the granite-monzogranite plutons have high K/eTh ratios, varied eU and eTh contents, and range in aeromagnetic character from low to moderate values to intense highs (Easton 2008). Associated with the Kensington suite in Quebec is a ca. 1070 Ma minette dyke containing foliated, gneissic and mylonitic fabric (Corriveau and Morin 2000). Previous descriptions of the plutons of the Kensington-Skootamatta suite have characterised them as having a relatively low SiO₂ content (45-60 wt%), TiO₂ > 0.8 and P₂O₅ > 0.21 and being alkalic, shoshonitic to ultra-potassic and metaluminous (Corriveau 1990; Corriveau et al. 1990). However, it is important to note that research of Corriveau et al. (1990) was restricted to the

syenite-monzonite plutons, and there is limited previous work on the granite-monzogranite plutons.

2.5 Local Geological and Structural Setting of Study Areas

Geological maps of the study areas, featuring studied plutons and sample locales, are shown in *figures 1.1, 1.2 and 1.3* and a schematic diagram showing the relative crustal levels of the constituent terranes and domains at ca. 1090-1060 Ma is shown in *figure 2.1*. A summary of the geology, geochronology and geochemical interpretations from previous work on the terranes/domains that host the plutons of interest are summarised in *table 1.1*, and previous geochronology data from ca. 1090-1060 plutons are shown in *table 1.2*.

2.5.1 Structural Setting of the Study Areas

The Grimsthorpe and Sharbot Lake domains and the Frontenac terrane were in the orogenic superstructure at ca. 1090-1060 Ma, thus did not apparently experience penetrative deformation or metamorphism during this time. The Mazinaw terrane, meanwhile, was in the orogenic infrastructure and was being penetratively deformed and metamorphosed during ca. 1060-980 Ma events (*figure 2.1*; Carr et al. 2000; Corfu and Easton 1995; Corfu and Easton 1997).

The Grimsthorpe domain is bounded on the east by the Mooroton shear zone (MMSZ), an east dipping mylonite zone interpreted to have thrust motion that is older than 1030 Ma (*figures 1.1, 1.2a and 2.1*; Cureton et al. 1997). The Mooroton shear zone separates the Grimsthorpe domain from the Mazinaw terrane (*figures 1.1, 1.2*). The crustal level of the Grimsthorpe domain at ca.

1090-1060 Ma is uncertain as there is a lack of thermochronology data or other relevant textural information, however, since the Grimsthorpe domain has apparently escaped deformation and metamorphism during the Ottawa orogeny then it was likely at a mid- to upper crustal level at that time (<15-12 km: *figure 2.1*; Rivers 2008; Rivers 2012).

The Sharbot Lake domain is bounded on the west by the Robertson Lake shear zone (RLSZ) and on the east by the Maberly shear zone (MSZ). These shear zones separate the Sharbot Lake domain from the Mazinaw terrane and Frontenac terranes, respectively (*figures 1.1, 1.2, 1.3, and 2.1*). At ca. 1090-1060 Ma, the Sharbot Lake domain dipped to the east and ranged from shallow (~12 km) to mid (~20 km) crustal depths based on $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology (Cosca et al. 1992; Busch and van der Pluijm 1995; Busch et al. 1996).

The Frontenac terrane was at a relatively high crustal-level (<8 km) by ca. 1160 Ma, as inferred by granophyric textures, little to no contact aureoles and miarolitic cavities in the ca. 1160 Ma Tichborne granite (Davidson 2001). This is further supported by $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende cooling ages within Frontenac terrane ranging from ca 1125 to 1100 Ma (Cosca et al. 1992; Davidson 2011; Rivers 2012). Furthermore, there has been little no deformation or metamorphism younger than ca. 1180-1140 Ma.

At ca. 1090-1060 Ma, the Mazinaw terrane was at a mid-crustal level (~25 km: Rivers 2012; Busch et al. 1996). Extensional events beginning ca. 1030 Ma, led to normal faulting and displacement along crustal scale faults such as the

Mooroton shear zone and Robertson Lake shear zone. These shear zones juxtaposed the Mazinaw terrane against the Grimsthorpe and Sharbot Lake domains, respectively (Busch et al. 1997; Busch et al. 1996; Cureton et al. 1997). The Mazinaw terrane was subsequently cooled below the hornblende cooling temperature by ca. 950 Ma (Cosca et al. 1991; Busch et al. 1996), finally reaching shallow crustal levels by ca. 590 Ma (Kamo et al. 1995)

2.5.2 Grimsthorpe domain – Skootamatta pluton

The Skootamatta pluton is located in the eastern part of the Grimsthorpe domain (*figures 1.1, 1.2, 2.1*). This part of the domain is bounded by the Partridge Creek shear zone to the west and the Mooroton shear zone to the east (Easton and Ford 1994). The geology of this area is dominated by >1267 Ma supracrustal mafic metavolcanic rocks and minor volcanic conglomerates intruded by gabbro, leucogabbro (preserving igneous layering), anorthosite and ultramafic rocks of the Killer Creek gabbro. Both the supracrustal and intrusive rocks were intruded by the ca. 1267 Ma Elzevir tonalite (*figures 1.1a, 1.2a*: Lumbers et al. 1990). The rocks in the eastern part of the Grimsthorpe domain have all been metamorphosed to greenschist facies (age of metamorphism uncertain) and show little, if any evidence of strain. The rocks of the Grimsthorpe domain are interpreted to have a primitive arc affinity (Easton and Ford 1994).

2.5.3 Sharbot Lake domain – Cranberry Lake pluton

The geology of the Sharbot Lake domain in the vicinity of the Cranberry Lake pluton (*figures 1.1a, 1.3a*) comprises ca. 1240 Ma amphibolite, metagabbro, mafic to felsic metavolcanic, pyroclastic rocks and marbles (Corfu

and Easton 1997; Easton 2001). These rocks have all been penetratively deformed and metamorphosed at ca. 1170 Ma (Corfu and Easton 1997) to produce strong mineral foliations striking to the northwest, and dipping to the northeast. Adjacent to the Robertson Lake shear zone, there are prominent mylonites, dipping 15-20° to the east, displaying hematite and epidote alteration cut by quartz vein stockwork. The Cranberry Lake pluton cuts across the regional structural trends, appears to have been emplaced concordant to the Robertson Lake shear zone, has an irregular map pattern and has a strong mineral foliation (*figure 1.3a*: Easton 2001a; 2001b).

2.5.4 The Sharbot Lake domain – Elphin and Barbers Lake pluton

The Elphin and Barbers Lake plutons are located in the central area of the Sharbot Lake domain (*figure 1.1; 1.3b*). The Elphin pluton intruded the massive, medium- to coarse-grained ca. 1224 Ma Lavant gabbro (*figure 1.3b*: Corfu and Easton 1997). The Barbers Lake pluton intruded the Dalhousie pyroxenite-gabbro amphibolite complex, locally bedded marbles and polydeformed mafic metavolcanic rocks, that strike to the northeast, and dip moderately to the southeast (*figure 1.3b*). There are U- and Th-rich pegmatite veins associated with the Barbers Lake pluton (Easton 2008).

2.5.5 The Sharbot Lake domain – McLean and Leggat Lake plutons

The southern part of the Sharbot Lake domain, in the vicinity of the McLean and Leggat Lake plutons is dominated mafic to intermediate metavolcanic rocks, and minor marbles and siliciclastic metasedimentary rocks of the Grenville Supergroup that were intruded by the ca. 1255 Ma (Wallach 1973)

Hinchinbrooke tonalite gneiss and the sub-circular dioritic ca. 1154 Ma Mountain Grove pluton (*figures 1.1a and 1.3c*; Davidson and van Breemen 2000c). The youngest age for the Grenville Supergroup in this area is constrained by the age of the Hinchinbrooke tonalite gneiss.

There have been multiple phases of deformation as evidenced by foliations striking east-northeast and dipping moderately- to steeply to the south-southeast and regional map-scale refolded isoclinal folds (*figure 1.3c*). The most recent phase of deformation and metamorphism is dated at ca. 1170 Ma (Corfu and Easton 1997). The Leggat Lake and McLean plutons cut across the regional structural trends, and the McLean pluton is bounded to the west by the Robertson Lake shear zone (*figure 1.3c*).

2.5.6 The Frontenac terrane – Westport area plutons

Around the Westport area plutons, the geology consists of marbles interlayered with quartzofeldspathic gneiss and two separate quartzite units, intruded by the ca. 1190-1160 Frontenac intrusive suite (*figures 1.1a and 1.2b*; Davidson and van Breemen 2000b). Detrital zircons from the upper quartzite indicate deposition after ca. 1306 Ma, whereas those from the lower quartzite indicate deposition after ca. 1400 Ma (Chiarenzelli et al. 2013; Wynne-Edwards 1967; Sager-Kinsman and Parrish 1993). The rocks have been both metamorphosed and deformed at ca. 1170 Ma (Corfu and Easton 1997) with foliations trending north-northeast, and moderately dipping to the south-southeast and at least two generations of map-scale regional folds (*figure 1.2b*). The Westport area plutons do not follow the regional structural trends and are

bounded to the south by the Rideau Lake fault (*Figure 1.2b*). Note that the Rideau Lake pluton may in fact, comprise 2 separate bodies. Sampling was focussed on the western of the 2 bodies.

Circa 1090-1060 Ma

Figure 2.1: Schematic cross-section of the Grenville Province at ca. 1060 Ma showing the relative structural levels of the constituent terranes and domains. This cross-section follows the model of White et al. (2000), whereby pre-Grenvillian Laurentia and the Laurentian margin extend beneath the CAB and the CMBbtz and CGB represent zones of ductile deformation during Ottawaan orogenesis. The terranes, domains and regions that were located within the orogenic infrastructure (grey) were undergoing penetrative deformation and metamorphism at ca. 1060 Ma. The terranes and domains that were located in the orogenic superstructure (white) remained unaffected by ca. 1060 Ma orogenesis. Domains and terranes are: BT-Bancroft Terrane; CAB-Composite Arc Belt; CGB-Central Gneiss Belt; FAB-Frontenac Adirondack Belt; FT-Frontenac Terrane; GD-Grimsthorpe Domain; MT-Mazinaw Terrane; and SLD-Sharbot Lake Domain. Shear zones or faults are: CMBbtz-Central Metasedimentary Belt boundary thrust zone; GFTZ-Grenville Front Tectonic Zone; MSZ-Maberly Shear Zone; MMSZ-Mooroton Shear Zone; RLSZ-Robertson Lake Shear Zone.

CHAPTER 3 - GEOCHEMISTRY

Petrography and geochemistry studies were undertaken to characterize the nine plutons in this study and to determine their tectonic and melt origins. These data will be used to establish similarities and differences of the syenite-monzonite and granite-monzogranite plutons.

3.1 Geochemistry methods

Samples were trimmed and chipped in the field to remove weathered surfaces and to facilitate the crushing procedure, sample preparation, and dissolution chemistry which were all carried out at GeoScience Laboratories, Ontario Geological Survey, in Sudbury, Ontario. Major and trace elements for all samples were analysed also at GeoScience Laboratories. Forty-three syenite-monzonite samples were analyzed: 10 from the Wolfe Lake and Rideau Lake plutons, 11 from the Foley Mountain pluton and 12 from the Skootamatta syenite. Previously published major and trace element analyses from 26 samples; excluding REEs, from Easton and Ford (1994), were included to complement the data-set. Twenty-four granite-monzogranite samples were analyzed: 3 from Barbers Lake granite, 10 from the Elphin and Leggat Lake plutons, 11 from the McLean pluton and 2 from the Cranberry Lake pluton. In addition, 11 samples from the Barbers Lake pluton, collected by Ken Ford of the Geological Survey of Canada (*unpublished data*), were re-analysed for this study. All 89 samples were crushed then powdered in an agate ball mill. Dissolution for trace element analysis was done using a closed vessel multi-acid digestion. Analysis for major

elements was carried out using X-ray fluorescence (XRF), and minor and trace elements were analysed using a combination of XRF, inductively coupled plasma - mass spectrometry (ICP-MS), and inductively coupled plasma - atomic emission spectroscopy (ICP-AES). Furthermore, some samples were analysed for carbon and sulphur using infrared absorption, and ferrous iron using titration. Representative geochemical analyses for each pluton are presented in *table 3.1* alongside analyses from Corriveau et al. (1990).

Sm/Nd and Sr isotopic analyses were carried out on two samples from each syenite pluton, 4 samples from the Barbers Lake pluton, 3 from each of the Elphin and Leggat Lake plutons, 2 from the McLean pluton and 1 from the Cranberry Lake pluton. The samples were crushed and powdered at Geoscience Laboratories in Sudbury, Ontario. Sample powder dissolution and chemistry were completed at the Isotope Geochemistry and Geochronology Research Centre (IGGRC) at Carleton University following chemical techniques outlined by Cousens (1996). Sm/Nd samples were analysed using isotope dilution - thermal ionization mass spectrometry (ID-TIMS) using a ^{148}Nd - ^{149}Sm spike with reproducibility of ± 0.0000012 . Uncertainty on ϵNd values is ~ 0.5 . Sr isotopic analyses were carried out using thermal ionization mass spectrometry (TIMS) methods; detailed descriptions of dissolution chemistry, column chemistry techniques, and mass spectrometry are summarized in *appendix A – MRD 311*. Sr and Sm-Nd isotopic analyses are presented in *table 3.2*. Uncertainties are presented at the 2σ level.

3.2 Results

The plutons of the Kensington-Skootamatta suite are divided into two geochemical suites on the basis of their rock-type (Easton 2008) and geochemistry signatures; a syenite-monzonite suite (*figure 1.2*) and a granite-monzogranite suite (*figure 1.3*). (Note: the use of the term suite is on the basis of similar rock types rather than indicating a formal lithostratigraphic unit). The plutons from this study that are included in the syenite-monzonite suite are the Skootamatta and the Westport area plutons, and the plutons from this study that are included in the granite-monzogranite suite are the Barbers Lake, Leggat Lake, and McLean plutons. Geochronology results for the Elphin and Cranberry Lake plutons (Cutts, Chapter 4) exclude them from the Kensington-Skootamatta suite.

3.2.1 Syenite-monzonite suite

The Skootamatta and Westport area plutons are included in the syenite-monzonite suite. In general, these plutons consist of medium- to coarse-grained, equigranular to bimodal grain size, biotite-rich syenite to monzonite to quartz monzonite rocks. The Westport area plutons show little variation in grain-size or rock-type whereas the Skootamatta syenite varies from biotite-syenite to monzonite to monzodiorite, and locally has up to 40% biotite. The plutons are on average K-feldspar- and plagioclase-rich, with minor quartz and biotite, and trace amounts of hornblende, garnet, pyrite, zircon and apatite. The Foley Mountain and Rideau Lake plutons show some localised variation in their proportions of K-feldspar (20-50%) and plagioclase (15-50%). Photomicrographs show localised

micrographic intergrowth between quartz and potassium feldspar. There is ~5-10% sericitic alteration. See *figure 3.1* for representative photographs and photomicrographs for each syenite-monzonite pluton.

The geochemical data (*table 3.1*) plot in the trachyte to monzonite to syenite fields on a total alkali-silica rock classification diagram (*figure 3.2a*), and are characterised by dominantly alkaline, shoshonitic and metaluminous compositions (*figure 3.2a-c*). Furthermore, they are primarily classified as ferroan and alkalic on the Frost et al. (2001) classification diagrams for granitoids (*figure 3.2d-e*). The three Westport area plutons cluster similarly on major element plots (*figure 3.2a-e*). Skootamatta samples, however, show a greater range of major element abundances. This is consistent with the greater range of rock-types observed within the pluton.

On primitive mantle-normalised extended multi-element plots, the syenite-monzonites are characterised by prominent negative Ti, Sr, and P anomalies, and a minor Nb anomaly (*figure 3.3a*), LREE enrichment (Westport area $La_n/Sm_n \sim 2-4$, Skootamatta $La_n/Sm_n \sim 3-4.5$: *figure 3.3a*), and low HREE enrichment (Westport $Gd_n/Yb_n \sim 1.5-3$; Skootamatta $Gd_n/Yb_n \sim 1.5-4.5$: *figure 3.3a, e*). The Foley Mountain and Rideau Lake plutons appear to have two trace element patterns; one set with a flatter curve (higher HREE), and minor Sr and P anomalies, and a second set that has the opposite pattern (*figure 3.3a*). Relative to the Westport area plutons, the Skootamatta pluton has non-depleted U and Th anomalies and a slight negative Nb anomaly. The Westport area plutons have Th and U concentrations of 3-10 ppm and 0.5-3.1 ppm, respectively, whereas the

Skootamatta pluton has Th and U concentrations of 1-82 ppm and 0.6-8 ppm, respectively.

On chondrite-normalised REE plots, both the Wolfe Lake and the Skootamatta plutons consistently do not exhibit Eu anomalies, whereas two samples from Rideau Lake pluton and six from the Foley Mountain pluton have higher overall REEs and negative Eu anomalies (*figure 3.3e*). The samples with higher HREE and negative Eu anomalies have a more intense pink-red colouration in hand sample and a higher proportion of K-feldspar (syenites), whereas the samples with lower HREE and neutral or positive Eu anomalies have a more pink-grey colouration in hand sample, and a higher proportion of plagioclase (monzonite). Relative to the other plutons, the Skootamatta pluton overall has a steeper REE pattern.

In the Pearce et al. (1984) tectonic discrimination diagram for granitoids, samples from the Skootamatta pluton plot in the volcanic arc granite (VAG) field, whereas the Westport area plutons plot in the within plate granite (WPG) to anomalous ocean-ridge granite fields (AORG: *figure 3.4a*). In the Whalen et al. (1987) tectonic discrimination diagrams for A-type granitoids, both the Skootamatta and Westport area plutons dominantly plot as A-type (*figure 3.4b*). On the Eby (1992) sub-classification diagram for A-type granitoids, the Skootamatta pluton plots as A₂; representing melts contaminated by partial melting of continental lithosphere whereas, the Westport area plutons plot as A₁; representing mantle differentiates (*figure 3.3c*).

Two samples from each of the four syenite-monzonite plutons were selected for Sr, and Sm/Nd isotopic analysis. In general, the samples from the four plutons yielded ϵ_{Nd} values of 1.88 to 5.07, although one sample from the Foley Mountain pluton yielded a more contaminated ϵ_{Nd} value of -0.40. Overall, these values suggest derivation of the melt from a depleted source. T_{DM} model ages range from 1196-1802 Ma. Initial Sr values are less diagnostic; however, they still suggest derivation of the melt from a depleted source (*figure 3.5, table 3.2*).

3.2.2 Granite-monzogranite suite

The Barber's Lake, McLean and Leggat Lake plutons are included in the granite-monzogranite suite. In general, these plutons consist of fine- to coarse-grained, equigranular to bimodal grain-size, granite to syenogranite to monzogranite to quartz syenite. Due mainly to the higher proportion of quartz in the mineralogy of the granite-monzogranite plutons than in the syenite-monzonite plutons, the granite-monzonite plutons have a greater range in rock-type both within each pluton and between plutons of the suite. In general, the plutons are K-feldspar, plagioclase and quartz rich with minor biotite, and hornblende along with trace amounts of chlorite, pyrite, garnet, apatite and zircon.

Photomicrographs show abundant micrographic intergrowth between potassium feldspar and quartz; particularly in the Barbers Lake pluton. See *figure 3.6* for representative photographs and photomicrographs for each granite-monzogranite pluton. The McLean pluton is relatively homogeneous in both modal abundance and grain size, whereas, the Leggat Lake pluton ranges from

fine- to coarse-grained and from granite to alkali feldspar granite to syenite. The Leggat Lake pluton is unique in that the grain-size appears to be related to the location within the pluton; fine-grained at the margin, coarse-grained at the center. The other plutons show no correlation between grain-size and spatial distribution. There are localized occurrences of tourmaline veins in the Barbers Lake pluton. All of the plutons have minor amounts of sericitic alteration (see *appendix A – MRD 311*).

The data dominantly plot as monzogranite to granite to quartz monzonite on a total alkali-silica rock classification diagram (*figure 3.2a*), and are characterised by dominantly alkaline and metaluminous to peraluminous compositions (*figure 3.2a-c*). On Frost et al. (2001) classification diagrams for granitoids, the data dominantly plot as ferroan and alkalic (*figure 3.2d-e*). The Barbers Lake data are easily distinguished from the other granites by their higher SiO₂ content. The Barbers Lake data plot as sub-alkaline (TAS: *figure 3.2a*), high-K calc-alkalic and alkali-calcic (*figure 3.2b-d*).

On primitive mantle-normalised extended multi-element plots, the granite-monzogranite samples are characterised by prominent negative Ba, Ti, Sr, and P anomalies, a minor Nb anomaly and a shallow negative trend; similar to the Westport area plutons, with LREE enrichment (e.g. Leggat Lake, McLean and Barbers Lake have La_n/Sm_n ~1.5-4: *figure 3.3b*), and low HREE enrichment (Leggat Lake, McLean, and Barbers Lake Gd_n/Yb_n ~1-1.4: *figures 3.3b, f*). Barber's Lake samples are distinguishable from the other granites by a greater depletion in Ba, La, Ce and Ti and greater enrichment in U, Th and Pb (*figure*

3.3b). The Leggat Lake and McLean plutons have Th and U concentrations of 3.8-58 ppm and 1.2-6.4 ppm, respectively, whereas the Barber's Lake pluton has Th and U concentrations of 25-109 ppm and 5.5-90 ppm, respectively.

On a chondrite-normalised REE plot, the granites dominantly have pronounced negative Eu anomalies ($\text{Eu}/\text{Eu}^* = \sim 0.1-0.5$ *figure 3.3f*). Three samples from the granite-monzogranite suite have different chondrite-normalised REE profiles than the other granite-monzogranite samples; and include sample JC-061 from the Leggat Lake intrusion and samples JC-001 and BL32 from the Barbers Lake intrusion. Sample JC-061 has a REE profile with a much steeper slope than the other granite-monzogranite samples with a concave up pattern. Samples JC-001 and BL-32 have much lower LREE concentrations than the other granite-monzogranite samples.

In the Pearce et al. (1984) tectonic discrimination diagram for granitoids, the data from the granite-monzogranite plutons plot in the WPG and AORG fields (*figure 3.4a*). On the Whalen et al. (1987) tectonic discrimination diagrams for A-type granitoids, the Barbers Lake data plot in the fractionated granite (FG) and the M/I/S-type granite (OGT) fields, whereas, the remaining granites plot in the A-type field (*figure 3.4b*). On an A-type sub-classification scheme of Eby (1992), the granites uniformly plot in the A_2 field; representing melts contaminated by partial melting of the continental lithosphere. Only the Barbers Lake pluton shows some ambiguity, with some data partially plotting in the A_1 field, which represents mantle differentiates (*figure 3.4c*).

Four samples from the Barbers Lake pluton, 2 from the McLean pluton, and 3 from the Leggat Lake pluton were selected for Sr, and Sm-Nd isotopic analysis. In general, these samples yielded ϵ_{Nd} values of +1.52 to +4.58, although 1 sample from the Barbers Lake pluton yielded a contaminated ϵ_{Nd} value of -6.39. T_{DM} model ages range from 1333-1997 Ma. Initial Sr ratios are less definitive, likely due to element mobility; however, they may be consistent with derivation of the melt from a depleted source (*figure 3.5, table 3.2*).

3.2.3 The Cranberry Lake pluton

The ca. 1157 Ma Cranberry Lake pluton is part of the Frontenac intrusive suite (Cutts, Chapter 4) and consists of medium- to coarse-grained, foliated granite to alkali feldspar granite. It is dominantly composed of K-feldspar, plagioclase feldspar and quartz with minor biotite and trace hornblende. There is a strong mineral foliation evident by the alignment of biotite, hornblende and quartz ribbons (*figure 3.6f*). Along fracture planes at outcrop scale, veins have undergone epidote alteration.

Geochemical data from the two Cranberry Lake samples plot in the granite field on a total alkali-silica rock discrimination diagram, and are characterised by shoshonitic and metaluminous compositions (*figure 3.2a-c*). On the Frost et al. (2001) classification diagrams for granitoids, the data plot in the ferroan and alkalic fields (*figure 3.2d-e*).

On a primitive mantle-normalised extended multi-element plot, the Cranberry Lake pluton is characterised by prominent negative Ti, Sr, P, and Nb

anomalies and a shallow negative trend with LREE enrichment ($\text{La}_n/\text{Sm}_n \sim 2\text{-}3$), and low HREE enrichment ($\text{Gd}_n/\text{Yb}_n \sim 1\text{-}1.4$: *figure 3.3c*). On a chondrite-normalised REE plot, the Cranberry Lake granite has a pronounced negative Eu anomaly ($\text{Eu}/\text{Eu}^* = \sim 0.1\text{-}0.5$: *figure 3.3g*).

On various tectonic discrimination diagram for granitoids, the data from the Cranberry Lake pluton plot as a WPG to AORG (*figure 3.4a*: Pearce et al. 1984), as anorogenic granites (*figure 3.4b*: Whalen et al. 1987), and as having a melt contaminated by partial melting of the continental lithosphere (*figure 3.4c*: Eby 1992).

One sample from the Cranberry Lake pluton was selected for Sr and Sm-Nd isotopic analysis. Analysis of this sample yielded an ϵNd value of 4.50, a T_{dm} age of 1339 Ma and an initial Sr value of 0.70196 (*figure 3.5*; *table 3.2*).

3.2.4 The Elphin pluton

The ca. 1178 Ma Elphin pluton is part of the Frontenac intrusive suite (Chapter 4) and ranges in rock-type and texture from fine- to coarse-grained granite to alkali feldspar granite to syenite to monzonite. It is dominantly composed of K-feldspar, plagioclase feldspar, quartz minor biotite and trace hornblende. There is a localised weak mineral foliation with minor sericitic alteration throughout the intrusion (*figure 3.6b*).

Samples from the Elphin pluton dominantly plot in the granite and syenite fields on a total alkali-silica rock classification diagram. Sample JC-012; a biotite-rich (~20%) sample, plots in the nepheline syenite field; however, there is no

petrographic evidence to support its designation as such. Samples from the Elphin pluton are further characterised by calc-alkaline/high-K calc-alkaline to shoshonitic and metaluminous to peraluminous compositions (*figure 3.2a-c*). On the Frost et al. (2001) classification diagrams for granitoids, the samples plot in the ferroan to magnesian and alkalic fields (*figure 3.2d-e*).

On a primitive mantle-normalised extended multi-element plot the Elphin pluton data are characterised by prominent negative Ti, P, and Nb anomalies and a steeper negative trend than the other plutons in this study with LREE enrichment ($\text{La}_n/\text{Sm}_n \sim 2-3$), and low HREE enrichment ($\text{Gd}_n/\text{Yb}_n \sim 3$: *figure 3.3d,h*). On a chondrite-normalised REE plot, the Elphin pluton data do not have a Eu anomaly and are depleted in HREEs relative to all of the other plutons in this study (*figure 3.3h*).

On various tectonic discrimination diagrams for granitoids, the Elphin pluton plots as a VAG (*figure 3.4a*; Pearce et al. 1984), a fractionated granite (*figure 3.4b*; Whalen et al. 1987), and as having a melt contaminated by partial melting of the continental lithosphere (*figure 3.4c*; Eby 1992).

Three samples from the Elphin pluton were selected for Sr and Sm-Nd isotopic analysis. These sample yielded positive to slightly negative ϵNd (-1.11 to 4.48, T_{dm} ages of 1318-1946 Ma and initial Sr values (0.70224 to 0.70323: *figure 3.5; table 3.2*).

3.3 Summary of Geochemistry Results

- The syenite-monzonite and granite-monzogranite plutons are petrographically distinct. The syenite-monzonite plutons contain higher proportions of K-feldspar, less quartz, and higher biotite content (10-20%), particularly the Skootamatta syenite. The Elphin pluton also contains more biotite than the granite-monzogranite plutons (*figure 3.6*).
- The syenite-monzonites have lower SiO₂ content (~60% vs. 66-75%), and higher alkali content (11% vs. 9%) relative to the granite-monzogranites (*figure 3.2a*).
- Both plutonic suites are dominantly alkalic, metaluminous to peraluminous, shoshonitic and ferroan; however, the syenite-monzonite plutons are more alkalic, more dominantly metaluminous and are less consistently ferroan than the granite-monzogranites (*figure 3.2b-e*).
- The multi-element profiles show depletions in the same trace elements in both suites (Nb, Sr, P, Ti; Eu on REE plot; *figures 3.3a,b,e,f*); however, the anomalies are more pronounced in the granite-monzogranite suite relative to the syenite-monzonite suite
- The Westport area, Barber's Lake, Leggat Lake and McLean plutons plot as within-plate granite to anomalous ocean ridge granite to volcanic arc granite.
- The Skootamatta and Elphin plutons plot as volcanic arc granites.
- The syenite-monzonite plutons and the granite-monzogranite plutons have similar ϵNd and initial strontium values that suggest a slightly depleted source with some possible contamination from continental crust.

- The Skootamatta pluton has a unique major and trace element geochemistry relative to the other syenite-monzonites, and has a steeper normalised trace-element profile (lower HREE), and lacks a Eu anomaly (*figures 3.3a,e*).
- Compared to the other granite-monzogranites, the Barbers Lake intrusion has a greater depletion in Ba, and greater enrichments in Th, U and Pb.
- The Cranberry Lake pluton is the only intrusion that appears deformed at the map-scale, and in outcrop and hand-sample.
- The Elphin pluton has a much more varied rock-type than the other plutons; based on the petrography and the total alkali-silica plot (*figure 3.2a*), a unique geochemistry that is consistent with more arc-like magmatism (*figures 3.3d, 3.4a-c*) and a depleted isotopic character.

Table 3.1: Representative Major and Trace Element Analyses from Each Pluton

	Wolfe Lake		Foley Mountain	¹ Foley Mountain	Rideau Lake	Skootamatta	Barbers Lake	McLean	Leggat Lake	Cranberry Lake	Elphin
Sample	JC-050	JC-081	JC-081	JC-081	JC-070	JC-031	JC-003	JC-075	JC-063	JC-066	JC-059
Easting	386915	391125	391125	391125	397084	321802	377251	353968	363103	348651	371169
Northing	4950517	4952410	4952410	4952410	4951588	4965569	4976087	4948494	4951414	4934172	4975085
Oxides (wt %)											
SiO2	60.16	61.64	61.64	61.59	59.63	57.97	76.87	68.21	67.02	67.8	61.01
TiO2	0.77	0.84	0.84	0.93	1.06	0.98	0.07	0.67	0.41	0.53	0.35
SiO2	17.61	17.41	17.41	17.42	18.25	17.44	12.14	14.06	15.3	14.88	18.78
Fe2O3	4.6	4.02	4.02	4.09	4.38	6.04	1.68	3.99	2.69	3.21	3.16
FeOt	4.14	3.62	3.62		3.94	5.43	1.51	3.59	2.42	2.89	2.84
Mn	0.12	0.067	0.067		0.086	0.10	0.01	0.058	0.026	0.057	0.021
MgO	1.33	1.06	1.06	1.4	1.55	1.53		0.8	0.42	0.68	0.71
CaO	1.63	1.599	1.599	1.41	2.152	2.47	0.84	1.728	1.52	1.957	1.62
Na2O	5.77	5.51	5.51	6.31	4.96	4.98	3.77	3.88	4.52	4.75	5.5
K2O	6.58	6.21	6.21	5.83	5.86	6.26	4.09	5.18	5.13	4.61	6.2
P2O5	0.39	0.288	0.288	0.27	0.388	0.50	0.01	0.158	0.099	0.164	0.189
LOI	0.71	0.95	0.95	0.66	0.86	0.83	0.69	0.64	1.41	0.33	1.71
Total	99.65	99.59	99.59	99.91	99.17	99.11	100.15	99.37	98.54	98.97	99.24

Trace Elements (ppm)

Ba	531	640.3	640.3	717	1576.2	1711	26.4	882.7	1361.8	822.9	2700
Be	1.77	3.56	3.56		3.23	1.59	6.4	3.25	3.53	2.27	1.37
Bi	<0.15	<0.15	<0.15		<0.15	<0.15	<0.15	<0.15	<0.15	<0.15	<0.15
Cd	0.102	0.08	0.08		0.054	0.086	0.03	0.065	0.052	0.082	0.038
Ce	162.87	307.67	307.67		177.79	205.9	167.06	244.65	187.13	101.81	45.52
Co	2.6	3.98	3.98		4.58	9	<6	4.46	2.81	3.49	4.25

Sample	Wolfe Lake		Foley Mountain	¹ Foley Mountain	Rideau Lake	Skootamatta	Barbers Lake	McLean	Leggat Lake	Cranberry Lake	Elphin
	JC-050	JC-081	JC-081	JC-081	JC-070	JC-031	JC-003	JC-075	JC-063	JC-066	JC-059
Cr	13	8			3	<4	29	21	11	19	5
Cs	0.579	0.482			0.833	1.421	3.249	0.529	0.606	0.912	0.211
Cu	6	1.6			<1.4	9	4	5	5.5	5.4	7
Dy	6.822	11.565			7.899	6.569	10.913	18.406	8.951	8.211	1.311
Er	3.408	6.455			3.857	2.902	6.549	11.008	5.72	5.193	0.597
Eu	3.1029	3.3272			4.1361	4.541	0.94	3.3277	2.0155	1.9498	1.7718
Ga	19.07	23.55			23.42	18.73	23.52	23.41	21.7	18.51	16.27
Gd	8.629	13.409			10.446	10.63	13.512	17.732	8.767	8.2	2.222
Hf	5.68	15.16			5.92	10.48	11.66	15.28	10.68	7.58	1.84
Ho	1.2619	2.2065			1.4252	1.127	2.141	3.6747	1.8334	1.6782	0.2209
In	0.0474	0.0466			0.0489	0.054	0.043	0.0667	0.0259	0.0375	0.0091
La	73.36	142.77			80.14	97.28	69.08	101.45	99.39	40.22	22.5
Li	12.8	21			21	18.4	8.4	16.7	16.6	6.3	5.8
Lu	0.4079	0.8786			0.4509	0.32	1.27	1.5488	0.8537	0.8113	0.0714
Mo	1.31	1.48			1.69	1.37	1.16	2.15	1.28	1.55	0.43
Nb	19.019	54.423		51	26.561	12.534	31.42	51.843	36.041	11.321	3.444
Nd	77.26	127.13			89.52	102.51	76.6	118.33	69.08	53.55	22.68
Ni	3	<1.6			<1.6	5	5	2.7	<1.6	1.7	5
Pb	13.8	7			10.5	15.3	20.5	5.2	3.7	7.9	2
Pr	20.57	36.056			22.968	26.251	20.906	31.378	20.28	13.75	5.796
Rb	97.1	121.43		124	98.98	101	213	114.61	144.16	121.69	55.06
Sb	0.1	0.05			0.06	0.1	0.31	0.08	0.13	0.12	0.21
Sc	5.5	5.6			5	6	2	6.5	2	3	2.8
Sm	12.572	19.862			15.029	16.62	17.305	22.48	11.458	10.177	3.627
Sn	1.81	3.98			2.57	1.8	3.37	5.45	3.1	2.18	0.54

Sample	Wolfe Lake		Foley Mountain	¹ Foley Mountain	Rideau Lake	Skootamatta	Barbers Lake	McLean	Leggat Lake	Cranberry Lake	Elphin
	JC-050	JC-081	JC-081	JC-081	JC-070	JC-031	JC-003	JC-075	JC-063	JC-066	JC-059
Sr	363	266.4	455	698.2	1226	27	232.1	288.5	223.4	>1560	
Ta	1.347	3.924	1.595	0.668	2.706	3.735	3.007	0.818	0.235		
Tb	1.1979	2.0002	1.3854	1.296	1.904	2.9289	1.3983	1.2859	0.2563		
Th	3.936	10.634	6.542	5.243	54.315	10.943	21.012	8.174	3.995		
Tl	0.567	0.631	0.555	0.788	1.931	0.692	0.735	0.634	0.178		
Tm	0.4722	0.9393	0.5194	0.369	1.039	1.6713	0.8877	0.7966	0.0757		
U	1.273	3.181	1.826	1.877	82.735	4.123	5.506	3.556	0.584		
V	30	37	33	54	1.5	35.4	19.9	22.9	41.7		
W	0.32	0.22	0.4	0.59	0.82	0.35	0.42	0.24	0.53		
Y	33.86	61.46	38.5	30.22	67.03	103.72	54.67	49.18	6.23		
Yb	2.883	6.164	3.194	2.235	7.496	10.943	5.941	5.403	0.484		
Zn	97	62	102	93	10	66	23	49	22		
Zr	582	956	889	467	790	654	419	381	83		

¹ From Corriveau et al. (1990)

Table 3.2: Sm-Nd and Rb-Sr isotope geochemistry analytical data for the plutons of interest in this study

Sample	Pluton	Age (Ma)	[Sm] ¹	[Nd] ¹	¹⁴³ Nd/ ¹⁴⁴ Nd	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd _i ²	2σ	εNd	T _{dm}	Sample	[Rb] ¹	[Sr] ¹	Sample
JC-001	Barbers Lake	1066 ⁴	2.373	4.28	0.51319	0.3216	0.51094	0.00002	-6.39		JC-001	108.64	101.2	JC-001
JC-003	Barbers Lake	1066 ⁴	17.305	76.60	0.51243	0.1358	0.51148	0.00001	4.27	1333	JC-003	224.06	28.0	JC-003
BL-14A ³	Barbers Lake	1066 ³	7.054	25.86	0.51252	0.1687	0.51134	0.00002	1.51	1997	BL-14A ³	222.23	37.2	BL-14A ³
BL-48 ³	Barbers Lake	1066 ³	3.868	14.68	0.51247	0.1571	0.51137	0.00002	2.12	1725	BL-48 ³	262.91	79.9	BL-48 ³
JC-016	McLean	1070 ⁵	30.099	144.26	0.51231	0.1173	0.51149	0.00001	4.58	1269	JC-016	138.69	244.8	JC-016
JC-018	McLean	1070 ⁵	23.792	129.30	0.51223	0.1102	0.51145	0.00001	3.84	1302	JC-018	134.28	328.4	JC-018
JC-026	Leggat Lake	1077	8.621	58.06	0.51208	0.0872	0.51146	0.00001	4.13	1249	JC-026	129.58	117.0	JC-026
JC-027	Leggat Lake	1077	22.395	130.60	0.51220	0.1234	0.51133	0.00001	1.52	1540	JC-027	179.97	75.3	JC-027
JC-063	Leggat Lake	1077	11.458	69.08	0.51217	0.1013	0.51145	0.00001	4.02	1278	JC-063	144.16	288.5	JC-063
JC-014	Wolfe Lake	1075.9	13.247	81.33	0.51214	0.1123	0.51135	0.00001	1.88	1461	JC-014	81.59	325.7	JC-014
JC-050	Wolfe Lake	1075.9	12.572	77.26	0.51218	0.1077	0.51143	0.00001	3.41	1333	JC-050	87.10	355.5	JC-050
JC-067	Rideau Lake	1072.4	41.172	234.48	0.51218	0.1066	0.51143	0.00001	3.47	1323	JC-067	106.95	18.3	JC-067
JC-070	Rideau Lake	1072.4	15.029	89.52	0.51215	0.1030	0.51143	0.00001	3.43	1318	JC-070	98.98	698.2	JC-070
JC-043	Foley Mountain	1076± ⁶	29.165	170.38	0.51216	0.0925	0.51150	0.00001	5.07	1196	JC-043	105.06	122.6	JC-043
JC-045	Foley Mountain	1076± ⁶	15.638	88.68	0.51219	0.1359	0.51123	0.00001	-0.40	1802	JC-045	86.96	954.1	JC-045
JC-031	Skootamatta	1086.3	16.620	102.51	0.51212	0.0919	0.51146	0.00001	4.44	1244	JC-031	98.42	1228.7	JC-031
JC-038	Skootamatta	1086.3	7.985	43.04	0.51222	0.1064	0.51147	0.00001	4.49	1261	JC-038	17.94	>1560 ⁵	JC-038
JC-034	Cranberry Lake	1157.2	10.977	57.60	0.51227	0.1174	0.51137	0.00001	4.50	1339	JC-034	141.31	271.7	JC-034
JC-010	Elphin	1178.4	1.933	12.64	0.51203	0.0882	0.51134	0.00001	4.48	1318	JC-010	53.83	513.3	JC-010
JC-012	Elphin	1178.4	9.073	50.99	0.51214	0.1059	0.51132	0.00001	4.11	1367	JC-012	96.25	>1560 ⁵	JC-012
JC-059	Elphin	1178.4	3.627	22.68	0.51210	0.1351	0.51106	0.00001	-1.11	1946	JC-059	55.06	>1560 ⁵	JC-059

¹Concentrations in ppm (ICP-MS) Detection Limits: Sm-0.012ppm; Nd-0.06ppm; Rb-0.23ppm; Sr-0.6ppm

²Initial concentrations

³Samples from Ford, unpublished data

⁴Sr concentration above ICP-MS detector calibration. Minimum value

⁵Davidson and van Breemen 2000b

⁶Corriveau et al. 1990

*NBS 987 Sr standard composition: ⁸⁷Sr/⁸⁶Sr = 0.710245, 2σ = 0.000021; ⁸⁴Sr/⁸⁶Sr = 0.056489, 2σ = 0.000008

**La Jolla Nd standard composition: ¹⁴³Nd/¹⁴⁴Nd = 0.511824, 2σ = 0.000014; ¹⁴⁵Nd/¹⁴⁴Nd = 0.348413, 2σ = 0.000053; ¹⁴⁸Nd/¹⁴⁴Nd = 0.241594, 2σ = 0.000015

$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	2σ	$^{87}\text{Sr}/^{86}\text{Sr} \pm 2\sigma$
2.995	0.75190	0.00001	0.70623
23.57	1.04144	0.00001	0.68193
17.56	0.87144	0.00001	0.60358
9.643	0.83878	0.00001	0.69170
1.612	0.72721	0.00001	0.70253
1.137	0.72047	0.00001	0.70305
6.734	0.79887	0.00001	0.69510
1.448	0.72387	0.00000	0.70155
0.724	0.71405	0.00003	0.70292
0.774	0.70748	0.00001	0.69557
17.30	0.94233	0.00013	0.67699
0.410	0.70941	0.00001	0.70312
2.501	0.73947	0.00001	0.70097
0.271	0.70748	0.00001	0.70331
0.238	0.70645	0.00002	0.70275
0.030	0.70348	0.00001	0.70301
1.439	0.72577	0.00003	0.70196
0.300	0.70740	0.00002	0.70235
0.085	0.70455	0.00001	0.70311
0.129	0.70441	0.00001	0.70224

Figure 3.1: Representative photomicrographs (cross-polarised on the left, plain-polarised on the right) and corresponding sample photographs for the syenite-monzonite plutons; a) Wolfe Lake biotite-rich quartz syenite: JC-050 Coarse-grained, massive texture displaying micrographic intergrowth between K-feldspar and plagioclase feldspar b) Foley Mountain syenite: JC-078. Coarse-grained, massive texture; c) Rideau Lake biotite-rich quartz monzonite: JC-070. Coarse-grained, massive texture; d) Skootamatta biotite-rich monzonite: JC-031. Coarse-grained, massive texture displaying micrographic intergrowth between K-feldspar and plagioclase feldspar; e) Skootamatta biotite-syenite: JC-038. Coarse-grained, massive texture with very coarse biotite laths. Kf = K-feldspar; Pl = plagioclase feldspar; Qz = Quartz; Bt = biotite; Hbl = hornblende.

Figure 3.2: Whole-rock major element rock-classification diagrams. Symbols shown in the legend are the same for the subsequent figures 3.3, 3.4, and 3.5. The data from the Kensington-Skootamatta suite samples from Corriveau et al. (1990) are also plotted on these diagrams. a) Total alkali-silica rock-classification diagram (Cox et al. 1979). b) K_2O vs. SiO_2 potassium enrichment diagram (Peccerillo and Taylor 1976). c) $Al/(Na+K)$ vs. $Al/(Ca+Na+K)$ aluminum saturation index diagram (Shand 1943). d) Modified Alkali Lime Index diagram (Frost et al. 2001). e) Iron-index diagram (Frost et al. 2001). See section 5.1 and 5.2 of text for interpretation

Figure 3.3: Normalised multi-element plots. a) Primitive mantle normalised multi-element diagram (Sun and McDonough 1989) for syenite-monzonite pluton data. b) Primitive mantle normalised multi-element diagram (Sun and McDonough 1989) for granite-monzogranite pluton data. (c) Primitive mantle normalised multi-element diagram (Sun and McDonough 1989) for Cranberry Lake pluton data. Also plotted are data from the Lyndhurst and Leo Lake intrusions (Grammatikopoulos et al. 2007). d) Primitive mantle normalised multi-element diagram (Sun and McDonough 1989) for Elphin pluton data. Also plotted are data from the Lyndhurst and Leo Lake intrusions (Grammatikopoulos et al. 2007) and data from a monzonite sample from the Lavant intrusion (Corfu and Easton 1997). e) Chondrite normalised REE diagram (Sun and McDonough 1989) for syenite-monzonite pluton data. f) Chondrite normalised REE diagram (Sun and McDonough 1989) for granite-monzogranite pluton data. g) Chondrite normalised REE diagram (Sun and McDonough 1989) for Cranberry Lake pluton data. Also plotted are data from the Lyndhurst and Leo Lake intrusions (Grammatikopoulos et al. 2007). h) Chondrite normalised REE diagram Sun and McDonough (1989) for Elphin pluton data. Also plotted are data from the Lyndhurst and Leo Lake intrusions (Grammatikopoulos et al. 2007) and a data from a monzonite sample from the Lavant intrusion (Corfu and Easton 1997).

Figure 3.4: Trace-element tectonic and melt discrimination plots. a) Ta-Yb tectonic discrimination diagram for granitoids (Pearce et al. 1984). AORG = anomalous ocean-ridge granite; ORG = ocean ridge granite; syn-COLG = syn collisional granite; VAG = volcanic arc granite; WPG = within plate granite. b) FeOt/MgO vs. Zr+Nb+Ce+Y, K₂O+Na₂O/CaO vs. Zr+Nb+Ce+Y, Na₂O+K₂O vs. 10000*Ga/Al tectonic discrimination diagram for A-type granitoids (Whalen et al. 1987); A: A-type granitoid; FG: fractionated felsic granite, OGT: M-, I- and S-type granites. c) Rb/Nd vs. Y/Nb melt discrimination diagrams for A-type granitoids (Eby 1992); A1: mantle differentiates, A2: melts contaminated by partial melting of the continental lithosphere.

Figure 3.5: Epsilon (ϵ_{Nd}) vs. $^{87}\text{Sr}/^{86}\text{Sr}_{\text{initial}}$ for syenite and granite plutons focussing on the cluster of samples from ϵ_{Nd} -1.1-5.0 and $^{87}\text{Sr}/^{86}\text{Sr}_{\text{initial}}$ 0.7010-0.7040. *Table 3.2* shows the complete data-set of results, including outliers.

Figure 3.6: Representative photomicrographs (cross-polarised on the left, plain-polarised on the right) and corresponding sample photographs for the granite-monzogranite plutons; a) Barbers Lake monzogranite: JC-002. Coarse-grained, massive texture displaying micrographic intergrowth between K-feldspar and quartz; b). Elphin biotite-rich granite-syenite: JC-059. Massive, coarse-grained texture displaying micrographic intergrowth between K-feldspar and quartz and sericitic alteration; c) Elphin grained granite-syenite: JC-055 Fine-grained, granular, crystalline K-feldspar, plagioclase and quartz; d) Leggat Lake alkali feldspar granite-monzogranite: JC-026. Coarse-grained, massive texture; e) McLean granite: JC-075. Coarse-grained, massive texture; f) Cranberry Lake foliated granite: JC-034. Coarse-grained, foliated texture. Kf = K-feldspar; Pl = plagioclase feldspar; Qz = quartz; Bt = biotite; Hbl = hornblende.

Chapter 4 – Geochronology

U-Pb zircon geochronology studies were undertaken in order to establish whether the 6 undated plutons; Skootamatta, Wolfe Lake, Rideau Lake, Leggat Lake, Elphin and Cranberry Lake were part of the Kensington-Skootamatta suite.

4.1 Geochronology Methods

One locale from each of the Skootamatta, Wolfe Lake, Rideau Lake, Leggat Lake, Elphin, and Cranberry Lake plutons was selected for sampling for U-Pb zircon geochronology studies. Samples are representative of the rock-type and morphology of each pluton, and are centrally located within the pluton (*figures 1.2 and 1.3*). Sample preparation, chemistry and analyses were carried out at the Isotope Geochemistry and Geochronology Research Centre (IGGRC) at Carleton University. Sample preparation and chemistry was carried out using methods modified after Parrish et al. (1987) and analyses were carried out using a ThermoFinnigan Triton TI Thermal Ionisation Mass Spectrometer. Treatment of analytical errors was carried out using Tripoli (Bowring 2012) and U-Pb Redux (Bowring 2013) programs.

From 5-10 kg of rock, a heavy mineral concentrate was prepared for each sample using standard crushing, grinding, Rogers™ table and heavy liquids techniques (Krogh 1982b). The highest quality, least magnetic zircons were separated from the remaining heavy minerals using a Frantz™ isodynamic separator. In separating out the least magnetic zircons, the probability of obtaining concordant grains; free of inclusions, is increased (Krogh 1982b). The

best quality zircons were reserved for analysis; however, representative but poorer-quality grains from each sample were selected for imaging on Carleton University's Cameca Camebax MBX electron microprobe to determine whether the grains contained any inherited components or overgrowths, and to image primary zircon growth features or alteration zones. Imaging was done primarily using cathodoluminescence (CL). See *figure 4.2* for scanning electron microprobe (SEM) images of zircons from each pluton. Further SEM images are shown in Appendix A – MRD311.

Zircons were hand-picked in ethanol based on their clarity with few fractures or inclusions, and the most euhedral crystal shape. See *figure 4.1* for images of representative zircons from each pluton. The zircon grains were then imaged in order to better assess their quality.

Chemical abrasion or leaching techniques were used to ostensibly eliminate areas of radiation damage and Pb loss from the exterior of the grains as well as from fractures, dislocations, altered zones or inclusions within the grains with the objective of reducing discordance in U-Pb results. The selected grains were annealed (for 48 hours in 1000°C) and chemically abraded (leached using HF and HNO₃ using methods modified after Mattinson (2005)). Selected grains were abraded for varying lengths of time depending on their crystal quality and in order to test the optimal time to achieve concordant data. Zircon morphology descriptions and chemical abrasion times are summarised in *table 4.1*. See appendix A –MRD311 for dissolution chemistry and column chemistry details.

Two fractions of zircon that had been physically abraded were analysed to compare the newer chemical leaching methods vs. the traditional air abrasion methods. Physical abrasion of zircon grains is done using compressed air and pyrite and is used to eliminate the outer areas of the zircon grains that are more susceptible to Pb-loss (Krogh 1982a).

4.2 Age interpretations

Data reduction, calculation of statistics and error propagation was done using the programs Tripoli (Bowring 2012) and U-Pb Redux (Bowring 2013). Data are considered to be concordant when the $^{238}\text{U}/^{206}\text{Pb}$, $^{235}\text{U}/^{207}\text{Pb}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ages are $\leq 0.3\%$ discordant. Errors on the ages are reported at the 2σ level. Concordant fractions are taken to represent the age of the rock. In cases where there is systematic Pb loss, then the weighted mean of the $^{207}\text{Pb}/^{206}\text{Pb}$ ages and/or the upper intercept of three or more fractions that fall on a line of discordia may be taken to represent the age of the rock. During this project, the U-Pb geochronology lab was being brought back into production after a long period of abeyance with attendant problems in reducing blanks and refining chemistry procedures. In addition, chemical abrasion techniques were implemented for the first time. There were some analytical problems, thus not all of the analysed fractions were used in the interpretations of the pluton ages. A procedural blank was analysed with each batch of zircon fraction. The blank composition has been calculated to be $^{206}\text{Pb}/^{204}\text{Pb} = 18.350 \pm 0.275$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.6 \pm 0.1$, $^{208}\text{Pb}/^{204}\text{Pb} = 38.08 \pm 0.38$. Fractions were excluded due to procedural errors or high blanks resulting in poor mass spectrometry data or

excessively large errors. Fractions that are displayed on the concordia plots in *figure 4.3* are shown in *table 4.1*, whereas rejected fractions are shown in *table 4.2*. The mass-spectrometry fractionation model that was used is: $\alpha_U = 0.03$ with a 1σ abs of 0.02, and $\alpha_{Pb} = 0.170$ with a 1σ of 0.03. Initial Pb was calculated using a Stacey-Kramers model (Stacey and Kramer 1975).

4.3 Results

4.3.1 Skootamatta pluton – 92RME-0402

Sample 92RME-0402 was collected by Drs. Michael Easton and Sharon Carr in 1992. The sample was taken from the same outcrop as JC-031; along Hughes Landing Rd, 4.6 km West of Cloyne, Ontario (NAD83 321802 E, 4965569 N: *figure 1.2a*). The sample is a coarse-grained, massive, biotite-rich monzonite consisting mainly of K-feldspar, plagioclase (and perthite), minor quartz, biotite and minor hornblende.

The sample yielded a large population of excellent quality, clear, colourless to pink, prismatic, euhedral and well-faceted grains with few to a moderate amount of fractures and inclusions (*figure 4.1a*). SEM imaging of the grains, show homogenous zircons or oscillatory zoning typical of magmatic zircons (*figure 4.2a*: Corfu et al. 2003). Some grains exhibit textures in the core that may be evidence of inheritance or irregular textures that may reflect overgrowths, metamict or altered zones.

Due to the abundant excellent quality zircon grains from this sample, and the fact that it was previously dated by Carr and Easton (1995 unpublished data),

this sample was used to test analytical methods during the reestablishment of U-Pb geochronology at the IGGRC at Carleton University. Many fractions were analysed to determine optimal laboratory and analytical procedures. In total, 16 fractions were analysed; 7 single grain fractions, and 7 multi-grain fractions that were chemically abraded for varying lengths of time, and two fractions that were physically air abraded for 5.5 hours. The fractions were chemically abraded for varying lengths of time to determine the optimal time required to reduce discordance in the results markedly. The Skootamatta grains survived up to 54 hours with no apparent degradation in the coherence of the grain. Two physically abraded fractions were used to compare the older conventional methods to the newer chemical abrasion methods. See *tables 4.1* and *4.2* for descriptions and analytical data for each fraction.

Five of the fractions yielded high quality data that are used to interpret the age of the rock (*table 4.1*). Analysis of multi-grain fraction I1 yielded data that is 0.28% discordant. This fraction is, therefore, interpreted to be concordant. The age of fraction I1 is calculated to be 1086.3 ± 0.6 Ma by taking the weighted mean of its $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{238}\text{U}$ ages (*figure 4.3a*). This is considered the best estimate for the age of crystallization. The age obtained in this study is within error of the 1083 ± 3 Ma age obtained by Carr and Easton (1995 *unpublished data*). Fraction I1 has a U concentration of 85 ppm and a Th/U ratio of 0.58.

Analysis of fractions B3, C1, E1, and G2 yielded data that are between 0.4-1.9% discordant and are interpreted to have undergone Pb loss. A regression

of the data from these 4 fractions and concordant fraction I1 yields an upper intercept of $1088.0 \pm 2.9/-1.5$ Ma with a mean square of the weighted deviates (MSWD) of 1.8. A weighted average of their $^{207}\text{Pb}/^{206}\text{Pb}$ ages is calculated to be 1087.4 ± 1.0 Ma with an MSWD of 1.5 (*table 4.1, figure 4.3a*). These 4 fractions have between 45-117 ppm U, and Th/U of 0.54-0.67.

Fractions I2, J1, and K1 were between -7.1-5.11% discordant. Fraction J1 (5.11% discordant) has a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1125.5 ± 2.4 Ma and is interpreted to have an inherited component of radiogenic Pb that is this age or older, as well as having undergone a component of Pb loss, based on the position of the error ellipse on the concordia diagram (*figure 4.3a*). The cause of the negative discordance in fractions I2 and K1 remains unclear. (See the geochronology summary for possible causes of negative discordance). These fractions have U concentrations of 85-117 ppm and a Th/U ratio of 0.54-0.64.

Fractions I1 and I2 were physically abraded for 5.5 hours and all other fractions that were analysed were chemically leached for 8-54 hours. Fraction I1 yielded the most concordant data for the Skootamatta pluton. Furthermore, analyses of physically abraded zircons from Carr and Easton (1995 *unpublished data*) yielded concordant to nearly concordant analyses. For the Skootamatta pluton, it is apparent that physical abrasion was the most effective method to obtain concordant data. The zircon grains from this pluton are of excellent quality and were able to withstand leaching in hydrofluoric acid (HF) in excess of 40 hours. It is therefore possible, that leaching was having little effect on the grains unless there were fractures or inclusions. Thus, it is recommended that for big,

robust zircons; such as those in the Skootamatta pluton, physical abrasion be used before chemical abrasion.

4.3.2 Wolfe Lake pluton – JC-050

Sample JC-050 was collected in the summer of 2011 from a road-cut outcrop along County Road 36, 2 km northwest of Westport, Ontario (NAD83 386915E, 4950517N: *figure 1.2b*). The sample is a coarse-grained biotite-rich quartz-syenite with a weak mineral foliation. It consists mainly of potassium feldspar with plagioclase (and perthite), quartz, biotite, with minor hornblende and trace apatite, zircon, titanite and pyrite.

The sample yielded a small population of moderate quality, clear, colourless to yellow, prismatic, subhedral and moderately faceted grains with few fractures and a moderate number of inclusions (*figure 4.1b*). The grains exhibit oscillatory zoning typical of magmatic zircons (*figure 4.2b*) or complex, curved zones that are of uncertain origin (Corfu et al. 2003; Hanchar and Miller 1993). There is no evidence of inherited cores; however, the irregular zonation may represent heterogeneities within the zircon such as inclusions. See *table 4.1* for descriptions and analytical data for each fraction.

At the time of writing, only two fractions (A2 and B1) have been analysed; both of them are multi-grain fractions that were chemically leached for 16 and 12 hours, respectively. Analysis of fraction B1 yielded data that is -0.18% discordant. This fraction is, therefore, considered to be concordant. The age of fraction B1 is calculated to be 1075.9 ± 1.4 Ma by taking the weighted mean of its

$^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{238}\text{U}$ ages (*figure 4.3b*). This is considered the best estimate for the age of crystallization of the Wolfe Lake pluton. Fraction B1 has a U concentration of 82 ppm and a Th/U ratio of 0.53.

Fraction A2 yielded nearly concordant data (i.e. 0.8% discordant) with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1075.0 ± 10 Ma (*table 4.1, figure 4.3b*) and falls within error of concordant fraction C1. Fraction A2 has a U concentration of 54 ppm, a Th/U ratio of 0.49. The discordance is interpreted to have been caused by minor Pb loss. In order to finalise the age determination, an additional one or two fractions will be analysed.

4.3.3 Rideau Lake pluton – JC-070

Sample JC-070 was collected from a road-cut outcrop along County Road 14, 700 m north-northwest of Narrows Lock (NAD83 397084E, 4951588N): *figure 1.2b*). The sample is a medium-grained, massive, biotite-rich quartz monzonite. It consists mainly of potassium feldspar with plagioclase (and perthite), minor quartz, biotite and hornblende and trace apatite, zircon, garnet, pyrite, and chalcopyrite.

The sample yielded a small population of moderate to good quality, clear, colourless, prismatic, subhedral, moderately- to well-faceted grains with few fractures or inclusions (*figure 4.1c*). The grains either exhibit oscillatory or banded zoning; both of which are typical of rapid growth in magmatic zircons (*figure 4.2c*: Corfu et al. 2003), however, there is also evidence in some grains of

possible metamictization or overgrowths. There is no evidence of inherited cores. See *table 4.1* for descriptions and analytical data for each fraction.

At the time of writing, 3 fractions have been analysed; 2 single grain fractions (C1, D1) that were chemically leached for 12 hours and 1 multi-grain fraction (B1) that was chemically leached for 16 hours. Single-grain fraction C1 yielded data that is -0.15% discordant. The fraction is, therefore, considered to be concordant. The age of fraction C1 is calculated to be 1072.4 ± 1.0 Ma by taking the weighted mean of its $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{238}\text{U}$ ages (*table 4.1, figure 4.3c*). This is considered the best estimate for the age of crystallization of the Rideau Lake pluton. Fraction C1 has a U concentration of 75 ppm and a Th/U ratio of 0.63.

Multigrain fractions B1 and D1 were 1.29 and 2.03% discordant and have $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1090.9 ± 3.4 Ma and 1084.9 ± 2.2 Ma, respectively. These fractions are interpreted to have an inherited component of radiogenic Pb that is this age or older, as well as having undergone Pb-loss. These fractions have U concentrations of 143-344 ppm and Th/U ratios of 0.46-0.54. In order to finalise the age determination, two additional fractions will be analysed with the goal of obtaining concordant analysis.

4.3.4 Leggat Lake pluton – JC-063

Sample JC-063 was collected in the summer of 2011 from a road-cut outcrop along Leggat Lake Rd, 3 km east-northeast of Long Lake, Ontario (NAD83 363103E, 4951414N: *figure 1.3c*). The sample is a medium-grained,

massive, alkali feldspar granite to leucogranite with a granular to sugary texture. It consists of potassium feldspar, plagioclase (and perthite), and quartz with minor biotite, and trace amounts of zircon, apatite, garnet, chalcopyrite, pyrite, and magnetite.

The sample yielded a small population of poor to moderate quality, clear to cloudy, colourless to yellow-orange, prismatic, subhedral to euhedral, moderately- to well-faceted grains with few inclusions or fractures (*figure 4.1e*). The grains exhibit either a homogeneous texture or oscillatory zoning typical of magmatic zircons (*figure 4.2e*; Corfu et al. 2003). There is no evidence of inherited cores; however, some grains may show evidence of overgrowths. See *table 4.1* for descriptions and analytical data for each fraction.

In total 4 fractions were analysed; 1 single grain fraction (C2), and 3 multi-grain fractions (A2, B1, C1) that were chemically leached for 12 to 16 hours. Analysis of 2 fractions (A2, C2) yielded concordant data within error of each other. Fraction C2 yielded data that is 0.06% discordant. The fraction is, therefore, considered to be concordant and had the smallest associated error ellipse. The age of fraction C2 is calculated to be 1077.0 ± 0.7 Ma by taking the weighted mean of its $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{238}\text{U}$ ages. This is considered the best estimate for the crystallization age of the Leggat Lake pluton. Analysis of fraction A2 also yielded concordant data (0.02%); however, it had a greater associated error. The weighted mean of the $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ ages of fraction A2 is calculated to be 1073.7 ± 7.3 Ma. This is within error of the age calculated using

the data from fraction C2. The U concentrations of fractions A2 and C2 are 340.96-445.4 ppm and the Th/U ratios are 0.40-0.57.

Fraction C1 is 5.65% discordant and is interpreted to have undergone Pb-loss. The $^{207}\text{Pb}/^{206}\text{Pb}$ age of fraction C1 is 1084.1 ± 1.9 Ma. A regression of the data from fractions A2, C1, and C2 yields an upper intercept of $1077.1 + 1.5/-1.4$ Ma with an MSWD of 0.85. A weighted average of the $^{207}\text{Pb}/^{206}\text{Pb}$ ages from these fractions is calculated to be 1079.8 ± 1.1 Ma with an MSWD of 17 (*table 4.1, Figure 4.3d*). Fraction C1 has a U concentration of 217 ppm and a Th/U ratio of 0.59. Fraction B1 was negatively discordant and has a U concentration of 186 ppm and a Th/U ratio of 0.50. The cause of the negative discordance is uncertain at the present time (See the geochronology summary for possible causes of negative discordance). No further analysis of this pluton is required.

4.3.5 Elphin pluton – JC-059

Sample JC-059 was collected in the summer of 2012 from a road-cut outcrop along Concession Road 4, 1.4 km east-southeast of Elphin, Ontario (NAD83 371169E, 4975085N: *figure 1.3b*). The sample is a coarse-grained, massive biotite-rich quartz syenite. It consists mainly of potassium feldspar with quartz and biotite, minor plagioclase and pyrite and trace apatite, zircon, chalcopyrite, and magnetite.

The sample yielded a small population of moderate quality, clear, colourless to yellow, prismatic, subhedral, moderately faceted grains with few inclusions and few to a moderate number of fractures (*figure 4.1d*). The grains

exhibit either complex, curved zones that are of unknown origin, or oscillatory zoning typical of magmatic zircons (*figure 4.2d*: Corfu et al. 2003; Hanchar and Miller 1993). There is no evidence of inherited cores; however, the unexplained zircon zoning may be a source of inheritance. See *table 4.1* for descriptions and analytical data for each fraction.

In total 6 fractions were analysed; 4 single grain fractions (B1, B2, B3, B4), 1 multi-grain fraction (A1), that was chemically leached for 16 hours and 1 multi-grain fraction (C1) that was leached for 12 hours. Fractions B1, B3, B4 and C1 ranged from 0.39-5.35% discordant. A regression of the data yielded a discordia line with an upper intercept of 1178.4 $\pm$ 2.5/-2.3 Ma and an MSWD of 20. A weighted average of $^{206}\text{Pb}/^{207}\text{Pb}$ ages is calculated to be 1168.33 $\pm$ 0.85 with an MSWD of 51 (*table 4.1*, *figure 4.3e*). The upper intercept age is taken as the best estimate for the crystallization age of the Elphin pluton. Fractions B1, B3 and B4 had U concentrations of 75-260 and Th/U ratios of 0.34-0.89.

Fractions A1 and B2 were between 6.78% and 11.01% discordant and have $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1227.3 $\pm$ 5.7 Ma and 1218.3 $\pm$ 5.7 Ma, respectively. These fractions are interpreted to have an inherited component of radiogenic Pb that is this age or older, as well as having undergone Pb-loss. The U concentration of these fractions is 103-245 ppm and their Th/U ratio is 0.95-1.04. Analysis of additional one or two fractions is required to constrain the age of this pluton with greater confidence.

4.3.6 Cranberry Lake pluton – JC-066

Sample JC-066 was collected in the summer of 2011 from a road-cut outcrop along Mountain Rd, 4.3 km northeast of Bellrock, Ontario (NAD83 346651E, 4934172N: *figure 1.3a*). The sample is a medium-grained, massive biotite-rich granite with a weak to moderate mineral foliation. It consists mainly of potassium feldspar, plagioclase, and quartz, with minor biotite and hornblende and trace zircon and apatite.

The sample yielded a moderate population of good quality clear, colourless, prismatic, euhedral, moderately- to well-faceted grains with few fractures or inclusions (*figure 4.1f*). The grains exhibit oscillatory zoning typical of magmatic zircons (*figure 4.2f*; Corfu et al. 2003). There is no evidence of inherited cores; however, some grains may have evidence of overgrowths that could cause inheritance. See *table 4.1* for descriptions and analytical data for each fraction.

In total 4 fractions were analysed; 1 single-grain fraction (D1) and 3 multi-grain fractions (A2, B1, C1) that were chemically leached for 12-22.5 hours. Analysis of multi-grain fraction A2 yielded data that was 0.10% discordant. Fraction A2 is, therefore, concordant. The age of fraction A2 is calculated to be 1157.2 ± 1.4 Ma by taking the weighted mean of its $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{238}\text{U}$ ages. This is considered as the best estimate for the crystallization age of the Cranberry Lake pluton. The U concentration of fraction A2 is 218 ppm and the Th/U ratio is 0.38.

Analysis of fraction D1 yielded data that was 5.05% discordant (*Table 4.1, Figure 4.3f*) and has a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1176.8 ± 2.0 Ma. The discordance is interpreted to have been caused by Pb-loss. This is not within error; by 16 million years, of the age calculated for concordant fraction A2. The U concentration of fraction D1 is 113 ppm and the Th/U is 0.98. Fractions B1 and C1 were negatively discordant. The cause of the negative discordance remains unclear. (See the geochronology summary for possible causes of negative discordance). Additional one or two fractions will be analysed to further constrain the age with greater confidence.

4.4 Summary of Geochronology Results

The dated samples are representative of the plutons and the zircons are indeed igneous; therefore, the ages are taken to represent the crystallization ages of the respective plutons. Their crystallization ages are summarized in *table 4.3*.

There appears to be no relationship between the U concentration, or the Th/U ratios of the fractions and their degree of discordance. The cause of the negative discordance observed in some of the analyses is unclear, however, some of the reported causes may include

- ^{230}Th disequilibria: decays to ^{206}Pb , thus causing excess ^{206}Pb in the analysis (Schoene and Bowring 2006).
- Excess ^{230}Th may be from Th incorporated in the zircon structure or into inclusions (Schoene and Bowring 2006).

- Excess ^{207}Pb may arise from the decay of ^{231}Pa , however, this is rare (Schoene and Bowring 2006 and references therein).
- Calibration of U/Pb ratios (as stated by van Breemen et al. 2005)

The Skootamatta, Wolfe Lake, Rideau Lake and Leggat Lake plutons have crystallization ages consistent with the age range of the Kensington-Skootamatta suite, whereas the Elphin and Cranberry Lake plutons have crystallization ages that are notably older than the Kensington-Skootamatta suite, but which are consistent with the age range of the Frontenac intrusive suite.

Table 4.1: U-Pb zircon ID-TIMS analytical data for the plutons of interest in this study

Fraction ¹	Description ²	Wt. (µg)	U (ppm)	Th/U	*Pb (pg)	³ 206Pb/2 04Pb	⁴ Pbc (pg)	Isotopic Ratios ⁶							
								⁵ 208Pb/ 206Pb	207Pb/ 235U	±2SE %	206Pb/ 238U	±2SE %	207Pb/ 206Pb	±2SE %	
92RME-0402: Skootamatta															
B3 (Z; 1)	Co, Clr, Eu, Tp, rFr, rIn, m2°, CA 16h	38.0	64.0	0.54	495	1439	20.03	0.165	1.8975	0.25	0.18216	0.08	0.07558	0.2	
C1 (Z; 1)	Co, Clr, Eu, Tp, rFr, rIn, m2°, CA 21h	20.5	58.2	0.67	234	1738	7.76	0.204	1.8956	0.25	0.18167	0.12	0.07571	0.2	
E1 (Z; 2)	Co, Clr, Sh-Eu, Tp, rFr, rIn, m2°, CA 12h	25.0	45.3	0.63	268	1271	12.11	0.191	1.8841	0.25	0.18045	0.09	0.07576	0.2	
G2 (Z; 4)	Co, Clr, Eu, Pr, rFr, rIn, m2°, CA 40h	45.0	89.9	0.67	906	2582	20.19	0.202	1.9068	0.2	0.18269	0.16	0.07573	0.08	
I1 (Z; 2)	Co, Clr, Eu, Pr, rFr, rIn, m2°, PA 5.5h	95.0	85.9	0.58	1700	12381	8.04	0.177	0.9147	0.18	0.18335	0.14	0.07578	0.067	
I2 (Z; 3)	Co, Clr, Eu, Pr, rFr, rIn, m2°, PA 5.5h	77.0	84.7	0.54	1340	2670	29.13	0.164	0.9127	0.2	0.18565	0.14	0.07476	0.11	
J1 (Z; 4)	Co, Clr, Eu, Pr, rFr, rIn, m2°, CA 38.5h	53.1	117.4	0.64	1160	2810	23.80	0.192	1.9172	0.21	0.18019	0.14	0.07720	0.12	
K1 (Z; 5)	Co, Clr, Eu, Pr, sFr, rIn, m2°, CA 22.5h	80.6	114.1	0.62	1860	4430	24.41	0.188	1.9174	0.19	0.18818	0.14	0.07323	0.086	
JC-050: Wolfe Lake															
A2 (Z; 2)	Co, Clr, Sh, Pr, rFr, rIn, CA 16h	23..6	53.8	0.49	204	630	19.95	0.148	1.866	0.54	0.17988	0.17	0.07527	0.51	
B1 (Z; 2)	Co, Clr, Eu, Pr and Tp, rFr, rIn, CA 12h	20.0	82.3	0.53	318	1229	15.31	0.16	1.885	0.27	0.18171	0.15	0.07526	0.2	
JC-070: Rideau Lake															
B1 (Z; 2)	Co, Clr, Eu, Pr&Tp, rFr, rIn, CA 16h	34.3	142.6	0.54	823	2358	20.81	0.164	1.8856	0.23	0.18032	0.16	0.07588	0.16	
C1 (Z; 1)	Co, Clr, Eu, Pr, rFr, rIn, CA 12h	23.4	74.7	0.63	295	4207	4.08	0.189	1.8756	0.21	0.18111	0.16	0.07514	0.12	
D1 (Z; 1)	Co, Clr, Eu, Tp, rFr, rIn, CA 12h	17.6	344.0	0.46	649	2235	17.29	0.138	1.8817	0.21	0.18056	0.14	0.07562	0.096	
JC-063: Leggat Lake															
A2 (Z; 2)	Co, Clr (black after abr), Eu, Pr, rFr, rIn, CA 16h	8.9	445.4	0.40	831	6762	7.55	0.122	1.879	0.65	0.18121	0.36	0.07523	0.41	
B1 (Z; 2)	Co, Clr, Eu, Pr, sFr, sIn, CA 16h	11.5	185.5	0.50	361	1093	20.12	0.152	1.863	0.36	0.18460	0.15	0.07323	0.31	
C1 (Z; 2)	Co, Clr, Eu, Pr, sFr, sIn, CA 12h	10.2	216.7	0.59	402	5586	4.22	0.178	1.7922	0.19	0.17196	0.14	0.07562	0.088	
C2 (Z; 1)	Co, Clr, Eu, Pr, sFr, CA 12h	14.3	341.0	0.57	666	2531	15.08	0.173	1.8881	0.21	0.18178	0.15	0.07536	0.066	

Fraction ¹	Description ²	Wt. (µg)	U (ppm)	Th/U	*Pb (pg)	3 206Pb/2 4 04Pb	Pbc (pg)	Isotopic Ratios ⁶							
								206Pb/ 207Pb/	±2SE	206Pb/ 238U	±2SE	207Pb/ 206Pb	±2SE	207Pb/ 206Pb	±2SE
								206Pb	%	235U	%	206Pb	%	206Pb	%
JC-059: Elphinstone															
A1 (Z; 2)	Co, Clr, Eu, Pr&Tp, rFr, rIn, CA 16h	9.5	245.1	1.04	572	3452	8.75	0.314	2.1756	0.21	0.19422	0.15	0.08128	0.11	
B1 (Z; 1)	Co, Clr, Eu, Tp, rFr, rIn, CA 16h	22.2	260.4	0.82	1190	2843	23.13	0.246	2.1827	0.22	0.19955	0.16	0.07937	0.12	
B2 (Z; 1)	Co, Clr, Eu, Pr, rFr, rIn, CA 16h	18.7	106.1	0.93	455	856	28.82	0.28	2.0421	0.34	0.18314	0.15	0.08091	0.29	
B3 (Z; 1)	Co, Clr, Sh, Tp, rFr, rIn, CA 16h	15.3	86.1	0.34	327	2398	8.38	0.103	2.0262	0.18	0.18664	0.14	0.07877	0.038	
B4 (Z; 1)	Co, Clr, Sh, Tp, rFr, rIn, CA 16h	8.6	75.3	0.89	165	1791	5.06	0.268	2.0597	0.25	0.18877	0.14	0.07917	0.19	
C1 (Z; 2)	Co, Clr, Eu, Pr, sFr, rIn, CA 12h	20.0	191.4	0.75	426	1529	15.53	0.225	2.1575	0.23	0.19824	0.15	0.07897	0.15	
JC-066: Cranberry Lake															
A2 (Z; 2)	Co, Clr, Eu, Pr, rFr, rIn, CA 16h	11.0	217.8	0.38	439	1627	16.80	0.113	2.1257	0.26	0.19655	0.14	0.07847	0.2	
B1 (Z; 4)	Co, Clr, Eu, Pr&Tp, rFr, rIn, CA 22.5h	31.1	156.0	0.30	926	2498	23.40	0.091	2.1194	0.23	0.19684	0.16	0.07812	0.14	
C1 (Z; 2)	Co, Clr, Eu, Pr&Tp, rFr, rIn, CA 16h	20.9	141.5	0.31	564	1630	21.90	0.093	2.098	0.26	0.19784	0.15	0.07695	0.2	
D1 (Z; 1)	Co, Clr, Eu, Tp, rFr, rIn, CA 12h	14.3	113.0	0.98	253	4271	3.17	0.297	2.0663	0.19	0.18926	0.14	0.07922	0.098	

Notes:

¹Z=zircon. Number in brackets refers to the number of grains in the analysis

²Fraction descriptions: Co=Colourless, Clr=Clear, Eu=Euhedral, Sh=Subhedral, Pr=Prismatic, Tp=Tip, rFr=Rare Fractures, sFr=Some Fractures, rIn=Rare Inclusions,

sln=Some Inclusions, Nm0°=Non-magnetic@1.8A 0°SS, Pa=Physically Abraded, Ca=Chemically, Abraded, L=Leaching

³Radiogenic Pb

⁴Measured ratio, corrected for spike and fractionation

⁵Total common Pb in analysis corrected for spike and fractionation

⁶Corrected for blank Pb and U and common Pb, errors quoted are 1 sigma absolute; procedural blank values for this study ranged from ... for U and ... for Pb based on the analysis of procedural blanks; corrections for common Pb were made using Stacey-Kramers compositions;

⁷Correlation Coefficient

⁸Corrected for blank and common Pb, errors quoted are 2 sigma in Ma

		Ages (Ma) ^g					
Fraction	²⁰⁶ Pb/ ²³⁸ U	±2SE	²⁰⁷ Pb/ ²³⁸ U	±2SE	²⁰⁷ Pb/ ²⁰⁶ Pb	±2SE	Corr. ^h %
							Coef. Disc
92RME-0402: Skootamatta							
B3 (Z; 1)	1077.8	0.82	1080.2	1.6	1083.1	4.0	0.692 0.40
C1 (Z; 1)	1076.1	1.2	1079.6	1.7	1086.5	4.1	0.572 0.96
E1 (Z; 2)	1069.5	0.90	1075.5	1.6	1087.8	4.0	0.665 1.69
G2 (Z; 4)	1081.7	1.6	1083.5	1.3	1087.1	1.7	0.91 0.50
I1 (Z; 2)	1085.2	1.4	1086.2	1.2	1088.2	1.5	0.92 0.28
I2 (Z; 3)	1097.8	1.4	1085.5	1.3	1061.0	2.3	0.841 -3.46
J1 (Z; 4)	1068.0	1.4	1087.1	1.4	1125.5	2.4	0.824 5.11
K1 (Z; 5)	1111.5	1.4	1087.2	1.3	1038.7	1.9	0.886 -7.01
JC-050: Wolfe Lake							
A2 (Z; 2)	1066.3	1.7	1069.1	3.6	1075.0	10.0	0.332 0.79
B1 (Z; 2)	1076.3	1.5	1075.7	1.8	1074.4	4.1	0.672 -0.18
JC-070: Rideau Lake							
B1 (Z; 2)	1068.7	1.6	1076.0	1.5	1090.9	3.4	0.671 2.03
C1 (Z; 1)	1073.0	1.6	1072.5	1.4	1071.4	2.4	0.83 -0.15
D1 (Z; 1)	1070.0	1.4	1074.7	1.4	1084.1	2.0	0.902 1.29
JC-063: Leggat Lake							
A2 (Z; 2)	1073.6	3.5	1073.6	4.3	1073.8	8.2	0.824 0.02
B1 (Z; 2)	1092.1	1.5	1068.0	2.3	1019.3	6.4	0.459 -7.13
C1 (Z; 2)	1022.9	1.3	1042.6	1.2	1084.1	1.9	0.875 5.65
C2 (Z; 1)	1076.7	1.5	1076.9	1.4	1077.3	1.5	0.957 0.06

Ages (Ma) ⁸									
	206Pb/ 238U	±2SE	207Pb/ 238U	±2SE	207Pb/ 206Pb	±2SE	Corr. Coeff.	% Disc	
JC-059: Elphin									
A1 (Z; 2)	1144.2	1.5	1173.3	1.4	1227.3	2.3	0.824	6.78	
B1 (Z; 1)	1172.9	1.8	1175.5	1.6	1180.4	2.4	0.849	0.64	
B2 (Z; 1)	1084.1	1.5	1129.6	2.3	1218.3	5.7	0.549	11.01	
B3 (Z; 1)	1103.2	1.4	1124.4	1.3	1165.5	1.0	0.989	5.35	
B4 (Z; 1)	1114.7	1.5	1135.5	1.7	1175.5	3.7	0.664	5.17	
C1 (Z; 2)	1165.9	1.6	1167.5	1.6	1170.4	3.1	0.764	0.39	
JC-066: Cranberry Lake									
A2 (Z; 2)	1156.8	1.5	1157.2	1.8	1157.9	4.1	0.626	0.10	
B1 (Z; 4)	1158.3	1.6	1155.1	1.6	1149.1	2.9	0.772	-0.80	
C1 (Z; 2)	1163.7	1.6	1148.2	1.8	1118.9	4.0	0.644	-4.00	
D1 (Z; 1)	117.4	1.4	1137.7	1.3	1176.8	1.3	0.854	5.05	

Table 4.2: Rejected U-Pb ID-TIMS analytical data for the Skootamatta pluton

Fraction ¹	Description ²	Wt. (μ g)	U (ppm)	Th/U	*Pb ³ (pg)	206Pb/ 204Pb	Pbc ⁵ (pg)	Isotopic Ratios ⁶						
								06Pb	208Pb/2 35U	207Pb/2 % $\pm$ 2SE	206Pb/ 238U % $\pm$ 2SE	207Pb/ 206Pb % $\pm$ 2SE		
92RME-0402: Skootamatta														
A1 (Z: 1)	Co, Clr, Eu, Pr, rFr, rln, m2°, CA 26h	11.9	103.4	0.80	219	70	220.0	0.242	1.98	7.3	0.1867	2	0.07690	6.7
B1 (Z: 1)	Co, Clr, Sh, Tp, rFr, rln, m2°, CA 32h	42.8	24.3	0.66	197	150	82.0	0.199	1.923	2.4	0.18424	0.51	0.07570	2.3
B2 (Z: 1)	Co, Clr, Eu, Pr, sFr, rln, m2°, CA 56h													
F4 (Z: 1)	Co, Clr, Eu, Pr, rFr, rln, m2°, CA 21 h?	26.7	37.4	0.71	228	741	17.3	0.216	1.8993	0.4	0.18238	0.098	0.07557	0.35
G1 (Z: 2)	Co, Clr, Eu, Tp, sFr, rln, m2°, CA 40h	51.4												
H1 (Z: 3)	Co, Clr, Eu, Pr, rFr, rln, m2°, CA 8h	36.2	74.1	0.67	600	1365	25.1	0.201	1.9185	0.27	0.18334	0.16	0.07593	0.19
H10 (Z: 1)	Co, Clr, Sh, Tp, rFr, rln, m2°, CA 12h	33.1	81.2	0.61	483	1179	24.0	0.183	1.9144	0.29	0.18309	0.15	0.07587	0.23
K2 (Z: 3)	Co, Clr, Eu, Pr, sFr, rln, m2°, CA 22.5h	91.3	64.6	0.67	1170	750	87.8	0.201	1.921	0.59	0.18348	0.31	0.07598	0.47

Notes:

¹Z=zircon. Number in brackets refers to the number of grains in the analysis

²Fraction descriptions: Co=Colourless, Clr=Clear, Eu=Euhedral, Sh=Subhedral, Pr=Prismatic, Tp=Tip, rFr=Rare Fractures, sFr=Some Fractures, rln=Rare Inclusions,

sln=Some Inclusions, Nm0°=Non-magnetic@1.8A 0°SS, Pa=Physically Abraded, Ca=Chemically, Abraded, L=Leaching

³Radiogenic Pb

⁴Measured ratio, corrected for spike and fractionation

⁵Total common Pb in analysis corrected for spike and fractionation

⁶Corrected for blank Pb and U and common Pb, errors quoted are 1 sigma absolute; procedural blank values for this study ranged from ... for U and ... for Pb

based on the analysis of procedural blankis; corrections for common Pb were made using Stacey-Kramers compositions;

⁷Correlation Coefficient

⁸Corrected for blank and common Pb, errors quoted are 2 sigma in Ma

Fraction	Ages (Ma) ^g						Reason	
	Disc							
	206Pb/ 238U	±2SE	207Pb/2 38U	±2S E	207Pb/ 206Pb	±2SE Coef.		
A1 (Z: 1)	1103.0	20.0	1108.0	49.0	1117.0	130.0	0.397	1.18 Poor MS runs due to separation in loading gel
B1 (Z: 1)	1090.1	5.2	1089.0	16.0	1087.0	45.0	0.395	-0.29 Poor MS runs due to separation in loading gel
B2 (Z: 1)								-1 Poor MS runs due to separation in loading gel (No Pb data)
F4 (Z: 1)	1080.0	1.0	1080.9	2.7	1082.7	7.1	0.555	0.25 Poor MS run: Pb signal loss of 50-80%/block
G1 (Z: 2)								Poor MS runs due to separation in loading gel (insufficient data)
H1 (Z: 3)	1085.2	1.6	1087.5	1.8	1092.2	3.9	0.691	0.65 Poor MS run, large errors
H10 (Z: 1)	1083.8	1.5	1086.1	1.9	1090.7	4.6	0.602	0.63 Poor MS run, large errors
K2 (Z: 3)	1085.9	3.1	1088.5	3.9	1093.6	9.4	0.607	0.7 Drop fell on counter while putting into column

Table 4.3: U-Pb zircon ID-TIMS results summary.

Pluton	Rock Type	Emplacement Age (Ma)
Skootamatta	bt-rich monzonite	1086.3 $\pm$ 0.6
Wolfe Lake	bt-rich qz-syenite	1075.9 $\pm$ 1.4
Rideau Lake	bt-rich qz-monzonite	1072.4 $\pm$ 1.0
Leggat Lake	alkali feldspar granite	1077.0 $\pm$ 0.7
Elphin	bt-rich syenite	1178.4 +2.5/-2.3
Cranberry Lake	bt-rich granite	1157.2 $\pm$ 1.4

Figure 4.1: Representative zircon grains from plutons selected for U-Pb Isotope Dilution – Thermal Ionisation Mass Spectrometry (ID-TIMS) geochronology studies. a) Skootamatta pluton: 92RME-0402; b) Wolfe Lake pluton: JC-050; c) Rideau Lake pluton: JC-070; d) Elphin pluton: JC-059; e) Leggat Lake pluton: JC-063; f) Cranberry Lake pluton: JC-066.

Figure 4.2: Scanning electron microscope images of representative single grains from the plutons of interest in this study. a) Skootamatta pluton: 92RME-0402; b) Wolfe Lake pluton: JC-050; c) Rideau Lake pluton: JC-070; d) Elphin pluton: JC-059; e) Leggat Lake pluton: JC-063; f) Cranberry Lake pluton: JC-066.

Chapter 5 – Discussion

5.1 The Kensington-Skootamatta suite

The crystallization ages of the Skootamatta, Westport area, Barber's Lake, McLean and Leggat Lake plutons (Cutts, Chapter 4.4) are consistent with the previously established age range of ca. 1090-1060 Ma for the Kensington-Skootamatta suite (*table 1.2, 5.1*; Corriveau et al. 1990; Easton 1992). Furthermore, the geochemistry of the syenite-monzonite plutons is consistent with that of the Kensington-Skootamatta suite plutons studied by Corriveau et al. (1990) and shown in *figure 3.2a-d*. It is, therefore, proposed that these seven plutons are all part of the Kensington-Skootamatta suite.

The emplacement ages of the Cranberry Lake and Elphin plutons suggest that they are not part of the Kensington-Skootamatta suite. Rather, the emplacement ages of the Cranberry Lake and Elphin plutons are consistent with the ca. 1175-1150 Ma Frontenac intrusive suite (Corfu and Easton 1997). The following discussion will focus on the Kensington-Skootamatta suite plutons.

5.1.1 Comparison of syenite-monzonite and granite-monzogranite suites

The petrography, geochemistry, and geochronology data in this study distinguish a slightly older ca. 1086-1072 Ma syenite-monzonite and a slightly younger ca. 1077-1066 Ma granite-monzogranite suite within the Kensington-Skootamatta suite. The seven plutons in this study that are part of the Kensington-Skootamatta suite can be separated into two principal groups on the basis of their rock-type, geochemistry and age; as was suggested by Easton (2008). The Skootamatta, Wolfe Lake, Foley Mountain and Rideau Lake plutons are part of an older ca. 1086-1072 Ma syenite-monzonite suite and the Leggat Lake, McLean and Barber's Lake plutons are part of a

ca. 1077-1066 Ma granite-monzogranite suite. These ages are consistent with other Kensington-Skootamatta suite plutons in Ontario (*table 5.1*). The two suites cannot be distinguished on age alone as there is some overlap; the Leggat Lake pluton is slightly older than the other granite-monzogranite plutons and the Rideau Lake pluton is slightly younger than the other syenite-monzonite plutons. Thus the geochemistry is key in the distinction between the two suites.

The granite-monzogranite plutons have higher SiO₂ contents and lower abundances in all other major elements than the syenite-monzonite plutons. Despite these differences in major element abundance (*figure 3.2 a-e; Table 2,*), the two groups have similar geochemical profiles on normalised multi-element plots (*figure 3.3 a, b, e, f*), however the anomalies are more pronounced in the granite-monzogranite group; particularly in the Barber's Lake pluton. Within the Westport area plutons, the Wolfe Lake pluton has a consistent multi-element profile, whereas the Foley Mountain and Rideau Lake plutons show two groups; one more enriched in HREEs and the other with lower HREE abundances resulting in a steeper curve (*figure 3.3a*). As expected, the syenite-monzonite plutons plot similarly on the rock discrimination diagrams in *figure 3.2* to those syenites-monzonites studied by Corriveau et al. (1990). In contrast, the granites plot in a slightly lower K₂O field (*figure 3.2b*), are more aluminum-rich (*figure 3.2c*), less alkaline (*figure 3.2d*), and more uniformly ferroan (*figure 3.2e*). The Barber's Lake data set is unique in that it is consistently peraluminous and alkali-calcic (*figure 3.2c, d*). In general, Skootamatta data plot similarly to those of the Westport area plutons, however, on the extended normalised multi-element plots, they have steeper

profiles (lower HREE; *figure 3.3a,e*) and they plot in the VAG field on the Pearce et al. (1984) tectonic discrimination diagram as opposed to the WPG field (*figure 3.4a*).

The Sm/Nd isotopic data for the two suites are similarly depleted ($\epsilon\text{Nd} \sim -2$ to -4.5 ; *figure 3.5*); however, there are some more 'contaminated' samples within the Foley Mountain pluton (JC-045: $\epsilon\text{Nd} -0.39$) and the Barber's Lake pluton (JC-001: $\epsilon\text{Nd} -6.39$).

5.2 Tectonic classification and melt origin of the Kensington-Skootamatta suite

5.2.1 Tectonic classification

The nature of post-orogenic magmatic suites was investigated by Bonin et al. (1998) who outlined several characteristics for rocks typical of this tectonic environment: (i) they are located in a linear belt parallel to major terrane boundary-related thrust and shear zones in a transtensional regime (ie. *figure 1.1*); (ii) they are felsic, and dominated by syenogranites and alkali feldspar granite rock-types; (iii) zircon morphologies are consistent with alkali-rich magmas (See *figure 4.1*; Pupin 1980); (iv) major and trace element whole-rock chemistry is typical of A-type and within-plate granites (*figure 3.4*: Pearce et al. 1984; Whalen et al. 1987). All of these characteristics are satisfied by the data characterizing the plutons of this study. It should be noted, however, that A-type and/or post-orogenic terminology has historically been used primarily for peralkaline plutonic rocks (cf. Barbarin 1990 and references therein); thus, as the plutons of interest are peraluminous to metaluminous, comparisons with present day proxies are difficult.

The tectonic discrimination diagrams in *figure 3.4* indicate that, in general, the geochemistry of the plutons is consistent with those found in an intraplate, post-orogenic-anorogenic tectonic setting despite their being emplaced during a main constructional period of Himalayan-scale orogenesis. The undeformed and

unmetamorphosed nature of the plutons could be consistent with anorogenic emplacement; however, current Grenville models (Rivers 2012) suggesting that there was limited metamorphism or deformation in the superstructure of the orogen may also explain these features.

The Kensington-Skootamatta plutons all retain a weak subduction signature (minor Nb depletion) and significant Ti depletion, LREE enrichment (*figure 3.3a,b*: Rollinson 1993) and the Skootamatta intrusion plots in the volcanic arc granite fields in *figure 3.4a*. These geochemical characteristics were attributed to an active subduction zone by Corriveau et al. (1990); however, it is believed that active subduction had ceased with the closure of the ocean basin separating Laurentia and the Composite Arc Belt-Frontenac-Adirondack Belt prior to ca. 1090 Ma (Carr et al. 2000). This is evidenced by stitching plutons of the Frontenac intrusive suite, which span both the Frontenac terrane and Sharbot Lake domain, and are dated at ca. 1150-1175 Ma (Carr et al. 2000; Corfu and Easton 1997; McLelland et al. 1996). A possible alternative to the active subduction model is mantle enrichment and metasomatism of the underlying asthenosphere during subduction prior to the Shawinigan orogeny. Epsilon Nd ($\sim +1$ - $+4.5$), initial Sr (~ 0.700 - 0.703), and T_{dm} values (~ 1200 - 1300) from the plutons of this study suggest derivation of the melt(s) from a relatively depleted source with minor involvement from ca. 1500-1200 Ma crust.

5.2.2 Melt origin – Geochemistry

Geochemical discrimination in felsic plutonic rocks is complicated and not always accurate. From formation of the melt to crystallisation, many processes can influence the melt and melt interaction with the surrounding rock. As a result, trace elements,

which are often compatible in accessory phases such as zircon, apatite, allanite and monazite may fractionate or be assimilated from the continental crust, thus skewing the typical classification schemes (Frost and Frost 2013b). However, when used in conjunction with major element discrimination, trace elements can be a powerful tool.

Frost et al. (2001); Frost and Frost (2013a; 2013b) studied granitoids in terms of the varying concentrations of the major oxides, namely iron, aluminum and alkali contents, in conjunction with the trace element geochemistry. Using these elemental concentrations, the granitoids were categorised based on their melt geneses. The Kensington-Skootamatta plutons of this study are magnesian to ferroan, metaluminous to weakly peraluminous and alkalic to alkali-calcic. As their geochemistry is not consistent with each other, the Kensington-Skootamatta suite intrusions do not collectively relate to any one of the categories outlined by Frost and Frost (2013a). The geochemistry of the granite-monzogranite plutons is most consistent with that of calc-alkalic ferroan leucogranites, which are interpreted to have been derived through partial melting of quartzofeldspathic crust (Frost and Frost 2013a). In contrast, the geochemistry of the syenite-monzonite plutons is most consistent with that of ferroan alkaline granitoids, which are interpreted to have been derived through fractionation of alkaline basalt with some partial melting of granitic crust (Frost and Frost 2013b).

Similarly to the Frost et al. (2001); Frost and Frost (2013a; 2013b) classification schemes, there are ambiguities in determining the tectonic setting of the Kensington-Skootamatta plutons using only trace element geochemistry. Using the Eby (1992) A-type discrimination diagram (*figure 3.4c*), the Westport area plutons represent mantle differentiates derived from sources similar to oceanic-island basalts emplaced in

continental rifts. In contrast, according to the Eby (1992) discrimination diagram the Skootamatta and the granite-monzogranite plutons have chemistry consistent with derivation from continental crust or underplated crust that has been incorporated into an orogeny during accretionary events.

U and Th concentrations show a similar trend to the isotopic data (Cutts, Chapter 3). In the syenite-monzonite plutons the concentrations of U and Th are low (1-3 ppm and 3-17 ppm respectively); U and Th are elements that are typically associated with continental crust (Faure and Mensing 2005), and low values are consistent with an interpretation of minimal crustal contamination. This is consistent with data from other syenite-monzonite Kensington-Skootmatta plutons outside the study area that have regional gamma-ray signatures indicating low U and Th (Easton 2008). In contrast, the more elevated levels of U (2-6 ppm) and Th (5 -58 ppm) in the Leggat Lake and McLean plutons, and the still more elevated levels in the Barber's Lake pluton (U 5-90ppm, Th 25- >110 ppm), are consistent with an interpretation involving some contribution to the melt of a partial-melt derived from a granitic source (Faure and Mensing 2005).

Certain trace element ratios can also indicate the degree of crustal involvement in a melt. Mantle derived melts typically have Nb/Ta values of 17.5 ± 2 , whereas, typical continental crust is $\sim 11-12$ (Mohammed and Hassen 2012 and references therein). The Kensington-Skootamatta plutons in this study have Nb/Ta ratios that range from 14-17, with the exception of Barbers Lake (~ 9.4). Th/Ta ratios of ~ 2 are typical of the mantle, whereas the lower crust typically has values of ~ 7.9 and the upper crust 6.9 (Mohammed and Hassen 2012 and references therein). The Westport area plutons

have tightly clustered values of 2.2-2.8. In contrast, the remaining plutons, in contrast, have values ranging from 8.4-24; significantly more enriched than typical crustal values.

Most of the Kensington-Skootamatta plutons have depletions in Sr, P, Ti, and minor Nb anomalies (*figure 3.3a,e*) in conjunction with negative Eu anomalies in the REE profiles (*figure 3.3b,f*). This may have resulted from fractionation of plagioclase, apatite and possibly titanite. Furthermore, the HREEs are relatively enriched, indicating that they were not retained in the source. The Skootamatta pluton, (and parts of Rideau Lake and Foley Mountain plutons), have only slightly negative P, Ti and Nb anomalies, and do not have a Sr anomaly (*figure 3.3a,e*) nor a Eu anomaly in their REE profiles (*figure 3.3e*). This suggests that apatite and titanite may have been minor fractionating phases, but not plagioclase. Furthermore, the Skootamatta intrusion is relatively depleted in HREE compared to the other Kensington-Skootamatta plutons, perhaps indicating a garnet-rich source that retained HREEs (*figure 3.3f*).

The trace-element depletions are more prominent in the granite-monzogranite plutons than the syenite-monzonite plutons. This implies that the quartzofeldspathic crust, from which the granite-monzogranite plutons were derived, was more depleted than the alkaline basalt, from which the syenite-monzonite plutons were derived. Furthermore, as the granite-monzogranite plutons in general have a depleted isotopic signature, this may reflect derivation from a juvenile quartzofeldspathic crust.

5.2.3 Geochemistry and geochronology interpretations summary

Using the petrography, geochemistry and geochronology studies of the Kensington-Skootamatta suite plutons, it is possible to subdivide them into four principal groups.

1. The ca. 1086 Ma Skootamatta syenite is the oldest pluton studied and is the most varied in terms of rock-type and geochemistry. Remnant arc-signatures are more prevalent relative to the other plutons. The pluton was possibly derived from melting of host arc-volcanic and -plutonic rocks in the Grimsthorpe domain.
2. The ca. 1076-1072 Ma Westport area plutons have very similar ages of emplacement; the Wolfe Lake and Foley Mountain plutons have crystallization ages that are within error of each other and Rideau Lake is 1.1 Ma younger. Furthermore, the geochemistry that is consistent with derivation from a depleted alkaline basalt and emplacement in an intra-plate setting with some interaction with the host marbles in the Frontenac terrane, as previously noted by Marcantonio et al. (1990).
3. The ca. 1077 Ma Leggat Lake and ca. 1070 Ma McLean plutons in the Sharbot Lake domain are in close proximity to one another and have similar geochemistry that is consistent with derivation by partial melting of juvenile quartzofeldspathic crust. They have a similarly depleted isotopic character.
4. The ca. 1066 Ma Barber's Lake intrusion is broadly similar to the Leggat Lake and McLean plutons. Key differences are that it is ca. 3-10 Ma younger, and has a geochemical signature consistent with derivation by partial melting of juvenile quartzofeldspathic crust that involved a greater amount of crustal contamination than any of the other plutons of the in this study.

5.3 Tectonic model

At the time of emplacement of the Kensington-Skootamatta suite ca. 1090-1060 Ma, the terrane and domains that hosted the plutons were at varying crustal levels and composed of different rock-types (*table 1.1, figure 2.1; figure 5.1*).

The Skootamatta syenite intruded into the Grimsthorpe domain rocks at ca. 1086 Ma. The country rocks include mafic metavolcanic rocks that had originated in a primitive-arc setting as well as Elzevirian plutonic rocks. At the time of emplacement of the syenite, the Grimsthorpe domain host rocks are interpreted to have been at <12 km depth in the superstructure (*figure 5.1*). The Barber's Lake, Leggat Lake and McLean plutons intruded at ca. 1077-1066 Ma into marbles, mafic and felsic meta-plutonic and metavolcanic rocks of the Sharbot Lake domain at 20-12 km depth (*figure 5.1*). The Westport Area plutons intruded at ca. 1072-1076 Ma into marbles, orthogneisses and gabbro of the Frontenac terrane at 8-10 km depth (*figure 5.1*). The Mazinaw terrane, in contrast, is devoid of Kensington-Skootamatta plutons, is currently located geographically between the Grimsthorpe and Sharbot Lake domains and was at >25 km depth at ca. 1060 Ma.

The Leggat Lake and McLean plutons, Barber's Lake, Skootamatta and Westport area plutons have similar geochemical signatures; however, in detail they can be distinguished on the basis of geochemistry and geochronology. Furthermore they were all emplaced over about 20 million years (ca. 1088-1066 Ma) into different domains and terranes which were at different crustal levels and were composed of varying rock-types. It is therefore proposed that the pluton(s) in each of the subdivisions of the suite highlighted in section 5.2.3, had a distinct melt that was derived from the re-melting of rock within each respective terrane or domain (*figure 5.1*). The Kensington-Skootamatta suite is regionally extensive in the Grenville Province of Ontario and Québec and the emplacement ages are generally consistent. It is therefore possible that this is the case with all of the Kensington-Skootamatta suite plutons.

Given that the age range of the plutons overlaps with the time of orogenesis, it is likely that they all may have resulted from a similar catalyst to cause widespread melting. Crustal delamination may have provided the heat necessary to cause this melting along with insulation of the overthickened crust to cause anatectic melting at mid-crustal levels. The latter is evidenced by ca. 1080-1060 Ma migmatite formation and granulite-facies metamorphism (Timmermann et al. 2002) in the Central Gneiss Belt; which was located in the orogenic infrastructure (*figure 2.1*).

Additionally, the oldest pluton from the Kensington-Skootamatta suite is the same age as stage 4 of the Midcontinent Rift (MCR) magmatic system (ca. 1086 Ma). Although centred in the Lake Superior region; ~1000 km from Composite Arc Belt-Frontenac-Adirondack Belt, the Midcontinent Rift may have heated the crust sufficiently to facilitate the ascent of plutons and facilitate melting (*figure 5.1*). This was similarly suggested by McLelland et al. (2001) for the generation of the 1100-1090 Ma Hawkeye granite suite in the Adirondack Highlands. This would also explain the lack of any time-lag between the waning stages of the MCR magmatism and the beginning of the Kensington-Skootamatta suite magmatism. See *figure 5.1* for a summary diagram for the emplacement of the Kensington-Skootamatta plutons in this study.

5.3.1 Apparent absence of Kensington-Skootamatta plutonism in the Mazinaw terrane?

The question as to why the Mazinaw terrane remains devoid of the Kensington-Skootamatta suite plutons remains unclear. Perhaps the temperature and pressure conditions and the deformational stresses in the infrastructure of the orogeny were unsuitable to the ponding of plutons. This conclusion is evidenced by ca. 1090-1050

deformation and metamorphism in the northernmost segment of the Mazinaw terrane and the ca. 1080 Ma pegmatite intrusion. Alternatively, perhaps the Mazinaw terrane was not geographically proximal to the other constituent terranes and domains of the superstructure ca. 1090-1060 Ma, thus melting was not initiated.

5.4 The Cranberry Lake pluton

The Cranberry Lake pluton has a crystallization age of 1157.2 ± 1.4 Ma. This age is consistent with the emplacement of the Frontenac intrusive suite. Furthermore, the Cranberry Lake pluton has similar geochemistry to the Frontenac intrusive suite plutons (See section 3.2.4). The Cranberry Lake pluton is, therefore, interpreted to be part of the Frontenac intrusive suite.

The trace element geochemistry of the Cranberry Lake granite indicates a mixture of tectonic environments; volcanic arc, within-plate, orogenic, and A-type (*figure 3.4a, b*). Trace element ratios suggest derivation from a mantle melt with contamination from an upper crustal source ($\text{Nb/Ta} = 13.8\text{-}14.1$; $\text{Th/Ta} = 6.75\text{-}9.99$) which is consistent with plotting in the A2 field in the Eby (1992) discrimination scheme (continental crust and/or underplated crust influenced by continental collision). The depletions in Nb, Ti, Sr and P on the extended mantle-normalised multi-element plots and depletion in Eu on the chondrite-normalised REE plot suggest fractionation of plagioclase, apatite and possibly titanite.

5.4.1 Implications for the Robertson Lake Shear Zone

The Robertson Lake shear zone is interpreted as a crustal-scale extensional fault active most recently ca. 1030-940 Ma (Busch et al. 1997; Carr et al. 2000). It has also been suggested that the shear zone may have been active at an earlier time during

crustal shortening. The ca. 1160 Ma Cranberry Lake pluton appears to have been injected or intruded concordantly into the Robertson Lake shear zone. The crystallisation age of the Cranberry Lake pluton may provide insight into a possible earlier period of compressional activity along the Robertson Lake shear zone that has been alluded to in previous studies (Busch et al. 1997).

5.5 The Elphin pluton

The Elphin pluton has a crystallization age of $1178.4 \pm 2.5/-2.3$ Ma, which is consistent with the emplacement of the Frontenac intrusive suite. The Elphin pluton, is therefore, interpreted to be part of the Frontenac intrusive suite.

The Elphin pluton is heterogeneous, ranging from syenite to granite in composition. The major element geochemistry of the Elphin intrusion is consequently varied, ranging from calc-alkalic to shoshonitic, strongly metaluminous to peraluminous, and strongly ferroan to strongly magnesian (*figure 3.2*). Using the Frost and Frost (2013) classification scheme for leucogranites, this corresponds to the chemistry of Cordilleran intrusions that were derived through extreme differentiation of cold, wet, oxidising magma. The trace-element tectonic discrimination diagrams (*figure 3.4*) and primitive mantle-normalised multi-element plots (*figure 3.3d*) similarly indicate that the Elphin pluton has a volcanic arc affinity (strong Nb depletion). The small negative P and Ti anomalies in the mantle-normalised multi-element plots may have resulted from minor fractionation of apatite and titanite. The steep (HREE depleted) chondrite-normalised REE profile (*figure 3.3h*) with no Eu anomaly indicates that the Elphin intrusion could have had a garnet-rich source that withheld the HREEs and likely did not fractionate plagioclase. Trace element ratios give mixed results. Nb/Ta 13.8-14.1 lie

between mantle and continental crust values and Th/Ta 6.75-9.99 are typical of lower to upper crustal values. Isotopic values (ϵNd -1.11 to +4.48) range from slightly contaminated by continental crust to depleted mantle.

The Elphin pluton intruded into the ca. 1224 Ma Lavant gabbro; an arc-affinity intrusive complex cut by monzogranite intrusive bodies (Corfu and Easton 1997). The geochemical character of the Elphin pluton is very similar to that of the Lavant gabbro. It is therefore possible that the Elphin pluton derived some of its geochemical signature from the Lavant gabbro which may also have been a potential source for the ca. 1226 Ma inheritance observed in the geochronology results.

Wu and Kerrich (1986) hypothesised that their major and trace element geochemistry and high ^{18}O data for the Elphin pluton may suggest partial melting from an ^{18}O enriched metadiorite-metagabbro precursor. This precursor was postulated to have been subjected to open-system enrichment with the high ^{18}O carbonate country rock. It has been interpreted herein that the Elphin pluton may have had some degree of interaction with the Lavant gabbro complex. This provides further credence to the conclusions made by Wu and Kerrich (1986).

5.6 Implications for the Frontenac intrusive suite

Frontenac intrusive suite plutons are dominantly found in east-central Sharbot Lake domain and throughout the Frontenac terrane. The Cranberry Lake and Elphin plutons are located along the western margin of the Sharbot Lake domain, and extend Shawinigan magmatism further westward into Sharbot Lake domain.

Lumbers et al. (1990) and Davidson and van Breemen (2000a) noted that the Kensington-Skootamatta and Frontenac intrusive suites have similar rock-type and

geochemistry. This conclusion was based only on the syenite-monzonite plutons. The Elphin and Cranberry Lake plutons were originally thought to be part of the Kensington-Skootamatta suite on the basis of their similar petrography and geochemistry to both the syenite-monzonite and the granite-monzogranite plutons. It is thus shown that the granites also, have similar petrography and geochemistry to the Frontenac intrusive suite.

Table 5.1: U-Pb Crystallization ages for the Kensington-Skootamatta suite plutons in Ontario

Pluton	Rock Type	Emplacement Age (Ma)	Source
Loon Lake	monzonite	1090 ± 2	Corriveau et al. (1990)
Calabogie	syenite	1088 ± 2	Corriveau et al. (1990)
Belmont Lake	granite	1088 +3/-2	Davis and Bartlett (1988)
Skootamatta	bt-rich monzonite	1086.3 ± 0.6	This study
Westport (Foley Mountain)	monzonite	1077 ± 4 or 1076 ± 2	Marcantonio et al. (1988); Corriveau et al. (1990)
Wolfe Lake	bt-rich qz-syenite	1075.9 ± 1.4	This study
Rideau Lake	bt-rich qz-monzonite	1072.4 ± 1.0	This study
Leggat Lake	alkali feldspar granite	1077.0 ± 0.7	This study
McLean	monzogranite	1070 ± 3	Davidson and van Breemen (2000b)
Cavendish Township	monzogranite	1067 ± 4	Easton and Kamo (2011)
Barber's Lake	granite, monzogranite	1066 +7/-4	Davidson and van Breemen (2000b)

Figure 5.1: Schematic summary diagram for the ca. 1086-1067 Ma emplacement of the plutons of this study. Syenite-monzonite plutons are shown in red, whereas the granite-monzogranite plutons are shown in pink. The depth of emplacement refers only to the depth of the host terranes and domains (rectangles) when the plutons were emplaced, not the depth at which the original melts were generated (ovals). The arrows represent the heat sources that have been interpreted to have generated the melts.

Chapter 6 – Conclusions

The plutons of the Kensington-Skootamatta suite are tectonically important in the Grenville Province as they were emplaced ca. 1090-1060 Ma, across multiple lithotectonic terranes and domains, which were at different crustal levels within the orogenic superstructure of a Himalayan-scale orogeny. The Kensington-Skootamatta suite provides the only body of evidence of magmatism in the Composite Arc Belt and Frontenac terrane during this time. When this project was initiated, the nine plutons studied were all thought to have been part of the Kensington-Skootamatta suite (Corriveau et al. 1990; Easton 1992; Easton 2001; Easton 2008). It was further proposed by Easton (2008) that the Kensington-Skootamatta suite was composed of two suites; an early ca. 1080-1070 Ma syenite-monzonite suite and a later ca. 1070-1060 Ma granite-monzogranite suite.

6.1 First order conclusions

1. The Skootamatta, Westport area, Barber's Lake, Elphin, McLean, and Leggat Lake plutons have a roughly round shape and they are not deformed, nor metamorphosed (section 3.2).
2. The Cranberry Lake pluton has an irregular map pattern, and has a strong foliation; however, it appears to be unmetamorphosed.
3. The Skootamatta and Westport area plutons have a syenite-monzonite rock-type, whereas the Barber's Lake, Elphin, McLean, Leggat Lake and Cranberry Lake plutons have a granite-monzogranite rock-type.
4. The syenite-monzonite plutons have lower SiO_2 and higher alkali content, are more alkalic, dominantly metaluminous, and ferroan to magnesian than the granite-

monzogranite plutons. The granite-monzogranite plutons, in contrast, are metaluminous to peraluminous and dominantly ferroan.

5. The granite-monzogranite plutons have more pronounced trace element anomalies than the syenite-monzonite plutons.
6. The Skootamatta and Elphin plutons have steeper multi-element profiles that are more HREE depleted than the other plutons and the Barber's Lake pluton has greater depletions in Ba, and greater enrichments in U, Th, and Pb than the other plutons.
7. The Skootamatta and Elphin pluton dominantly have trace-element signatures consistent with that of volcanic arc granites, whereas the other plutons plot as within-plate/A-type to anomalous ocean ridge granites.
8. Of the syenite-monzonite plutons that were dated in this study, the Skootamatta pluton has a crystallization age of 1086.3 ± 0.6 Ma; the Rideau Lake pluton has a crystallization age of $1072. \pm 1.0$ Ma, and the Wolfe Lake pluton has a crystallization age of 1075.9 ± 1.4 Ma. Of the granite-monzogranite plutons that were dated in this study, the Leggat Lake pluton has a crystallization age of 1077.0 ± 0.7 Ma.
9. The crystallization ages of the Elphin and Cranberry Lake plutons were determined to be $1178.4 +2.5/-2.3$ Ma and 1157.2 ± 1.4 Ma, respectively.

6.2 Second order conclusions

1. On the basis of age, the Skootamatta, Westport Area, Leggat Lake, McLean and Barber's Lake intrusions are part of Kensington-Skootamatta suite.
2. On the basis of geochemistry and age, the Cranberry Lake pluton is part of the Frontenac intrusive suite.

3. On the basis of age, the Elphin pluton is part of the Frontenac intrusive suite and has inherited age and geochemical characteristics from the Lavant gabbro.
4. This study confirms the suggestion of Easton (2008) that the Kensington-Skootamatta suite consists of both syenite-monzonite and granite-monzogranite intrusions that can be distinguished petrographically and geochemically. The Skootamatta, and Westport Area plutons are part of an early 1086-1072 Ma syenite-monzonite suite, and the Leggat Lake, McLean and Barber's Lake plutons are part of a later 1077-1066 Ma granite-monzogranite suite.
5. The geochemistry of the Kensington-Skootamatta plutons do not consistently indicate a particular tectonic setting or melt origin. They range from a volcanic arc to within-plate to A-type tectonic setting, and have depleted isotopic signatures and geochemistry indicative of melts that originated from an alkaline basalt or juvenile quartzofeldspathic crust.
6. The granite-monzogranite plutons show more evidence of involvement from continental crust than the syenite-monzonite plutons.
7. There are differences in the host-terrane and –domains that could account for the differences observed between the plutons: i) The geochemical signature of the Skootamatta pluton was possibly derived from the host volcanic-arc rocks of the Grimsthorpe domain; ii) The granite-monzogranite plutons in the Sharbot Lake domain may have been sourced from juvenile quartzofeldspathic crust and later contaminated by granitic crust; iii) The Westport area plutons may have been sourced from alkaline basalt with later interaction with the host marbles in the Frontenac terrane.

8. Due to their emplacement over 20 million years, at varying crustal levels, across different domains/terrane within the orogenic superstructure, each pluton in the Kensington-Skootamatta suite had a discrete source melt.
9. A possible catalyst to initiate coeval melting for all of the plutons may include crustal delamination, insulation due to crustal overthickening, and the waning Mid-Continent Rift magmatic system. This is consistent with current tectonic models for Grenville orogenesis.
10. The Mazinaw terrane is devoid of Kensington-Skootamatta plutons. This may be due to the pressure and temperature conditions and deformation stresses at that crustal level at ca. 1060 Ma.

Future Work

Future work on the Kensington-Skootamatta plutons may include studies on Ar-Ar thermochronology on mica and hornblende within the plutons and comparison of this data with their crystallisation ages to determine their crustal level during emplacement. Further study of the granite-monzogranite plutons of this age in the Composite Arc Belt is required to determine whether the age, rock-type and geochemistry results from this study are as widespread as the characteristics from the syenite-monzonite plutons.

The Elphin pluton has a much more complex geochemistry than previously thought and mapping could help to establish the heterogeneities in rock-type in relation to the geochemistry. As was alluded to in Chapter 4, the age of emplacement of the Cranberry Lake pluton may indicate an earlier period of activation than previously thought for the Robertson Lake shear zone. Detailed mapping and structural analysis of

the pluton and its relationship to the shear zone could help to prove or disprove this hypothesis.

REFERENCES

- Barbarin, B., 1990. Granitoids: main petrogenetic classifications in relation to origin and tectonic setting. *Geological Journal*, 25: 227-238.
- Beaumont, C., Nguyen, M.H., Jamieson, R.A. and Ellis, S., 2006. Crustal flow modes in large hot orogens. In: R.D. Law, M.P. Searle and L. Godin (Editors), *Channel flow, ductile extrusion, and exhumation of lower-mid crust in continental collision zones*. Geological Society of London Special Publication 268: 91-145.
- Bonin, B., Azzouni-Sekkal, A., Bussy, F. and Ferrag, S., 1998. Alkali-calcic and alkaline post-orogenic (PO) granite magmatism: petrologic constraints and geodynamic settings. *Lithos*, 45: 45-70.
- Bowring, J., 2012. Tripoli, Cyber Infrastructure Research & Development Lab for the Earth Sciences. College of Charleston - Department of Computer Science, Charleston, South Carolina.
- Bowring, J., 2013. U-Pb Redux, Cyber Infrastructure Research & Development Lab for the Earth Sciences. College of Charleston - Department of Computer Science, Charleston, South Carolina.
- Busch, J.P., Mezger, K. and van der Pluijm, B.A., 1997. Suturing and extensional reactivation in the Grenville orogen, Canada. *Geology*, 25(6): 507-510.
- Busch, J.P. and van der Pluijm, B.A., 1995. Late orogenic, plastic to brittle extension along the Robertson Lake shear zone: Implications for the style of deep-orogenic extension in the Grenville orogen, Canada. *Precambrian Research*, 77: 83-100.
- Busch, J.P., van der Pluijm, B.A., Hall, C.M. and Essene, E.J., 1996. Listric normal faulting during postorogenic extension revealed by $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology near the Robertson Lake shear zone, Grenville orogen, Canada. *Tectonics*, 15(2): 387-402.
- Carr, S.D., Easton, R.M., Jamieson, R.A. and Culshaw, N.G., 2000. Geologic transect across the Grenville orogen of Ontario and New York. *Canadian Journal of Earth Sciences*, 37: 193-216.
- Chiarenzelli, J.R., Hudson, M.R., Dahl, P.S. and deLorraine, W.D., 2013. Constraints on deposition in the Trans-Adirondack Basin, Northern New York: Composition and origin of the Popple Hill Gneiss. *Precambrian Research*, 214-215: 154-171.
- Corfu, F. and Easton, R.M., 1995. U-Pb geochronology of the Mazinaw terrane, an imbricate segment of the Central Metasedimentary Belt, Grenville Province, Ontario. *Canadian Journal of Earth Sciences*, 32: 959-976.
- Corfu, F. and Easton, R.M., 1997. Sharbot Lake terrane and its relationships to Frontenac terrane, Central Metasedimentary Belt, Grenville Province: new insights from U-Pb geochronology. *Canadian Journal of Earth Sciences*, 34: 1939-1257.
- Corfu, F., Hanchar, J.M., Hoskin, P.W.O. and Kinny, P., 2003. Atlas of Zircon Textures. In: J.M. Hanchar and P.W.O. Hoskin (Editors), *Zircon. Reviews in Mineralogy and Geochemistry*. 469-500

- Corrigan, D. and Hanmer, S., 1997. Anorthosites and related granitoids in the Grenville orogen: A product of convective thinning of the lithosphere. *Geology*, 25: 61-64.
- Corriveau, L., 1990. Proterozoic subduction and terrane amalgamation in the southwestern Grenville province, Canada: Evidence from ultrapotassic to shoshonitic plutonism. *Geology*, 15: 615-617.
- Corriveau, L. and Gorton, M.P., 1993. Coexisting K-rich alkaline and shoshonitic magmatism of arc affinities in the Proterozoic: a reassessment of syenitic stocks in the southwestern Grenville Province. *Contributions to Mineralogy and Petrology*, 113: 262-279.
- Corriveau, L. and Morin, D., 2000. Modelling 3D architecture of western Grenville from surface geology, xenoliths, styles of magma emplacement, and Lithoprobe reflectors. *Canadian Journal of Earth Sciences*, 37: 235-251.
- Corriveau, L., Heaman, L.M., Marcantonio, F. and van Breemen, O., 1990. 1.1 Ga K-rich alkaline plutonism in the SW Grenville Province. *Contributions to Mineralogy and Petrology*, 105: 473-485.
- Corriveau, L., Morin, D., Tellier, M., Amelin, Y. and van Breemen, O., 1996a. Insights on minette emplacement and the lithosphere underlying the southwest Grenville Province of Quebec at 1,08 Ga. *Geological Survey of Canada Open File*, 3228: 139-142.
- Corriveau, L., Tellier, M.L. and Morin, D., 1996b. Le dyke de minette de Rivard et le complexe gneissique cuprifère de Bondy; implications tectonique et métallogénique pour la région de Mont-Laurier, Province de Grenville, Québec. *Commission géologique du Canada, Dossier public*, 3078.70p
- Cosca, M.A., Essene, E.J., Kunk, M.J. and J.F., S., 1992. Differential unroofing within the Central Metasedimentary Belt of the Grenville Orogen: constraints from $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology. *Contributions to Mineralogy and Petrology*, 110: 211-225.
- Cousens, B.L., 1996. Magmatic evolution of Quaternary mafic magmas at Long Valley Caldera and the Devils Postpile, California: Effects of crustal contamination on lithospheric mantle-derived magmas. *Journal of Geophysical Research*, 101(B12): 27673-27689.
- Cox, K.G., Bell, J.D. and Pankhurst, R.J., 1979. *The Interpretation of Igneous Rocks*. George Allen & Unwin. 450p
- Culshaw, N. and Dostal, J., 1997. Sand Bay gneiss association, Grenville Province, Ontario: a Grenvillian rift (and -drift) assemblage stranded in the Central Gneiss Belt. *Precambrian Research*, 85: 97-113.
- Culshaw, N.G., Jamieson, R.A., Ketchum, J.W.F., Wodicka, N., Corrigan, D. and Reynolds, P.H., 1997. Transect across the northwestern Grenville orogen, Georgian Bay, Ontario: Polystage convergence and extension in the lower orogenic crust. *Tectonics*, 16(6): 966-982.
- Culshaw, N., Beaumont, C. and Jamieson, R.A., 2006. The orogenic suprastructure -infrastructure concept: Revised, quantified, and revived. *Geology*, 34: 733-736.

- Cureton, J.S., van der Pluijm, B.A. and Essene, E.J., 1997. Nature of the Elzevir-Mazinaw domain boundary, Grenville Orogen, Ontario. *Canadian Journal of Earth Sciences*, 34: 976-991.
- Cutts, J., Carr, S.D. and Easton, R.M. 2011. Characterization of syntectonic to posttectonic intrusions of circa 1090 to 1065 Ma age in the southeastern Central Metasedimentary Belt, Grenville Province; *in* Summary of Field Work and Other Activities, 2011, Ontario Geological Survey, Open File Report 6270, p.6-1 to 6-7.
- Cutts, J., Easton, R.M., and Carr, S.D. 2012. Major, Trace element, and isotope geochemistry of plutons intruded circa 1090 to 1065 Ma in the southeastern Central Metasedimentary Belt, Grenville Province; *in* Summary of Field Work and Other Activities, 2012, Ontario Geological Survey, Open File Report 6280, p.15-1 to 15-5.
- Cutts, J., Easton, R.M. and Carr, S.D. 2013. Circa 1060-1090 Ma syn- to post-orogenic plutonism in the Grenville Province of Ontario: Insights from major, trace element and isotope geochemistry; Geological Association of Canada–Mineralogical Association of Canada, Winnipeg'13, Program with Abstracts, v.36, p.83-84.
- Davidson, A., 2001. Evidence for and significance of high-level plutonism in the southeastern composite arc belt, Grenville Province, Ontario. *In* Geological Association of Canada - Mineralogical Association of Canada annual meeting, St. John's, NL, Abstract Vol 26, p. A34.
- Davidson, A. and van Breemen, O., 2000a. Age and extent of the Frontenac plutonic suite in the Central metasedimentary belt, Grenville Province, southeastern Ontario. *Geological Survey of Canada Current Research*, 2000-F4: 1-17.
- Davidson, A. and van Breemen, O., 2000b. Late Grenvillian granite plutons in the Central metasedimentary belt, Grenville Province, southeastern Ontario. *Geological Survey of Canada Current Research*, 2000-F5: 1-11.
- Davidson, A. and van Breemen, O., 2000c. Geology of the Mountain Grove pluton, Central Metasedimentary Belt, Grenville Province, Ontario. *Current Research*, 2000-C23: 1-7.
- Davis, D.W. and Bartlett, J.R., 1988. Geochronology of the Belmont Lake Metavolcanic Complex and implications for crustal development in the Central metaseimentary Belt, Grenville Province, Ontario. *Canadian Journal of Earth Sciences*, 25: 1751-1759.
- Easton, R.M., 1986. Geochronology of the Grenville Province. In: J.M. Moore, A. Davidson and A.J. Baer (Editors), *The Grenville Province. Special Paper - Geological Association of Canada*, v.31: p. 127-173.
- Easton, R.M., 1992. The Grenville Province and the Proterozoic History of Central and Southern Ontario. In: P.C. Thurston, H.R. Williams, R.H. Sutcliffe and G.M. Stott (Editors), *Geology of Ontario. Ontario Geological Survey, Special Volume 4, part 2*, p. 713-904.

- Easton, R.M., 2001a. Geology and Mineral Potential of the Puzzle Lake Area, Central Metasedimentary Belt, Grenville Province. Ontario Geological Survey, Open File Report 6064: 26p.
- Easton, R.M., 2001b. Precambrian geology, Mazinaw Lake area. Ontario Geological Survey, Preliminary Map P3439, 1:50 000 scale.
- Easton, R.M., 2001c. Precambrian Geology, Sharbot Lake area. Ontario Geological Survey, Preliminary Map P3440, 1:50 000 scale..
- Easton, R.M., 2001d. Precambrian geology, Tichborne area. Ontario Geological Survey, Preliminary Map P3443, 1:50 000 scale..
- Easton, R.M., 2008. Rossing-Style Uranium Potential of Late Granites and Pegmatites of the Central Metasedimentary Belt, Grenville Province. *In* Summary of Field Work and Other Activities 2008, Ontario Geological Survey, Open File Report 6226: 16.1-16.10.
- Easton, R.M. and Ford, F.D., 1994. Geology of the Grimsthorpe Area, Hastings and Lennox and Addington Counties, Grenville Province. Ontario Geological Survey, Open File Report, 5894, 153p.
- Easton, R.M. and Kamo, S.L., 2008. New U-Pb zircon ages reveal a long-lived magmatic history of the Harvey-Cardiff domain of the Composite Arc Belt of the Grenville Province in Ontario. Geological Society of America, Abstracts with Program, 40: p. 228.
- Easton, R.M. and Kamo, S.L., 2011. Harvey-Cardiff domain and its relationship to the Composite Arc Belt, Grenville Province: insights from U-Pb geochronology and geochemistry. Canadian Journal of Earth Sciences, 48: 347-370.
- Eby, G.N., 1992. Chemical subdivision of the A-type granitoids: Petrogenetic and tectonic implications. Geology, 20: 641-644.
- Faure, G. and Mensing, T.M., 2005. The U-Pb, Th-Pb, and Pb-Pb Methods, Isotopes - Principles and Applications. 3rd ed. John Wiley & Sons, Inc., Hoboken, NJ. 897p
- Frost, C.D., and Frost, R.B. 2013b. Geochemical classification of high-silica granites (leucogranites), Geological Society of America, Abstracts with Program, 45(7), 389.
- Frost, C.D. and Frost, R.B., 2013a. Proterozoic ferroan feldspathic magmatism. Precambrian Research, 228: 151-163.
- Frost, B.R., Barnes, C.G., Collins, W.J., Arculus, R.J., Ellis, D.J. and Frost, C.D., 2001. A Geochemical Classification for Granitic Rocks. Journal of Petrology, 42(11): 2033-2048.
- GeoLabs, 2009. Schedule of Fees and Services. Geoscience Laboratories, Sudbury.
- Grammatikopoulos, T.A., Clark, A.H. and Archibald, D.A., 2007. Petrogenesis of the Leo Lake and Lyndhurst plutons, Frontenac terrane, Central Metasedimentary Belt, southeastern Ontario, Canada. Canadian Journal of Earth Sciences, 44: 107-126.
- Hewitt, D.F., 1964. Gananoque Area; Ontario Department of Mines, Map 2054; scale 1:126 640.

- Hanchar, J.M. and Miller, C.F., 1993. Zircon zonation patterns as revealed by cathodoluminescence and backscattered electron images: Implications for interpretation of complex crustal histories. *Chemical Geology*, 110: 1-13.
- Hanmer, S. and McEachern, S., 1992. Kinematical and rheological evolution of a crustal-scale ductile thrust zone, Central Metasedimentary Belt, Grenville orogen, Ontario. *Canadian Journal of Earth Sciences*, 29: 1779-1790.
- Hanmer, S., Corrigan, D., Pehrsson, S. and Nadeau, L., 2000. SW Grenville Province, Canada: the case against post-1.4 Ga accretionary tectonics. *Tectonophysics*, 319: 33-51.
- Kamo, S.L., Krogh, T.E. and Kumarapeli, P.S., 1995. Age of the Grenville dyke swarm, Ontario - Quebec: Implications for the timing of Iapetan rifting. *Canadian Journal of Earth Sciences*, 32: 273-280.
- Krogh, T.E., 1982a. Improved accuracy of U-Pb zircon ages by the creation of more concordant systems using an air abrasion technique. *Geochimica et Cosmochimica Acta*, 46: 637-649.
- Krogh, T.E., 1982b. Improved accuracy of U-Pb zircon dating by selection of more concordant fractions using a high gradient magnetic separation technique. *Geochimica et Cosmochimica Acta*, 46: 631-635.
- Lumbers, S.B., Heaman, L.M., Vertolli, V.M. and Wu, T.-W., 1990. Nature and timing of Middle Proterozoic magmatism in the Central Metasedimentary Belt, Ontario, *In* Mid-Proterozoic Laurentia-Baltica. Geological Association of Canada, Special Paper 38, pp. 243-276.
- Marcantonio, F., McNutt, R.H., Dickin, A.P. and Heaman, L.M., 1990. Isotopic evidence for the crustal evolution of the Frontenac Arch in the Grenville Province of Ontario, Canada. *Chemical Geology*, 83: 297-314.
- Mattinson, J.M., 2005. Zircon U-Pb chemical abrasion ("CA-TIMS") method: Combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages. *Chemical Geology*, 220: 47-66.
- McEachern, S. and van Breemen, O., 1993. Ages of deformation within the Central Metasedimentary Belt boundary thrust zone, southwest Grenville Orogen: Constraints on the collision of the mid-Proterozoic Elzevir terrane. *Canadian Journal of Earth Sciences*, 30: 1155-1165.
- McLelland, J., Daly, J.S. and McLelland, J.M., 1996. The Grenville Orogenic Cycle (ca. 1350-1000 Ma); an Adirondack perspective. *Tectonophysics*, 265: 1-28.
- McLelland, J.M., Hamilton, M., Selleck, B., McLelland, J., Walker, D. and Orrell, S., 2001. Zircon U-Pb geochronology of the Ottawa Orogeny, Adirondack Highlands, New York: regional and tectonic implications. *Precambrian Research*, 109: 39-72.
- Mohammed, E.-B. and Hassen, I.S., 2012. The late Ediacaran (580-590 Ma) onset of anorogenic alkaline magmatism in the Arabian-Nubian Shield; Katherina A-type rhyolites of Gabal Maëain, Sinai, Egypt. *Precambrian Research*, 216: 1-22.
- Ontario Geological Survey 2011. 1:250 000 scale bedrock geology of Ontario. Ontario Geological Survey, Miscellaneous Release, Data 126-Revision 1.

- Parrish, R.R., Roddick, J.C., Loveridge, W.D. and Sullivan, R.W., 1987. Uranium-lead analytical techniques at the Geochronology Laboratory, *In* Radiogenic age and Isotopic Studies; Report 1; Geological Survey of Canada Paper 87-2: 3-7.
- Pearce, J.A., Harris, N.B.W. and Tindle, A.G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of Petrology*, 25: 956-983.
- Peccerillo, A. and Taylor, S.R., 1976. Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastamonu area, northern Turkey. *Contributions to Mineralogy and Petrology*, 25: 63-81.
- Pehrsson, S., Hanmer, S., and van Breemen, O., 1996. U/Pb geochronology of the Raglan gabbro belt, central metasedimentary belt, Ontario: Implication for an ensialic marginal basin in the Grenville orogen. *Canadian Journal of Earth Sciences*, 33: 691-702
- Pupin, J.P., 1980. Zircon and Granite Petrology. *Contributions to Mineralogy and Petrology*, 73: 207-220.
- Rivers, T., 2008. Assembly and preservation of lower, mid, and upper orogenic crust in the Grenville Province - Implications for the evolution of large hot long-duration orogens. *Precambrian Research*, 167: 237-259.
- Rivers, T., 2012. Upper-crustal orogenic lid and mid-crustal core complexes: signature of a collapsed orogenic plateau in the hinterland of the Grenville Province. *Canadian Journal of Earth Sciences*, 49: 1-42.
- Rollinson, H.R., 1993. Using geochemical data: Evaluation, presentation, interpretation. Longman Scientific & Technical, Harlow, Essex, England. 352p
- Sager-Kinsman, E.A. and Parrish, R.R., 1993. Geochronology of detrital zircons from the Elzevir and Frontenac terranes, Central Metasedimentary Belt, Grenville Province, Ontario. *Canadian Journal of Earth Sciences*, 30: 465-473.
- Schoene, B. and Bowring, S.A., 2006. U-Pb systematics of the McLure Mountain syenite: thermochronological constraints on the Age of the $^{40}\text{Ar}/^{40}\text{Ar}$ standard MMhb. *Contributions to Mineralogy and Petrology*, 151: 615-630.
- Shand, S.J., 1943. Eruptive Rocks. Their Genesis, Composition, Classification and Their Relation to Ore Deposits with a Chapter on Meteorite. John Wiley & Sons, New York. 444p
- Shieh, Y., 1985. High- ^{18}O granitic plutons from the Frontenac Axis, Grenville Province of Ontario, Canada. *Geochimica et Cosmochimica Acta*, 49: 117-123.
- Stacey, J.S. and Kramers, J.D., 1975. Approximation of Terrestrial Lead Isotope Evolution by a 2-stage Model. *Earth and Planetary Science Letters*, 26: 207-221.
- Sun, S.S. and McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. *In* Geological Society Special Publication, 42: 313-345.

- Timmermann, H., Jamieson, R.A., Parrish, R.R. and Culshaw, N., 2002. Coeval migmatites and granulites, Muskoka domain, southwestern Grenville Province, Ontario. *Canadian Journal of Earth Sciences*, 39: 239-258.
- van Breemen, O., Peterson, T.D. and Sandeman, H.A., 2005. U-Pb zircon geochronology and Nd isotope geochemistry of the Proterozoic granitoids in the western Churchill Province: intrusive age pattern and Archean source domains *Canadian Journal of Earth Sciences*, 42: 339-377.
- Wallach, J., 1973. The metamorphism and structural geology of the Hinchinbrooke gneiss and its age relationship to metasedimentary and metavolcanic rocks of the Grenville Group; Unpublished PHd thesis, Queen's University, Kingston, Ontario, 141 pp.
- Whalen, J.B., Currie, K.L. and Chappell, B.W., 1987a. A-type granites: geochemical characteristics, discrimination and petrogenesis. *Contributions to Mineralogy and Petrology*, 95: 407-419.
- White, D.J., Forsyth, D.A., Asudeh, I., Carr, S.D., We, H., Easton, R.M. and Mereu, R.F., 2000. A seismic-based cross-section of the Grenville Orogen in southern Ontario and western Quebec. *Canadian Journal of Earth Sciences*, 37: 183-192.
- Wu, T. and Kerrich, R., 1986. Combined oxygen isotope - compositional studies of some granitoids from the Grenville Province of Ontario, Canada: implications for source regions. *Canadian Journal of Earth Sciences*, 23: 1412-1432.
- Wynne-Edwards, H.R., 1967. Westport-Area, Ontario, with special emphasis on the Precambrian rocks. *Geological Survey of Canada Memoir*, 346: 142p.