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**IN-SITU ZIRCON AND MONAZITE GEOCHRONOLOGY FROM
COMPOSITIONALLY DISTINCT LAYERS IN A SINGLE MIGMATITIC
PARAGNEISS SAMPLE LOCATED IN THE EASTERN ADIRONDACK
MOUNTAINS, NY**

A Thesis Presented

by

KAITLYN A. SUAREZ

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE

May 2019

Geosciences

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Michael Williams, Chair

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Timothy Grover, Member

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Geosciences

DEDICATION

This work is dedicated to my parents, Joseph and Kalliopi Suarez, for encouraging my dreams and for supporting me in every step of the journey. This work is also dedicated to my siblings, Kristen and James, for being a constant source of inspiration and motivation, and for being there for me when I need it the most.

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ABSTRACT

IN-SITU ZIRCON AND MONAZITE GEOCHRONOLOGY FROM COMPOSITIONALLY DISTINCT LAYERS IN A SINGLE MIGMATITIC PARAGNEISS SAMPLE LOCATED IN THE EASTERN ADIRONDACK MOUNTAINS, NY

MAY 2019

KAITLYN SUAREZ, B.S., UNION COLLEGE

M.S., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Michael Williams

Migmatites are a common rock type in the Adirondack Mountains, NY. We analyzed a single sample of biotite-garnet-sillimanite paragneiss with foliation parallel leucosome along Route 22 south of Whitehall, NY in order to determine the timing of melting using both in-situ monazite and zircon U/Pb geochronology from the restite and leucosome layers of the same rock. Monazite was analyzed via in-situ EMPA on the Ultrachron microprobe at the University of Massachusetts. Zircon was analyzed via LA-ICP-MS (in-situ and mounted mineral separates) at the LaserChron Center. Monazite analyses from the restite yielded six compositionally distinct populations with dates of 1178 ± 16 , 1139 ± 4 , 1064 ± 6 , 1049 ± 4 , 1030 ± 5 , and 1004 ± 10 Ma. Yttrium and heavy REEs decrease in monazite in two steps: one dramatic drop from ca. 1150 to 1065 Ma and another between ca. 1065 and 1050, interpreted to reflect two periods of garnet growth and melting. Analyses from the restite zircon separate yielded a significant single peak near 1050 Ma. These zircon grains exhibit fir-tree sector zoning texture which is interpreted to indicate crystallization from melt. Monazite from leucosome yielded a unimodal population at ca. 1050 Ma, however, backscatter images document alteration of monazite to apatite on the edges of the grains, and abundant uranothorite inclusions.

Leucosome zircon analyses yielded a ca. 1150 Ma population from cores and a 1050 Ma population from rims. Cathodoluminescence imaging reveals that the zircon rims have textures indicative of fluid alteration. The data are consistent with these rocks undergoing two periods of melting. The first event at ca. 1150 Ma may have involved a non-garnet producing melting reaction, such as muscovite dehydration-melting. The second event at 1065 Ma involved significant garnet growth, interpreted to represent biotite dehydration-melting. Subsequently, the rocks underwent hydrothermal alteration at 1050 Ma.

Monazite grains with dates at 1030 ± 5 and 1004 ± 10 Ma have higher yttrium concentrations suggesting garnet breakdown and monazite growth during decompression and retrograde metamorphism. A combination of monazite and zircon dating techniques from each compositional layer is necessary to constrain leucosome-restite relationships and to accurately interpret the timing of melting from migmatites that have experienced multiple phases of melting.

TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS	v
ABSTRACT.....	vi
LIST OF TABLES	ix
LIST OF FIGURES	x
CHAPTER	
1. INTRODUCTION	1
2. BACKGROUND	4
2.1 Geologic Setting.....	4
3. SAMPLE DESCRIPTION.....	7
4. METHODS	10
4.1 Monazite U-Th-Pb Geochronology Methods	10
4.2 Zircon U-Pb Geochronology Methods.....	14
5. RESULTS	15
5.1 Field Observations	15
5.2 Restite Monazite Results.....	15
5.3 Restite Monazite Composition-Date Relationships	18
5.4 Leucosome Monazite Results	20
5.5 Leucosome and Restite Monazite Compositional Comparison	22
5.6 In-situ Restite Zircon Results.....	24
5.7 Separate Restite Zircon Results	26
5.8 In-situ Leucosome Zircon Results	28
5.9 Leucosome Separate Zircon Results.....	31
5.10 Restite and Leucosome Zircon Comparison	33
5.11 Thin Section Scale Compositional Comparison	34
6. DISCUSSION	37
6.1 Timing of Melting.....	37
6.2 Timing of Leucosome Production	40
6.3 Retrograde Metamorphism, Decompression, and Fluid Influx	45
6.4 Evidence for Heterogeneous Melting	48
6.5 Overview of Metamorphic and Deformational History.....	49
6.6 Limitations of Zircon and Monazite Geochronology	50
7. CONCLUSIONS.....	52
APPENDICES	
A- MONAZITE DATA	54
B - ZIRCON DATA.....	58
C - MAJOR MINERAL COMPOSITIONS	65
BIBLIOGRAPHY.....	69

LIST OF TABLES

Table	Page
1: Restite Monazite Analyses.....	54
2: Leucosome Monazite Analyses	57
3: Restite Zircon U/Pb Analyses	58
4: Leucosome Zircon U/Pb Analyses	64

LIST OF FIGURES

Figure	Page
1: Geologic map of the Adirondack Mountains, NY.....	6
2: Photo of the road cut outcrop facing west along Rt. 22 south of Whitehall, NY where the paragneiss samples were collected.	8
3: Sample 16TG-143 is representative of the garnet-biotite-sillimanite paragneisses collected in the study.	9
4: Full section x-ray maps of Ca, K, and Mg for samples 16-TG-143-1 (restite), 16-TG-143-2 (restite + leucosome), and 16-TG-143-5 (leucosome).....	12
5: Full-section map (16-TG-144) with arrows connecting monazite grain maps to the monazite location in the thin section in order to evaluate the textural and zoning significance	13
6: Schematic and yttrium x-ray map showing the three compositional zones and associated dates for a monazite grain in the restite.....	17
7: Monazite date results from the restite layer.....	17
8: Restite monazite composition vs calculated date.	19
9: A) BSE images of the leucosome (16TG-143-5) monazite with uranothorite inclusions and alteration to apatite on the edges.....	21
10: Monazite date results from the leucosome layer.	22
11: Comparison of the restite and leucosome monazite compositions for Y, HREE, U, LREE, Th and Ca against calculated date	23
12: In-situ zircon results from the restite.	26
13: Separate zircon results from the restite.....	27
14: In-situ and separate restite zircon dates plotted against uranium	28
15: Results from the in-situ leucosome zircon analysis.....	30
16: Results from the leucosome separate zircon analysis.	32
17: Th/U vs. Date for the leucosome and restite zircon grains from both in-situ and separate analyses.	33

18: A) Magnesium and potassium x-ray maps of 16-TG-143-1 with lines delineating the layers in the thin section that are inferred to have retained melt (plagioclase-rich) and lost melt (K-feldspar-rich).	35
19: Comparison of monazite composition vs date between the K-feldspar and plagioclase-rich layers.	36
20: Restite monazite results with the interpreted tectonic event.....	40
21: Comparison of the restite and leucosome monazite and zircon grains with associated dates.	44
22: Schematic showing the interpreted timeline of melting, garnet growth, monazite growth, and zircon crystallization based on the data from the restite layers	47
23: Comparison of the composition of garnet in all samples (restite and leucosome)	65
24: Calcium x-ray microprobe maps of the garnet grains analyzed in the restite.....	66
25: Calcium x-ray microprobe maps of the garnet grains analyzed in the leucosome	67
26: Comparison of the composition of K-feldspar in the restite (143-1) and leucosome (143-5)	68
27: Potassium x-ray microprobe map of K-feldspar in the leucosome (143-5).....	68
28: Compositional comparison of plagioclase in the restite (143-1) and leucosome (143-5)	69
29: Calcium x-ray microprobe map of plagioclase in the leucosome (143-5).....	69

CHAPTER 1

INTRODUCTION

Monazite ((Ce, La, Th) PO₄) is a powerful geochronometer for revealing the timing of melting during high-temperature metamorphism (Williams et al., 2011; Wong et al., 2012; Wang et al., 2017). Monazite is particularly useful for “reaction dating” (petrochronology) (Williams et al., 2017), a method in which in-situ monazite dates and associated geochemistry are linked to specific melt reactions, such as biotite dehydration-melting (Dumond et al., 2015; Williams et al., 2017; Williams et al., in review). Monazite petrochronology has provided a number of insights about the prograde and retrograde path during partial melting events. However, there are issues that complicate interpretations, especially in near peak metamorphism, one of which is that monazite can be quite soluble in some granitic melts, and therefore data from zircon may provide additional constraints (Kelsey et al., 2008). Zircon is also a commonly used geochronometer, however there are fewer studies relating zircon growth to melt reactions due, in part, to the low abundance of trace elements in zircon (Bickford et al., 2008; Rubatto, 2017). Trace elements in geochronometers can provide a number of insights into orogenic processes (Rubatto, 2017; Williams et al., in review). Zircon is a key mineral for constraining the timing of melting because zircon is durable in melt and has been shown to grow from crystallizing partial melt (Rubatto, 2017). The combination of zircon petrochronology and monazite petrochronology may provide the most complete record of melting, melt crystallization, exotic melt injection, and melt extraction events in migmatites, especially in multiply melted regions.

The rocks of Adirondack Mountains of New York are uplifted Precambrian basement of the North American Grenville Province that are interpreted to have undergone multistage melting and deformation (Rivers, 1997; Chiranzelli et al., 2017). Previous studies have delineated the timing of the Mesoproterozoic events, and it is widely accepted that two events may have contributed to widespread melting and garnet growth: 1) the (ca. 1190-1140 Ma) Shawinigan Orogeny and associated (ca. 1160-1140 Ma) anorthosite-mangerite-charnockite-granite (AMCG) plutonism and 2) the (ca. 1080 – 1020 Ma) Ottawa Orogeny and associated unroofing and tectonic collapse phase (Rivers, 1997; McLelland and Selleck, 2011; Wong et al., 2012; Regan et al., in review; Williams et al., in review). Curiously, some migmatitic rocks in the eastern Adirondack Mountains record either the older (ca. 1150 Ma) or the younger (ca. 1050 Ma) melt history, but not both events (Williams et al., in review; Pless et al., pers comm). A close examination of the layers of a migmatite may elucidate the reasons for the heterogeneities in the record of melting in order to better understand the timing of melting in the Adirondack Mountains in general (Williams et al., 2017; Williams et al., in review).

Metapelitic migmatitic paragneiss outcrops are present along highway 22 south of Whitehall, NY. Previous work on these outcrops show that monazite grew during both the Shawinigan and Ottawa orogenies (Wong et al., 2012), thus making this location a suitable focus for our study. We analyzed rock-scale and thin-section scale restite and leucosome layers in order to better understand the monazite and zircon geochronological record, geochemistry, and growth/dissolution during anatexis. This study explores links between monazite/zircon crystallization and melting reactions, such as biotite dehydration-melting, and aims to 1) clarify the timing of melting in the eastern

Adirondack Mountains through combined in-situ zircon and monazite petrochronology and 2) explore the mineral assemblage and geochronological heterogeneities between the restite and leucosome layers in order to interpret the record of melting and melt crystallization in migmatitic rocks.

CHAPTER 2

BACKGROUND

2.1 Geologic Setting

The Adirondack Mountains are a domical uplift and outlier of the Grenville Province rocks in upstate New York (Figure 1). They are connected to the Grenville Province exposed in eastern Canada by the Frontenac Arc. The Grenville Province of eastern and southern North America are the products of a protracted period of Mesoproterozoic orogenesis and accretion along the eastern margin of Laurentia, the culmination of which resulted in the formation of the supercontinent Rodinia (Rivers, 1997; Chiranzelli et. al., 2017). The Adirondack Mountains are predominantly composed of a lithologically and compositionally diverse suite of high-grade metasedimentary and metaigneous rocks. The northeast-trending Carthage Colton Shear zone forms the boundary between the Adirondack Lowlands to the northwest and the Adirondack Highlands to the southeast. The Highlands and the Lowlands have overlapping yet distinctly different geologic histories (Figure 1) (McLelland and Selleck, 2011).

The Adirondack Mountains record a series of Mesoproterozoic accretionary/collisional orogenic events. The (ca. 1245–1225 Ma) Elzevirian orogeny is interpreted to represent a phase of magmatism and metamorphism related to the accretion of the Elzevir terrane (Rivers, 1997). The (ca. 1190 – 1140 Ma) Shawinigan orogeny involved thrusting, crustal thickening, and regional granulite facies metamorphism in the Adirondack Highlands. It is interpreted to represent the closure of the trans-Adirondack basin and subsequent back arc collisional tectonism (Rivers, 1997; Heumann et al., 2006; Chiarenzelli et al., 2010 Wong et. al., 2012). The Adirondack Lowlands are interpreted to

have been thrust over the Highlands along the Carthage-Colton shear zone following the closure of the trans-Adirondack basin. Emplacement of a major suite of intrusive igneous rocks including anorthosite-mangerite-charnockite-granite and gabbro known as the AMCG suite (1165 –1145 Ma) is interpreted to be a result of delamination of the lithospheric mantle (Chiarenzelli et al., 2010). The (ca. 1080 – 1020 Ma) Ottawa orogeny resulted in granulite-facies metamorphism in the Adirondack Highlands. It is interpreted to represent a Himalayan-style continent-to-continent collision, possibly between Laurentia and Amazonia (Rivers, 1997, Heumann et al., 2006; Bickford et. al., 2008; Wong et. al., 2012). The Adirondack Highlands likely reached temperatures near 800 °C and 7-9 kbar during the Ottawa orogeny (Spear and Markesson, 1997; Storm and Spear, 2005). The Rigolet orogeny is interpreted to be a significant event in the western Grenville Province. However, in the Adirondack Mountains the Rigolet event is characterized by metasomatism and pegmatite emplacement with minimal structural or metamorphic impact (Rivers, 2008; Williams et al, in review).

Outcrops along Rt. 22 south of Whitehall, NY have been recently interpreted to record evidence of a shear zone that accommodated extension during the later stages of the Ottawa orogeny (Wong et al., 2012). The Eastern Adirondack shear zone is interpreted to have undergone top-to-the-southeast normal faulting synchronous with top-to-the-northwest normal shearing on the Carthage Colton shear zone in the western Adirondack Highlands (Wong et al., 2012). The Adirondack Highlands may have been exhumed as a metamorphic core complex or symmetrical gneiss dome during the late-stage gravitational collapse of the Ottawa orogeny (Wong et al., 2012; Regan et al., in press).

Figure 1: Geologic map of the Adirondack Mountains, NY. The study area is along Rt. 22 south of Whitehall, NY. The inset shows the location of the Adirondack Mountains relative the Grenville Province in Canada. Modified from McLelland et al., 2013.

CHAPTER 3

SAMPLE DESCRIPTION

Two paragneiss samples, 16-TG-143 and 16-TG-144, were collected from a road cut south of Whitehall, NY (Figure 2). The two paragneiss samples are composed of a mineral assemblage of biotite, garnet, sillimanite, plagioclase, quartz, K-feldspar with zircon, monazite, rutile, and ilmenite as accessory phases. Sample 16-TG-143 was selected because the sample has discrete restite and leucosome layers, including one larger (3 cm) garnet-rich leucosome layer (Figure 3). Sample 16-TG-144 is distinct from sample 16-TG-143 in that there is very coarse garnet and sillimanite with discrete, thin leucosome layers. The restite and leucosome layers were separately analyzed in order to evaluate the melting history in each layer. Four polished sections that are representative of the restite and leucosome layers from both samples were selected for monazite and zircon dating.

Figure 2: Photo of the road cut outcrop facing west along Rt. 22 south of Whitehall, NY where the paragneiss samples were collected. A leucosome vein is present in the upper left corner.

Figure 3: Sample 16TG-143 is representative of the garnet-biotite-sillimanite paragneisses collected in the study. The top of the sample is mostly restitic with layers and the bottom layer has a 2.5 cm thick leucosome layer. The restite and leucosome layers were separately analyzed in this study.

CHAPTER 4

METHODS

4.1 Monazite U-Th-Pb Geochronology Methods

In-situ monazite electron microprobe geochronologic data has been used to place constraints on the timing of anatexis and fabric formation in the Eastern Adirondack Mountains (Williams et. al., 2006; Williams et. al., 2017). The oriented samples were cut parallel to lineation and perpendicular to foliation. In this study, multiple polished microprobe sections were made from each sample to characterize the discrete layers in the rock. The entire thin sections were compositionally mapped for Mg, K, Ca, Ce, and Zr in order to observe the distribution of major silicate phases, kinematic indicators, and to locate monazite and zircon grains (Figure 4) (Williams et. al., 2006).

Approximately 25 monazite grains from each polished section were mapped at high resolution to qualitatively show compositional variation of Y, Th, U, Ca and Si to delineate distinct compositional domains. The compositional grain maps were simultaneously processed to compare the intensity of element abundances in each domain across all of the grains. All of the monazite grain maps were placed around the full-section map in Adobe Illustrator to characterize the monazite setting and to evaluate the textural and zoning significance (see Williams et. al., 2006) (Figure 5). The monazite grain maps display an average of three to six compositional domains in a typical thin section (Figure 5). All domains in a single grain were analyzed to show the relative changes in monazite composition, even if the date uncertainties overlapped.

The monazite grains were analyzed on the SX-100 Cameca Ultrachron electron microprobe at the University of Massachusetts Amherst. The Ultrachron microprobe is

used to make high-precision U-Th-Pb analyses with simultaneous trace and rare earth elements (REEs) analyses. HREE analyzed in this study are Eu, Tb, Dy, Ho, Er, Tm, and Yb. LREE analyzed in this study are La, Ce, Pr, Nd, and Sm. The standard used for consistency in the dating is the Moacir Brazilian pegmatite monazite with a weighted mean $^{207}\text{Pb}/^{235}\text{U}$ age of 504.3 $\pm$ 0.2 Ma (2σ , MSWD = 0.64) (Gasquet et al., 2010; Dumond et al., 2015). The analytical methods for U-Th-total Pb, domain-specific date and trace element analysis are summarized in Williams et. al., 2006 and Dumond et. al., 2008.

Figure 4: Full section x-ray maps of Ca, K, and Mg for samples 16-TG-143-1 (restite), 16-TG-143-2 (restite + leucosome), and 16-TG-143-5 (leucosome).

Figure 5: Full-section map (16-TG-144) with arrows connecting monazite grain maps to the monazite location in the thin section in order to evaluate the textural and zoning significance.

4.2 Zircon U-Pb Geochronology Methods

Zircon grains were dated at the University of Arizona LaserChron laboratory using a Thermo Element2 single-collector laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) in order to place additional constraints on the timing of anatexis and fabric formation in the eastern Adirondack Mountains. Grains were dated using both in-situ and mounted mineral separate dating techniques. Two restite samples (16TG-143-1+2) and one leucosome sample (16TG-143-5) were dated via the in-situ method. In-situ zircon textures were first characterized using cathodoluminescence (CL) at the University of Massachusetts Amherst in order to evaluate zoning and identify targets based on texture prior to dating. The in-situ zircon analyses were made using a 15 μm spot size. Zircon separates were made at the University of Arizona for the restite (16TG-143-1) and leucosome (16TG-143-2) samples. The zircon grains were first separated from the rock and then grains were hand-picked and mounted in epoxy on a round disk. Low-resolution CL and BSE imaging was used to characterize grains prior to dating. 300 spots were analyzed in the restite and 40 spots were analyzed in the leucosome. Each sample was dated with the goal of collecting dates from core and rim domains from the same grain. Zircon grain mounts were dated using a 20 μm spot size. Results with 95% to 100% concordance were evaluated, and all other discordant grains were removed from the populations. See Gehrels et al., (2006, 2008) for the Laser Ablation ICP Mass Spectrometry methods at the LaserChron laboratory.

CHAPTER 5

RESULTS

5.1 Field Observations

Field observations were made at a road cut along Rt. 22 south of Whitehall, NY at the GPS coordinate of -73.4403 longitude, 43.4656 latitude (Figure 2). This outcrop was previously analyzed in the Wong et al., 2012 study. The rocks are garnet-rich paragneisses with leucosome layers. The leucosome layers were interpreted to represent local anatexis, consistent with the interpretation from Bickford et al., 2008. The outcrops in the study area have a well-developed foliation with a mean strike and dip of 019°/21°. The lineation of the area is defined by aligned sillimanite needles, quartz ribbons, and aligned biotite in the paragneisses. The lineation gently plunges southeast with a mean orientation of 16→131. Mesoscopic kinematic indicators are largely absent in the metasedimentary unit, but the region has predominately top-to-the-southeast (normal) shear sense based on asymmetric tails on the σ -type, K-feldspar and garnet porphyroclasts in the nearby granitic gneiss units (Wong et al., 2012).

5.2 Restite Monazite Results

Monazite grains from three restite thin sections were analyzed for a U/Pb date and trace elements via EMPA. Restite monazite grains range from 5-80 μm in size and commonly have two or three domains defined by distinct differences in yttrium concentration (Figure 6). Restite yttrium compositional domains are categorized as: 1) high-Y 2) low-Y and 3) rim. High-Y monazite domains are found as small inclusions (10-20 μm) in garnet, and less commonly in matrix grains as small, anhedral cores inside

a low-Y domain. Monazite grains with a high-Y core domain account for approximately one third of all grains. Low-Y domain is only present in the matrix and is the most abundant domain. The domain is approximately 30-80 μ m in size and commonly has an elongated shape parallel with the foliation. A thin (2-5 μ m thick) rim with higher Y surrounds nearly all the matrix grains.

The monazite dates from each compositional domain type are consistent across the three restite thin-sections. The six monazite populations that resulted from the restite monazite analyses include: 1178 ± 16 , 1139 ± 4 , 1064 ± 6 , 1049 ± 4 , 1030 ± 5 , and 1004 ± 10 Ma. Sixteen high-Y core domain dates range from 1222 to 1148 Ma. Thirty-eight low-Y domain dates range from 1080 to 1049 Ma. Nineteen high-Y rim domain dates range from 1051 to 978 Ma. The results are presented in Figure 7. Each probability distribution represents one monazite date, obtained from one compositional domain. The color codes show the main domain types (i.e. high-Y, low-Y, rim). Typical uncertainties (1σ) range from ca. 4 m.y. to 10 m.y., and are rarely greater than 20 m.y. See appendix A for a complete table of the results.

Figure 6: Schematic and yttrium x-ray map showing the three compositional zones and associated dates for a monazite grain in the restite.

Figure 7: Monazite date results from the restite layer. Green histograms are the inner core domain with high-Y, blue histograms are the outer core domains with low-Y, and red histograms are the rim domains.

5.3 Restite Monazite Composition-Date Relationships

Figure 8 shows the composition of Y, HREE, U, Ca, Th in restite monazite grains. Arrows connect core and rims from single monazite grains to demonstrate the relative compositional changes over time, even if the calculated uncertainties overlap. In general, the high-Y core domain has higher Y, U, HREE but lower Ca and Th compared to the low-Y domain.

Figure 8: Restite monazite composition vs calculated date. Arrows connect cores to rims of the same grain.

5.4 Leucosome Monazite Results

Monazite grains in the 3 cm leucosome layer (Figure 3) are distinctly different from the restite monazite grains within the same rock. The most obvious difference is that there are only 13 grains in the layer compared to over 50 grains in the restite. There is no monazite included in garnet. Based on high resolution compositional maps, yttrium domains are irregular, anhedral, and patchy (Figure 9). The leucosome monazite domains are also distinguished by distinct differences in yttrium concentrations and are similarly categorized as: 1) high-Y 2) low-Y and 3) rim. The high-Y domain is present as small (2-10 μm), anhedral domains located in the center or near an edge of a lower-Y grain. The low-Y domain ranges from 10-100 μm and has a heterogeneous, patchy texture with irregular edges. Some, but not all, of the grains are surrounded by a thin rim with a higher Y concentration. Backscatter (BSE) scanning electron microscope (SEM) images reveal that apatite and uranothorite inclusions surround the edge of nearly all monazite grains (Figure 9c). The location of apatite around the edges of the monazite grain is clearly defined in the calcium compositional map (Figure 9d).

The calculated dates for the three domains are all younger than ca. 1065 Ma. The two high-Y domain dates are 1062 ± 9 and 1048 ± 9 Ma. The high-Y domains have a date that is younger than the date of the low-Y domain in the same grain, a relationship that is opposite from the relationship in the restite grains. Seven low-Y domains range from 1067 to 1048 Ma. The two rim domain dates are 1049 ± 4 and 1030 ± 16 Ma. The results are presented in Figure 10. Each probability distribution represents one monazite date, obtained from one compositional domain. The color codes show the main domain types

(i.e. high-Y, low-Y, rim). Typical uncertainties (1σ) range from ca. 4 m.y. to 10 m.y., and rarely greater than 20 m.y.

Figure 9: A) BSE images of the leucosome (16TG-143-5) monazite with uranothorite inclusions and alteration to apatite on the edges. B) Yttrium electron microprobe x-ray map showing the compositional zoning and associate date for the leucosome layer monazite grains. C) Close up of alteration texture including uranothorite and apatite alteration textures D) Calcium x ray map showing apatite alteration on monazite edge

Figure 10: Monazite date results from the leucosome layer. Purple histograms are the low-Y domains, blue histograms are the high-Y domains, and red histograms are the rim domains. There are no monazite grains older than 1067 Ma.

5.5 Leucosome and Restite Monazite Composition Comparison

Figure 11 shows the comparison of Y, HREE, U, Th, Ca, LREEs in the restite and leucosome monazite grains. The leucosome does not have dates older than 1067 Ma. Compared to the restite, the leucosome has a higher content of Th and Ca, a lower content of LREEs, and a comparable content of Y, HREE and U at ca. 1050 Ma.

Figure 11: Comparison of the restite and leucosome monazite compositions for Y, HREE, U, LREE, Th and Ca against calculated date.

5.6 In-situ Restite Zircon Results

Zircon textures in cathodoluminescence (CL) are commonly indicative of the environment from which the grain grew (Pidgeon et al., 2000; Hermann and Rubatto, 2003; Rubatto et al., 2009; Rubatto, 2017), and therefore provide a basis to subdivide different populations. The zircon grains from the in-situ restite samples have three distinct textures in CL: 1) dark CL with oscillatory zoning; 2) fir-tree sector zoning texture (Raven and Dickson, 1989); 3) bright CL with no visible zoning (Figure 12a). Fir-tree sector zoning texture is characterized as sector zoning with a distinct zigzag boundary (Raven and Dickson, 1989). Dark CL and oscillatory zoning texture are typically present as small cores (~10-20 μm) within larger grains. Fir-tree sector zoning is a predominate population in the restite and commonly surrounds the CL dark cores. Fir-tree grains are typically round in shape with sizes ranging from ~30 to 60 μm . Bright CL texture is present primarily as rims, but also as large domains around cores. Bright CL domain ranges in size from ~2 to 60 μm . The three main textures were targeted for in-situ dating. Results are presented below (Figure 12b). See appendix B for a complete table of the results.

- 1) Dark CL, oscillatory cores yield $^{207}\text{Pb}/^{206}\text{Pb}$ dates of 1188 – 1135 Ma, with a weighted mean of 1162 ± 25 Ma (2σ , mean square of weighted deviates [MSWD]= 0.33, $n = 6$). The U/Th ratios range from 3.9 to 55.8 with a mean of 16.3. The U content ranges from 407 to 768 ppm with a mean of 575 ppm.
- 2) Fir-tree sector zoning textures yield $^{207}\text{Pb}/^{206}\text{Pb}$ dates of 1064 – 1019 Ma, with a weighted mean of 1049 ± 14 Ma (2σ , MSWD= 0.48, $n = 8$). The U/Th ratios range from 8.8 to 19.5 with a mean of 14.6. The U content ranges from 140 to 292 with a

mean of 187 ppm.

- 3) Bright CL textures yield $^{207}\text{Pb}/^{206}\text{Pb}$ dates of 1053 – 1011 Ma, with a weighted mean of 1037 ± 14 Ma (2σ , MSWD= 1.7, $n = 9$). The U/Th ratios range from 9.3 to 203.0 with a mean of 61.3. The U content ranges from 143 to 468 with a mean of 231 ppm.

Figure 12: In-situ zircon results from the restite. A) BSE and CL images of the in-situ restite zircon. The CL reveals three primary textures that were the target for dating: 1) oscillatory zoned cores 2) fir-tree sector zoning textures and 3) bright CL rims. B) Concordia diagram of the in-situ results. There are two populations at 1) 1162 ± 7 Ma and 2) 1051 ± 7 Ma

5.7 Separate Restite Zircon Results

The zircon separate was initially imaged with a low-resolution CL at the University of Arizona. Therefore, domains were dated without careful characterization of textures prior to dating. 300 analyses were placed in the center and edge of grains in an attempt to date the rims and cores of the grains. Zircon textures for the populations were imaged after dating using high-resolution CL at the University of Massachusetts. Zircon grains from the restite separate have two distinct textures in CL: 1) dark CL with oscillatory zoning and 2) fir-tree sector zoning texture (Raven and Dickson, 1989) Results are presented below (Figure 13a):

- 1) Dark CL, oscillatory zoned core yielded a population at 1206 ± 8 Ma (2σ , $n=6$). The dates range from 1286 to 1116 Ma. The U/Th ratio ranges from 3.4 – 24.9 with a mean of 12.6. The U content ranges from 239 to 345 ppm with a mean of 275 ppm.
- 2) Fir-tree texture zircon yielded a population at 1046 ± 2 Ma (2σ , $n=113$). The dates range from 1088 to 1018 Ma. The U/Th ratios range from 10.2 to 341.4 with a mean of 29.9. The U content ranges from 84 to 441 ppm with a mean of 147 ppm.

The dark CL with oscillatory zoning grains are commonly located in the center of larger grains. A majority (95%) of the zircon grains in the mineral separate have the fir-tree sector zoning texture (Rubatto, 2017) and are very large (~80-120 μm) in size (Figure 13b). The U vs. date for the in-situ and separate zircon data shows that the fir-tree sector zoning zircon crystallized from ca. 1070 to 1030 Ma with relatively low U (Figure 14).

Figure 13: Separate zircon results from the restite. A) The probability density plot shows one population at 1046 Ma. The two populations are 1) 1206 ± 8 Ma and 2) 1046 ± 2 Ma. B) CL images of the separate restite zircon. CL reveals that the 1046 ± 2 Ma grains have fir-tree sector zoning textures.

Figure 14: In-situ and separate restite zircon dates plotted against uranium. The highlighted area represents the zircons with the fir-tree sector zoning.

5.8 In-situ Leucosome Zircon Results

Zircon from the 3 cm leucosome layer were analyzed in a polished thin section and also as a separate. Thirty zircon grains in the polished thin section were imaged using high-resolution CL at the University of Massachusetts Amherst. Leucosome zircon grains have three distinct textures in CL: 1) oscillatory zoning; 2) soccer ball texture; 3) bright CL (Figure 15a). The most common texture is oscillatory zoning, present as the core of medium to large (20–80 μm) size grains. Only one grain displays a soccer ball texture, a texture suggested to indicate metamorphic growth (Hoskin and Schaltegger, 2003). The zircon rims typically have bright CL, but some also have dark CL rims. Many rim domains are too thin (2–10 μm) to date with laser ablation. The three different textures

were targeted for dating (Figure 15b).

- 1) Oscillatory zoned grains yielded $^{207}\text{Pb}/^{206}\text{Pb}$ dates of 1167 – 1110 Ma, with a weighted mean age of 1151 ± 27 Ma (2σ , MSWD= 1.2, $n = 5$). U/Th ratios range from 1.5 to 5.8 with a mean of 2.8. The uranium content ranges from 339 to 1009 with a mean of 612 ppm.
- 2) The soccer ball texture yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ date of 1031 ± 18 Ma. The U/Th ratio is 7.9. The U content is 217 ppm.
- 3) Bright CL domain yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ date of 1030 ± 22 Ma. The U/Th ratio is 49.1. The U content is 330 ppm.

Figure 15: Results from the in-situ leucosome zircon analysis. A) BSE and CL photos of representative zircon textures. The most common texture is an ca. 1150 Ma oscillatory zone grain with a thin CL bright rim. Soccer ball zoning is present in the ca. 1030 grain. B) Concordia diagram showing the two populations at 1151 $\pm$ 9 Ma and 1031 $\pm$ 14 Ma.

5.9 Leucosome Separate Zircon Results

The leucosome zircon separate was dated with 40 spot analyses. Cores and rims were targeted for dating. Zircon grains are very large (up to 300 μm). All analyzed grains were characterized after dating using high-resolution CL at the University of Massachusetts Amherst. Zircon grains from the leucosome separate have two distinct textures in CL: 1) dark CL cores with oscillatory zoning and 2) Rims with bright CL. Results are presented below (Figure 16a):

- 1) Dark CL with oscillatory zoning cores yielded a population at 1163 ± 6 Ma

$^{207}\text{Pb}/^{206}\text{Pb}$ (2σ , $n=12$). The dates range from 1202 – 1117 Ma. The U/Th ratio ranges from 2.0 – 6.0 with a mean of 2.8. The U content ranges from 471 to 1674 with a mean of 939 ppm.

- 2) Rims with bright CL yielded a population at 1050 ± 13 Ma $^{207}\text{Pb}/^{206}\text{Pb}$ (2σ , $n=2$).

The two dates are 1050 Ma. The U/Th ratios are 7.7 and 8.1. The U is 452 ppm for the two dates. Many rims were too small to date, but a few rims were as large as 20 μm (Figure 16b).

Figure 16: Results from the leucosome separate zircon analysis. A) Population density plot with two major populations at 1162 ± 6 Ma and 1050 ± 13 Ma. B) CL image of a representative grain from the separate. The grain has a large, 1165 Ma core with a 20 μm 1050 Ma rim.

5.10 Restite and Leucosome Zircon Comparison

Th/U vs. calculated date for the restite and leucosome zircon grains are plotted to observe zircon heterogeneities between the layers (Figure 17). Leucosome zircon grains constitute a majority of the older, ca. 1150 Ma population and commonly have a Th/U above 0.1. Restite zircon grains make up most of the younger, ca. 1050 Ma, population and commonly have a Th/U below 0.1. Many grains in the ca. 1150 population have oscillatory zoning, while grains in the younger (ca. 1050) population typically display fir-tree sector zoning.

Figure 17: Th/U vs. Date for the leucosome and restite zircon grains from both in-situ and separate analyses. The leucosome grains are primarily ca. 1150 Ma in age with a Th/U above 0.1 while the restite grains are primarily ca. 1050 Ma in age with a Th/U below 0.1.

5.11 Thin Section Scale Compositional Comparison

Distinct compositional (gneissic) layers in the restite have distinctive mineral assemblages and monazite characteristics. We compared the compositional layers restitic thin-section 16TG-143-1. The discrete layers have either predominately K-feldspar-rich or a plagioclase-rich matrix (Figure 18a). The K-feldspar-rich layer is characterized as having small, euhedral garnet, little or no sillimanite or biotite, and little or no monazite (Figure 18b). The plagioclase-rich layer has abundant, large, anhedral garnet, biotite, sillimanite and abundant monazite grains (Figure 18c). Biotite is present around garnet in the plagioclase-rich layer (Figure 18c). The monazite grains from each layer were compared to see if there are differences between the layers.

Figure 19 shows the comparison of Y, HREE, LREE, U, Ca, Th content in the monazite from the K-feldspar-rich and plagioclase-rich layer. In general, the monazite in the K-feldspar-rich layer has higher Y, U, HREE, lower LREE, and comparable Ca and Th.

Figure 18: A) Magnesium and potassium x-ray maps of 16-TG-143-1 with lines delineating the layers in the thin section that are inferred to have retained melt (plagioclase-rich) and lost melt (K-feldspar-rich). B) BSE image of garnet and Y maps of monazite in the K-feldspar-rich layer. Note: Monazite grain 16TG-143-m43 was not yet mapped. C) Garnet and Y maps of monazite in the plagioclase-rich layer

Figure 19: Comparison of monazite composition vs date between the K-feldspar and plagioclase-rich layers.

CHAPTER 6

DISCUSSION

The (1190-1140 Ma) Shawinigan orogeny and the (1080-1020 Ma) Ottawa orogeny may have both contributed to widespread melting in the Adirondack Mountains (Rivers, 2008; McLelland et al., 2013; Chiarenzelli et al., 2017). One challenge in delineating the timing of melting in the Adirondack Mountains is that both events have been interpreted to have involved granulite facies metamorphism and partial melting (Heumann et al., 2006; Bickford et al., 2008; McLelland et al., 2013). Some studies suggest that melting occurred during the Shawinigan/AMCG event (ca. 1150 Ma) (Heumann et al. 2006; Williams et al., in review), whereas others suggest further melting in the Ottawa event (ca. 1050 Ma) (Bickford et al., 2008). In this study, samples were collected from a single outcrop located along Rt. 22 south of Whitehall, NY. Layering in the outcrop is typical of the compositional variation seen in the migmatites of the Adirondack Mountains (Williams et al., in review). The following discussion integrates both in-situ zircon and monazite geochronology to understand the variation in the record of melting in a single outcrop in order to better understand the variation in the Adirondack Mountains in general.

6.1 Timing of Melting

Monazite domains from the restite yielded dates in six populations, including two major populations near ca. 1150 and ca. 1050 Ma (Figure 20). The two major monazite populations correlate with the interpreted regional tectonic melt events. However, monazite dates alone do not sufficiently provide a basis for delineating tectonic

interpretations, and therefore additional data from trace elements is necessary to constrain the timing of melting.

Previous studies suggest that the significant melting in the Adirondack Mountains occurred due to biotite dehydration-melting (Williams et al., in review). Additional melt reactions, such as muscovite dehydration-melting, may have occurred at lower temperatures (Williams et al., in review). The samples collected from Rt. 22 are indicative of melting from a biotite dehydration reaction based on the lack of peak biotite and plagioclase and the abundance of garnet and K-feldspar (Storm and Spear, 2005; Yakumchuk and Brown, 2014; Williams et al., in review). Generally, biotite dehydration-reactions have the form:

Yttrium zoning in monazite has been linked to the timing of garnet growth when no other Y-bearing assemblages are present (Zhu & O’Nions, 1999; Foster et al., 2002, 2004; Pyle & Spear, 2003; Gibson et al., 2004; Kohn et al., 2005; Kelly et al., 2006; Dumond et al., 2015; Williams et al., in review). Garnet readily incorporates Y + HREE, and thus monazite is expected to become depleted in Y + HREE when it crystallizes during or after garnet growth (Dumond et al., 2015; Williams et al., 2017; Williams et al., in review). Similarly, U zoning in has been linked to melt loss from the system. During partial melting, U is partitioned from the whole rock into melt, and thus removal of melt decreases the concentration of U in monazite (Stephanov et al., 2012). Variation in trace elements within monazite domains may indicate the timing of growth of garnet and melt loss at Rt. 22.

Restite monazite grains have two major Y compositional domains: high-Y and low-Y. The (ca. 1050) low-Y monazite domains are depleted in Y + HREE and, to a lesser extent, U relative to the (ca. 1150 Ma) high-Y domains. The depletion of Y + HREE suggests that garnet grew prior to monazite crystallization, because monazite and garnet are the only Y + HREE bearing phases in the assemblage. Y + HREE drop in two steps (Figure 8 b,c), suggesting that garnet grew in two steps: 1) growth between ca. 1150 and 1065 Ma and 2) further growth between 1065 and 1050 Ma. The absence of low-Y monazite as inclusions in garnet supports a post-garnet interpretation for monazite precipitation between ca. 1150 and ca. 1065 Ma; however, it difficult to interpret exactly when the garnet grew within the ~85 m.y. window. U drops slightly between ca. 1150 and ca. 1065, suggesting that some melt may have been lost from the system prior to ca. 1065 Ma.

Evidence for biotite dehydration-melting near ca. 1065 Ma is bolstered by the zircon results from restite layers. Zircon analyses from the restite separate display a unimodal population at 1046 ± 2 Ma with dates ranging from 1070 to 1020 Ma. The entire population is characterized by fir-tree sector zoning textures that have been suggested to be indicative of partial melting (Bickford et al., 2008; Rubatto, 2017). The fir-tree texture data suggests a melt event beginning at ca. 1070 Ma. U is also depleted in the ca. 1050 zircon grains, supporting some melt loss prior to ca. 1070 Ma. If significant melting occurred during the Shawinigan orogeny, we expect to find older, preserved fir-tree sector zoning zircon based on the robustness of zircon in melt (Kelsey et al., 2008), however we do not find any Shawinigan age zircon grains with fir-tree texture. While it is possible that the rock underwent some earlier melting, we suggest that the rock

underwent biotite dehydration-melting at ca. 1070 Ma during the Ottawa orogeny based on monazite and zircon geochronology, geochemistry, and zircon cathodoluminescence textures.

Figure 20: Restite monazite results with the interpreted tectonic event.

6.2 Timing of Leucosome Production

Monazite and zircon were also analyzed from a 3 cm leucosome layer in the rock. The results from the monazite grains show populations at ca. 1050, but no populations at ca. 1150 Ma, as in the restite. However, zircon data from the leucosome show a significant population from the cores at ca. 1150 Ma, with smaller populations from the rims at ca. 1050 Ma. The contradictory geochronology results from the monazite grains

(ca. 1050) and zircon cores (ca. 1150 Ma) in the leucosome layer, creates a fundamental challenge for interpreting the timing of leucosome production (Figure 21).

There are two alternative hypotheses, either the leucosome crystallized at ca. 1150, based on the zircon cores, or at ca. 1050, based on the monazite grains and zircon rims. An additional consideration is whether the leucosome layer originated in the rock or represents a foreign injection. One possibility is that the leucosome was produced in-situ at 1065 Ma, consistent with the hypothesized timing of melting from the restite data. Therefore, the monazite dates may represent the timing of leucosome crystallization. The zircon cores may have been inherited from the local rock during the melting, and the zircon rims may represent either the timing of melt crystallization or a subsequent alteration at ca. 1050 Ma. The primary concern with this hypothesis is that there is no fir-tree sector zoning zircon in the leucosome layer. Fir-tree zircon is expected to be inherited in the leucosome at ca. 1065 Ma due to the abundant number of fir-tree grains in the restite. There is evidence for one soccer ball texture zircon at ca. 1030 Ma, a texture that may represent metamorphic zircon (Hoskin and Schaltegger, 2003). Alternatively, the leucosome may have originated outside of the rock at ca. 1065 Ma, thus inheriting ca. 1150 Ma zircon grains from another source.

The second possibility is that the leucosome was produced at ca. 1150 due to an in-situ melt reaction, such as muscovite dehydration-melting. Th/U less than 0.1 in zircon can be indicative of metamorphic formation while a Th/U greater than 0.1 may represent magmatic formation (Rubatto, 2017). Therefore, magmatic Th/U signature in the leucosome zircon cores may suggest leucosome crystallization at ca. 1150 Ma. The primary concern with this hypothesis is the monazite grains and zircon rims with ca. 1050

Ma dates. In this hypothesis, monazite grains and zircon rims may represent either remelting of the leucosome or a period of alteration and resetting of the U-Pb system associated with events at ca. 1065 Ma and younger (Nasdala et. al., 2002; Williams et al., 2011). Alternatively, it is also possible that the layer originated from outside the rock at ca. 1150 Ma. However, understanding the ca. 1050 Ma age of the monazite grains still poses a challenge when interpreting leucosome production at ca. 1150 Ma

A close examination of the leucosome monazite textures reveals intense alteration of the grains. Nearly all of the monazite grains in the leucosome are partly altered to apatite and uranothorite along the edge of the grain. Yttrium compositional x-ray maps show that the texture of the leucosome monazite domains are irregular and heterogeneous, suggesting that the entire grain may have underwent a degree of alteration (Figure 9b). Y is also significantly enriched in certain domains of the monazite grain, but the high-Y domain does not correspond to an older date, as in the restite grains. Similarly, rims surrounding the leucosome zircon grains have an irregular border and the cloudy texture in cathodoluminescence (Rubatto, 2017) (Figure 16b). Fluid alteration in both zircon and monazite has been characterized by partial or full resetting of the U-Pb system, formation of uranothorite inclusions, and production of rims (Nasdala et. al., 2002; Geisler et al., 2007; Valley et al., 2011; Williams et al., 2011; Tyson McKinney et al., 2015). Therefore, the monazite grains and zircon rims may represent the timing of fluid alteration, and not melt crystallization.

The leucosome geochronometers have clear evidence for fluid alteration, however there is minimal evidence for alteration to the restite geochronometers (Figure 21). Na and K-rich fluids are suggested to be extremely effective at altering monazite and zircon

(Valley et al., 2011; Williams et al., 2011). One possibility is that fluids reacted with the leucosome to release Na or K that increased the alteration strength of the fluids to preferentially alter the leucosome layer. Alternatively, radiation damage due to the decay of actinides, such as U and Th, can make a grain more susceptible to alteration as the damage provides a pathway for fluids in the grain (Nasdala et. al., 2002; Karioris et al., 1981; Seydoux-Guillaume et al., 2012). It is possible that the monazite from 1150 Ma accumulated ~85 m.y. of radiation damage after crystallization, and thus the grains were more prone to alteration at 1050 Ma compared to the newly crystallized restite monazite grains. It is important to note that monazite is rarely present as metamict in nature (Karioris et al., 1981; Seydoux-Guillaume et al., 2012), and thus further research is necessary to understand if these monazite grains accumulated substantial radiation damage. We suggest that the geochronology data suggests that this particular leucosome could have been produced at ca. 1150 or ca. 1065 due to either in-situ melting or inheritance from outside the rock, however alteration processes to the geochronometers must be better understood in order to make a more robust interpretation.

RESTITE

Zircon

ca. 1050 Ma

LEUCOSOME

Zircon

Figure 21: Comparison of the restite and leucosome monazite and zircon grains with associated dates.

6.3 Retrograde Metamorphism, Decompression, and Fluid Influx

Monazite grains examined in this study show evidence for retrograde metamorphism starting at approximately 1050 Ma. Monazite rim domains from the restite and leucosome are characterized by a distinct Y + HREE enrichment (Figure 6). This marked enrichment observed in the rim domain is most consistent with incorporation of Y + HREE due to garnet break down (Dumond et al., 2015; Williams et al., in review). In addition, the monazite rims are characterized by Th depletion after 1050 Ma. Fluids, and specifically a dissolution-reprecipitation mechanism, have been shown to effectively remove Th from monazite (Williams et al., 2011). High-Y+HREE and low-Th in the rim domain may represent a period of garnet break down and flux influx after ca. 1050.

Data from zircon rims provide additional support for fluid influx after ca. 1050 Ma. Zircon in the leucosome and restite have bright CL rim domains marked with depleted U and 1053 – 1011 Ma dates. Previous workers have demonstrated that bright CL domains in zircon may reflect a depletion of trace elements due to fluids rich in chlorine, fluorine or CO₂ (Pidgeon et al., 2000; Bickford et al., 2008; Valley et al., 2011), bolstering an interpretation for fluid alteration after 1050 Ma. In addition, Pidgeon et al., 2000 suggests that solid state zircon with fir-tree sector zoning can grow in the presence of fluids containing low concentrations of fluorine. One hypothesis is that zircon grains with fir-tree sector zoning were produced due to both anatexis and metamorphic fluid alteration (Pidgeon et al., 2000; Bickford et al., 2008; Rubatto, 2017). Further work to understand the reactions that form zircon with fir-tree texture is needed to clarify this interpretation. In this study, we suggest that zircon rims and fir-tree sector zoning suggest fluid influx from ca. 1050 Ma to ca. 1011 Ma.

Evidence from the monazite and zircon rims have evidence for retrograde metamorphism and fluid influx after ca. 1050 Ma. Garnet breakdown was most likely driven by decompression and cooling, and thus the monazite rims may mark the timing of post-orogenic collapse (Williams et al., in review). Wong et al., 2012 previously interpreted the Rt. 22 outcrop to occur within the East Adirondack shear zone. Evidence for syntectonic monazite growth is present as symmetrical, elongated growth in the lineation-parallel ends of the grains found in the matrix (Wong et al., 2012). Fluid influx was likely associated with shearing (Wong et al., 2012). The rim domain is interpreted to represent decompression associated with post-orogenic collapse, shearing and fluid influx after ca. 1050 Ma. A summary timeline is presented in Figure 22.

Figure 22: Schematic showing the interpreted timeline of melting, garnet growth, monazite growth, and zircon crystallization based on the data from the restite layers. High-Y monazite crystallized at ca. 1150 Ma. There may have been some melt due to muscovite dehydration-melting at ca. 1150 Ma. The 2.5 cm leucosome layer may have been produced at 1150 Ma. At ca. 1090 Ma, biotite dehydration-melting produces melt + garnet. The garnet grows around pre-existing high-Y monazite grains, and the melt dissolves the matrix monazite grains. Some melt is lost from the system by ca. 1070 Ma. Zircon fir-tree and low-Y monazite crystallization occurs from ca. 1070 to 1050 Ma. At 1030 Ma, rims on the monazite and zircon grains begin to crystallize due to decompression and fluid influx during post-orogenic collapse.

6.4 Evidence for Heterogeneous Melting

Mineral assemblages from restite thin section 16TG-143-1 show differences along foliation-parallel layers. Some layers are predominately K-feldspar-rich while other layers are plagioclase-rich (Figure 18). There are several possible explanations for the differences. One possibility is that a layer that was initially biotite poor, and thus produced less melt and therefore less K-feldspar (Williams et al., in review). Another possibility is that reversal of Reaction-1 during melt crystallization may have produced the biotite in the plagioclase-rich layer. The presence of biotite around garnet and anhedral garnet is further evidence for reversal of Reaction-1, as garnet would be consumed in the reaction to produce biotite. If so, the evidence may suggest that layers record differences in retention of melt. A recent study suggests that the eastern Adirondack Mountains underwent heterogeneous partial melting (i.e., some layers crystallized melt while other layers lost melt) based on the rock mineral assemblages and monazite composition (Williams et al., in review). Differences in mineral assemblages in thin section 16-TG-143-1 may suggest that different amounts of melting or melt loss occurred within the rock.

In addition to differences in the major mineral phases, monazite trace elements in the two assemblages (plagioclase-rich and K-feldspar-rich) have distinctive compositions (Figure 17). Monazite in the K-feldspar-rich layer have enriched Y + HREE. Garnet is less abundant in this layer, thus there may have been more Y + HREE available to monazite. LREE are depleted in monazite from the K-feldspar layer. During monazite dissolution, LREE are enriched in melt and thus if melt is lost, LREE are also removed – reducing fertility for monazite crystallization (Kelsey et. al., 2008). The fewer monazite

grains and lower abundance of LREE in the K-feldspar layer is consistent with melt loss, or alternatively, relatively less melting. We suggest that the plagioclase-rich layers likely retained melt, thus LREE, and were more fertile for monazite crystallization. The variable major phase and monazite composition in the layers may be evidence for heterogeneous melting or melt loss.

6.5 Overview of the Metamorphic and Deformational History

Recent workers have concluded that the Adirondack Mountains experienced at least two periods of melting, one at the ca. 1150 Ma Shawinigan/AMCG event and another at the ca. 1050 Ma Ottawan event (Heumann et al., 2006; Bickford et al., 2008; McLelland et al., 2013; Williams et al., in review). The low Y + HREE monazite population and the fir-tree texture zircon population from the restite samples supports the argument for melting at ca. 1050 Ma, during the proposed timing of the Ottawan event (McLelland et al., 2013).

A recent study from a location west of Lake George shows that Y + HREE in the 1150 Ma population significantly decreases (Y: ~7500 to 2000 ppm) between 1170 to 1150 Ma that is interpreted to be a result of garnet growth (Williams et al., in review). The Lake George samples are interpreted to have undergone biotite dehydration-melting during the Shawinigan/AMCG event with local melting during the Ottawan event. The Lake George and Rt. 22 data combined provides evidence for two melting events in the Adirondack Mountains. However, the two melt events are not equally preserved in the migmatite record. Bohlen et al., 1985 suggested that there is a ‘bullseye’ shape temperature gradient in the Adirondack Highlands with the highest temperatures near the AMCG intrusions. One explanation for the lack of significant Shawinigan melting at Rt.

22 is that the rocks may have been located away from the high temperatures associated with the major AMCG intrusions. Still, the polymetamorphism in the region makes it difficult to discern if the ‘bullseye’ shape is accurate representation of the temperature gradient. Another hypothesis is that initial bulk composition played a role in determining the degree of melting in each event. At Lake George, biotite may have been consumed during a complete progression of Reaction-1 in the Shawinigan event, and therefore the rock was unfertile for further melting in the Ottawa event (Williams et al., in review). Further work is needed to understand the distribution and geometry of melting events throughout the entire Adirondack Mountains.

6.6 Limitations of Zircon and Monazite Geochronology

The petrochronological record from migmatites in the Adirondack Mountains provide meaningful insight into the tectonic history of the region, however there are limitations when interpreting tectonic histories – especially melt histories. One limitation is that monazite is soluble in melt, and thus periods of monazite growth may be erased or reset from the record (Kelsey et al., 2008). In our study, monazite was effectively preserved as inclusions in garnet, and therefore we do not believe that any populations were erased in the restite. However, it is likely that monazite was dissolved or reset, or both, in the leucosome layer based on the textures. Examining both the monazite date and associated trace element composition is essential to determine the timing of melting and garnet growth (Dumond et al., 2015; Williams et al., 2017; Williams et al., in review).

Zircon is more robust in melt (Kelsey et al., 2008), but zircon crystallization is more difficult to relate to melt reactions because trace element abundance is low and difficult to analyze via non-destructive techniques, such as electron microprobe analysis.

Many zircon grains in this study are small (20 μm), thus dating via LA-ICPMS destroys nearly the whole grain. Recent studies suggest that REE partitioning in zircon is an effective indicator of garnet growth in partially melted rocks (Taylor et al., 2015). Further exploratory work using the new Cameca SX-5 at the University of Massachusetts Amherst is underway to analyze trace elements in zircon. Further, Th/U ratios may not always be indicative of the source, suggesting that the ratio may not always accurately distinguish metamorphic from igneous zircon (Rubatto, 2017). More work using zircon as an indicator of melting is needed to complement the timing of melting from monazite.

A period of intense fluid alteration adds complexity when interpreting dates from monazite and zircon. Hydrothermal fluids have been known to be extremely destructive and may completely alter the U/Pb system in geochronometers (Pidgeon et al., 2000; Nasdala et al., 2002; Williams et al., 2011). Some dates from zircon and monazite in the leucosome are suspected to reflect a period fluid alteration, evidenced by the alteration of monazite to apatite, uranothorite inclusions, and zircon rims depleted in U. Careful attention is needed with minerals suspected of hydrothermal fluid alteration as the dates may record a period of fluid alteration and not a period of crystallization.

CHAPTER 7

CONCLUSIONS

A single roadcut near Whitehall, NY shows evidence for monazite and zircon growth at ca. 1150 and ca. 1050 Ma, however compositional and geochronological evidence strongly suggests that significant melting occurred at ca. 1050 Ma. Garnet growth and melt loss occurred prior to ca. 1065 Ma as suggested by a decrease in Y + HREE + U in monazite and zircon grains. Zircon fir-tree sector zoning suggests melting beginning at ca. 1070. Rim domains enriched with Y + HREE and depleted in Th are indicative of retrograde metamorphism after ca. 1050 Ma and likely signify decompression and post-orogenic collapse. The elongated shape of the restite monazite rim domains may indicate syndeformational monazite growth during shearing associated with the collapse phase.

An important conclusion from this study is that it is difficult to relate a leucosome layer to the host rock. The timing of leucosome production is difficult to interpret due to the contradictory date results from the ca. 1150 Ma zircon cores and ca. 1050 Ma monazite grains. In addition, both monazite and zircon have evidence for fluid alteration around 1050 Ma. The leucosome may have been produced at ca. 1150 Ma, based on the dates and the magmatic Th/U signature of the zircon cores. Alternatively, the leucosome may have been produced at ca. 1065 Ma melt based on the dates from monazite grains and zircon rims. It is also possible that the leucosome was injected from outside of the rock at either time. The study highlights the importance of separating layers in a migmatite in order to accurately determine the timing of melt and melt production.

Plagioclase-rich and K-feldspar-rich layers within the metapelitic gneisses have

differences in major phases and monazite composition. Evidence from the K-feldspar-rich layers suggest melt removal or less melting. Plagioclase-rich layers are interpreted to represent layers with melt retention and melt crystallization. Melt loss likely inhibits monazite crystallization as suggested by the low abundance of monazite in K-feldspar-rich layers. A large-scale study comparing monazite grains within melt-rich and melt-poor layers is needed to better understand monazite crystallization during melting, melt loss and melt crystallization.

Timing of melting in polymetamorphic rocks is difficult to delineate based on geochronology alone. Migmatites in the eastern Adirondack Mountains have evidence for both ca. 1150 and ca. 1050 Ma melt events, however a careful examination of additional outcrops may provide further evidence for the full tectonic history in the region. Textural and geochemical data from monazite and zircon in combination with geochronology from all layers of a migmatite is essential for constraining the timing of metamorphism, deformation, and especially anatexis.

APPENDIX A

MONAZITE DATA

Contact Kaitlyn Suarez at kaitlynsuarez93@gmail.com or Professor Michael Williams at mlw@geo.umass.edu for excel spreadsheet files of monazite data.

Table 1: Restite Monazite Analyses

Analysis	Date	unc	sigma	Y	Th	U	Ca	HREE	LREE
	(Ma)			(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
48 2018-9-28-16-TG-143-1-m03-purple-core	1069	4.1	1	2158	31581	1413	13135	3306	544459
49 2018-9-28-16-TG-143-1-m24-upper-left-orange	1039	9.3	1	3455	32066	2614	7355	6254	548390
50 2018-9-28-16-TG-143-1-m04-high-Y-core	1148	7.4	1	17134	32540	782	6062	10320	524389
51 2018-9-28-16-TG-143-1-m04-outer-core-purple	1059	3.9	1	1224	31219	961	14054	2503	548149
52 2018-9-28-16-TG-143-1-m04-outer-core-red-left	1057	3.3	1	2264	35337	961	12612	3838	540178
53 2018-9-28-16-TG-143-1-m04-rim	1020	3	1	4056	26081	4065	7003	6150	544468
54 2018-9-28-16-TG-143-1-m14-core-purple	1031	6.4	1	1168	34432	957	14549	1477	543815
55 2018-9-28-16-TG-143-1-m15-core-purple	1059	6.2	1	1371	35294	1026	14458	2080	544742
56 2018-9-28-16-TG-143-1-m26-high-Y	1177	14.3	1	13334	19678	4074	4182	12229	539640
59 2018-9-30-16-TG-143-1-m17-purple-center	1065	23.9	1	2293	29993	1546	10604	4165	531920
60 2018-9-30-16-TG-143-1-m13-purple-center	1058	4.6	1	1218	32890	1031	13681	2461	547012
61 2018-9-30-16-TG-143-1-m13-red-right	1048	5.5	1	2189	30767	3021	6565	3202	553618
62 2018-9-30-16-TG-143-1-m39-purple-center	1038	12.8	1	1187	30143	1609	11910	1271	543736
63 2018-9-30-16-TG-143-1-m25-high-Y-core	1166	23	1	13410	21967	2941	4137	10339	532323
64 2018-9-30-16-TG-143-1-m25-purple-upper	1079	9.2	1	1497	25401	1051	9103	2525	556900
13 ADK-16TG-143-1-m1-rightside-purple	1062	5.6	1	1049	32886	980	14765	2023	538349
14 ADK-16TG-143-1-m2-leftside-purple	1057	5.6	1	1779	36377	1077	14141	2393	539352
15 ADK-16TG-143-1-m5-bright-orange-right	1056	9.1	1	7805	31545	2037	12735	6382	531157

17	ADK-16TG-143-1-m40-purple-upper-left	1073	10.8	1	1204	31112	860	13718	1866	549320
18	ADK-16TG-143-1-m38-purple-lowCa-core	1056	6.9	1	2004	26727	2603	6897	2776	557346
22	ADK-16TG-143-1-m40-rim	999	4	1	4672	24853	3519	6644	6865	533834
23	ADK-16TG-143-1-m32-bright-center-core	1165	15.5	1	15421	26196	3626	4479	11334	519413
24	ADK-16TG-143-1-m38-red-highCa-upperleft	1055	3.8	1	1230	30747	995	13124	1984	542722
25	ADK-16TG-143-1-m15-rim-bottom	1011	6.6	1	5619	20812	3893	6063	6359	541043
26	ADK-16TG-143-1-m35-purple-center	1042	4	1	1135	28952	936	13504	1292	539326
28	ADK-16TG-143-1-m28-bright-center-core	1155	13.6	1	15348	22167	3894	4696	10225	521137
30	ADK-16TG-143-1-m20-bright-core-yellow	1056	13.8	1	2094	25258	1136	7908	2018	548217
31	ADK-16TG-143-1-m20-midTh-rim	1008	4.1	1	4240	10704	4757	4610	6139	556170
32	ADK-16TG-143-1-m20-dark-orangeTh-core	1034	10.9	1	2721	13473	3623	4721	3855	562697
34	ADK-16TG-143-1-m43-core	1050	6.1	1	3512	31154	1822	13172	5201	533261
35	ADK-16TG-143-1-m43-rim	978	11	1	3824	28330	2415	9093	5985	529325
36	ADK-16TG-143-1-m19-center-orange	1065	10	1	3305	30850	1360	12577	3941	531152
74	2018-10-4-16-TG-143-1-m10-high-Y-center	1145	15.3	1	15484	26334	3143	6394	12087	534589
75	2018-10-4-16-TG-143-1-m10-purple-center	1055	5	1	1282	29953	1240	9712	2086	556626
76	2018-10-4-16-TG-143-1-m10-orange-rim	1040	6	1	3066	24399	4365	6403	5281	558268
77	2018-10-4-16-TG-143-1-m06-purple-center	1035	3.2	1	1288	29694	944	12225	1467	551417
78	2018-10-4-16-TG-143-1-m36-purple-center	1033	10.3	1	1093	30375	848	14110	1443	550215
79	2018-10-4-16-TG-143-1-m37-purple-center	1038	7.7	1	1047	31177	850	13840	1555	552974
4	2017-05-27-16TG144-1-m2-core	1041	8.2	1	1449	37804	1046	15041	1560	525822
5	2017-05-27-16TG144-1-m2-up-right-rim	1012	5.4	1	8577	28090	10036	8941	9072	505029
6	2017-05-27-16TG144-1-m3-core	1037	4.2	1	2440	33843	2523	12582	3876	530377
7	2017-05-27-16TG144-1-m3-up-rim	1028	3.3	1	6937	30967	10474	10055	7915	512146
10	2017-05-27-16TG144-1-m9-left-in-rim	1051	6	1	2610	34453	2939	13067	4373	529744
14	2017-05-27-16TG144-1-m13-low-right	1062	9.5	1	19363	29839	4165	7829	13395	497464
15	2017-05-27-16TG144-1-m13-core-left	1145	4.6	1	22494	29737	6387	5951	15479	500556

16	2017-05-27-16TG144-1-m6-core	1043	4.7	1	1188	42757	1659	16171	2264	527986
17	2017-05-27-16TG144-1-m6-low-rim	1024	3.1	1	5121	34700	8081	10083	5607	521753
90	2018-10-08-16Tg144-1-m17-core-right	1167	7.4	1	17666	11147	9114	4323	15198	515383
91	2018-10-08-16Tg144-1-m17-center-left	1054	3.4	1	5230	28731	13384	11549	6969	509244
92	2018-10-08-16Tg144-1-m8-core	1170	5.8	1	14195	19635	5647	4099	13135	522157
93	2018-10-08-16Tg144-1-m4-core	1032	6	1	1417	34638	1123	15466	1355	534180
94	2018-10-08-16Tg144-1-m4-upper-high-Y	1054	2.5	1	6392	32151	8869	9773	7633	512303
95	2018-10-08-16Tg144-1-m1-core	1029	5.9	1	1410	35089	820	14989	1629	534641
96	2018-10-08-16Tg144-1-m1-up-right-rim	1053	8.8	1	7422	29924	9392	10527	8049	513751
97	2018-10-08-16Tg144-1-m12-core	1065	4.8	1	2126	32924	1956	13018	6048	535296
98	2018-10-08-16Tg144-1-m9-core-re	1221	3.7	1	14703	32608	4437	6164	13934	515701
12	ADK-16TG-143-2-m5-purple-center	1080	4.7	1	1062	34080	1285	13267	1628	533421
13	ADK-16TG-143-2-m6-orange-rim-Y	1079	3.5	1	2455	20551	5393	5674	4181	543987
14	ADK-16TG-143-2-m17-bright-yellow-Y	1180	7.5	1	14501	24196	4920	4398	13364	515558
15	ADK-16TG-143-2-m17-upper-left-orange-Y	1040	3.6	1	2962	27376	2135	10245	4566	539778
16	ADK-16TG-143-2-m20-center-purple-Y	1044	6.4	1	1133	41356	1522	14815	2052	530212
17	ADK-16TG-143-2-m22-center-purple-Y	1047	3.1	1	1045	43791	1388	15987	2490	523324
18	ADK-16TG-143-2-m25-bot-right-Y	1063	4.6	1	2057	26980	3779	7096	2310	543441
21	ADK-16TG-143-2_m20-rim-orange-Y	1047	5.5	1	3022	28165	4874	6873	3495	534837
22	ADK-16TG-143-2_m24-center-bright-yellow-Y	1147	10.5	1	20033	34805	2114	6859	11451	503123
23	ADK-16TG-143-2_m31-center-bright-yellow-Y	1169	6.6	1	22993	33849	1129	6593	11933	498837
80	2018-10-4-16-TG-143-2-m26-right-red	1083	8.4	1	2285	30809	1159	11226	2032	549410
81	2018-10-4-16-TG-143-2-m13-center-purple	1046	8.4	1	1045	39071	1039	14785	1571	543071
82	2018-10-4-16-TG-143-2-m16-center-purple	1012	2.7	1	1263	38221	1499	14432	712	531942
83	2018-10-4-16-TG-143-2-m19-right-purple	1051	5.5	1	1817	31700	3317	7415	2576	558427
84	2018-10-4-16-TG-143-2-m28-center-purple	1042	8	1	935	34942	965	14765	646	541960
85	2018-10-4-16-TG-143-2-m29-right-purple	1035	5.8	1	896	33790	794	14311	827	540943

Table 2: Leucosome Monazite Analyses

Analysis	Date	unc	sigma	Y	Th	U	Ca	HREE	LREE
	(Ma)			(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
3 ADK-16TG-143-5-m7-upper-core	1057	3.6	1	4163	51126	3116	16623	3830	508184
4 ADK-16TG-143-5-m7-lower-core	1057	8.1	1	2385	79678	2078	20204	3347	483593
5 ADK-16TG-143-5-m6-upper	1061	2.1	1	4996	97023	1169	20434	2160	455478
6 ADK-16TG-143-5-m2-upper	1067	3.5	1	4365	84378	2141	20141	3333	470414
7 ADK-16TG-143-5-m2-bottom	1066	2.2	1	7381	80895	3571	19535	5649	467912
8 ADK-16TG-143-5-m12-core-bottom	1067	11.8	1	3090	87008	2347	20506	1146	467549
10 adk-16tg-143-5-M6-high-Y-core	1048	8.9	1	15526	85386	2046	21232	7643	449139
11 adk-16tg-143-5-M12-high-Y-core	1062	8.5	1	15585	77699	4774	17033	8671	465295
12 adk-16tg-143-5-M07-right-edge	1030	16.3	1	6006	63094	2972	11809	4737	501624
37 ADK-16TG-143-5-m13-highU-right	1049	3.5	1	5342	69368	6013	13680	4279	485442

APPENDIX B

ZIRCON DATA

Table 3: Restite Zircon U/Pb Analyses

Analysis	U	Th	206Pb	Th/U	206Pb	±	Conc	Texture
	(ppm)	(ppm)	204Pb		207Pb	(Ma)	(%)	
In-situ Analysis								
16TG143-2_thin_section-SAMPLE 1 Spot 1	190	163	12941	0.856	1011.0	26.3	100.3	Bright CL rim
16TG143-2_thin_section-SAMPLE 1 Spot 25	181	18	70792	0.099	1019.9	22.4	100.5	Fir-tree rim
Williams 16TG-143-1-TS june 9 2017-SAMPLE 1 Spot 16	143	15	129308	0.105	1027.5	21.6	99.8	Bright CL rim
16TG143-2_thin_section-SAMPLE 1 Spot 13	468	2	19625	0.004	1027.9	19.1	98.4	Bright CL rim
16TG143-2_thin_section-SAMPLE 1 Spot 27	224	12	70645	0.054	1032.2	23.0	99.4	Fir-tree
Williams 16TG-143-1-TS june 9 2017-SAMPLE 1 Spot 31	146	9	108319	0.062	1032.2	20.1	100.2	Bright CL rim
16TG143-2_thin_section-SAMPLE 1 Spot 34	384	2	22854	0.005	1039.8	21.6	98.4	Rim
16TG143-2_thin_section-SAMPLE 1 Spot 26	311	32	32820	0.103	1040.4	22.2	100.9	Bright CL core
Williams 16TG-143-1-TS june 9 2017-SAMPLE 1 Spot 34	122	11	13046	0.090	1048.7	20.7	98.4	Bright CL rim
16TG143-2_thin_section-SAMPLE 1 Spot 32	140	8	13094	0.057	1049.2	20.8	98.8	Fir-tree rim
Williams 16TG-143-1-TS june 9 2017-SAMPLE 1 Spot 4	151	7	15772	0.046	1050.0	27.5	98.0	Bright CL
16TG143-2_thin_section-SAMPLE 1 Spot 14	141	16	37249	0.113	1050.6	26.3	98.9	Bright CL Core
Williams 16TG-143-1-TS june 9 2017-SAMPLE 1 Spot 32	292	24	179460	0.082	1050.8	17.1	98.8	Fir-tree
16TG143-2_thin_section-SAMPLE 1 Spot 3	166	13	81581	0.078	1053.8	21.4	99.6	Bright CL Core
Williams 16TG-143-1-TS june 9 2017-SAMPLE 1 Spot 35	185	10	54470	0.054	1054.0	17.4	98.9	Fir-tree
16TG143-2_thin_section-SAMPLE 1 Spot 24	259	17	121460	0.066	1062.5	19.8	99.1	Bright CL Rim
Williams 16TG-143-1-TS june 9 2017-SAMPLE 1 Spot 25	141	12	77638	0.085	1064.3	21.5	95.1	Bright CL Core
Williams 16TG-143-1-TS june 9 2017-SAMPLE 1 Spot 15	191	10	38498	0.052	1065.8	23.4	98.5	Bright CL Core
Williams 16TG-143-1-TS june 9 2017-SAMPLE 1 Spot 19	377	15	31182	0.040	1096.1	30.0	95.1	Core

Williams 16TG-143-1-TS june 9 2017-SAMPLE 1 Spot 11	473	8	97238	0.017	1135.6	23.5	95.8	Core
Williams 16TG-143-1-TS june 9 2017-SAMPLE 1 Spot 29	768	42	1364473	0.055	1140.4	14.0	96.5	Core
Williams 16TG-143-1-TS june 9 2017-SAMPLE 1 Spot 18	407	48	67931	0.118	1149.1	21.8	97.1	Core
Williams 16TG-143-1-TS june 9 2017-SAMPLE 1 Spot 7	516	125	1687613	0.242	1173.3	19.3	97.5	Core
Williams 16TG-143-1-TS june 9 2017-SAMPLE 1 Spot 13	657	168	138077	0.256	1183.4	21.7	95.2	Core
Williams 16TG-143-1-TS june 9 2017-SAMPLE 1 Spot 27	627	87	178615	0.139	1188.4	15.2	95.2	Core
16TG143-2_thin_section-SAMPLE 1 Spot 16	493	227	41932	0.460	1292.0	19.5	98.7	Core

Separate Analysis

16TG-143-1-Spot 018	120	5	91677	0.042	1018.0	20.8	100.5	Fir-tree
16TG-143-1-Spot 232	162	9	13413	0.055	1019.3	22.7	99.6	Fir-tree
16TG-143-1-Spot 026	133	7	12819	0.053	1021.2	19.7	99.4	Fir-tree
16TG-143-1-Spot 043	157	8	45933	0.051	1021.6	21.3	100.5	Fir-tree
16TG-143-1-Spot 175	212	5	66085	0.024	1023.7	17.6	100.3	Fir-tree
16TG-143-1-Spot 188	118	6	32156	0.051	1024.6	26.0	100.1	Fir-tree
16TG-143-1-Spot 121	125	8	24603	0.064	1025.3	26.1	100.7	Fir-tree
16TG-143-1-Spot 025	139	9	26522	0.065	1025.7	20.8	99.4	Fir-tree
16TG-143-1-Spot 044	166	9	23281	0.054	1025.9	19.5	99.5	Fir-tree
16TG-143-1-Spot 165	120	5	25045	0.042	1026.2	25.4	100.8	Fir-tree
16TG-143-1-Spot 031	142	7	42568	0.049	1026.5	19.4	100.9	Fir-tree
16TG-143-1-Spot 227	151	10	10507	0.066	1026.7	27.2	99.8	Fir-tree
16TG-143-1-Spot 100	232	1	30348	0.004	1027.9	20.8	100.0	Fir-tree
16TG-143-1-Spot 186	106	7	20079	0.066	1028.4	26.7	100.9	Fir-tree
16TG-143-1-Spot 259	133	9	66118	0.068	1028.7	25.2	100.5	Fir-tree
16TG-143-1-Spot 046	276	4	65179	0.014	1029.8	15.3	100.4	Fir-tree
16TG-143-1-Spot 178	134	6	118985	0.045	1030.5	19.3	100.2	Fir-tree
16TG-143-1-Spot 124	147	7	48952	0.048	1030.6	21.9	99.8	Fir-tree
16TG-143-1-Spot 302	134	8	60270	0.060	1030.6	19.6	100.7	Fir-tree

16TG-143-1-Spot 184	357	4	64691	0.011	1030.9	17.4	100.1	Fir-tree
16TG-143-1-Spot 234	161	7	90533	0.043	1031.7	21.9	100.2	Fir-tree
16TG-143-1-Spot 182	126	7	30564	0.056	1032.2	20.9	100.6	Fir-tree
16TG-143-1-Spot 208	175	10	96941	0.057	1034.0	20.4	98.9	Fir-tree
16TG-143-1-Spot 210	122	6	36564	0.049	1034.9	21.7	99.6	Fir-tree
16TG-143-1-Spot 007	135	9	42180	0.067	1035.6	20.0	99.8	Fir-tree
16TG-143-1-Spot 290	217	6	36500	0.028	1036.3	17.6	100.2	Fir-tree
16TG-143-1-Spot 218	113	6	30569	0.053	1036.5	23.2	100.6	Fir-tree
16TG-143-1-Spot 313	138	5	116426	0.036	1036.7	19.4	100.1	Fir-tree
16TG-143-1-Spot 061	125	8	58431	0.064	1037.0	23.0	100.8	Fir-tree
16TG-143-1-Spot 237	122	6	74230	0.049	1037.2	23.6	100.1	Fir-tree
16TG-143-1-Spot 216	123	8	36110	0.065	1037.3	20.5	98.8	Fir-tree
16TG-143-1-Spot 099	110	6	17761	0.054	1037.4	24.8	100.2	Fir-tree
16TG-143-1-Spot 209	125	5	79415	0.040	1037.8	18.5	100.1	Fir-tree
16TG-143-1-Spot 131	135	6	70007	0.044	1037.8	23.4	98.9	Fir-tree
16TG-143-1-Spot 201	131	6	860900	0.046	1038.0	23.4	99.8	Fir-tree
16TG-143-1-Spot 212	131	9	146496	0.069	1038.3	16.7	99.4	Fir-tree
16TG-143-1-Spot 243	143	5	24842	0.035	1038.4	23.0	98.4	Fir-tree
16TG-143-1-Spot 057	143	10	78182	0.070	1038.7	22.5	98.9	Fir-tree
16TG-143-1-Spot 211	133	6	36041	0.045	1039.4	21.5	99.4	Fir-tree
16TG-143-1-Spot 249	127	6	20096	0.047	1039.7	23.0	100.1	Fir-tree
16TG-143-1-Spot 012	111	8	114130	0.072	1039.8	16.5	100.2	Fir-tree
16TG-143-1-Spot 143	165	9	310640	0.054	1040.3	18.7	98.5	Fir-tree
16TG-143-1-Spot 082	130	7	17730	0.054	1040.5	19.7	100.0	Fir-tree
16TG-143-1-Spot 270	111	7	38120	0.063	1041.2	21.1	100.9	Fir-tree
16TG-143-1-Spot 288	146	6	26869	0.041	1041.9	15.3	99.0	Fir-tree
16TG-143-1-Spot 303	145	7	102784	0.048	1042.0	20.1	100.6	Fir-tree

16TG-143-1-Spot 291	379	1	130762	0.003	1042.2	19.3	98.2	Fir-tree
16TG-143-1-Spot 128	126	8	51122	0.063	1042.9	20.2	99.8	Fir-tree
16TG-143-1-Spot 033	117	8	34666	0.068	1043.0	22.3	98.5	Fir-tree
16TG-143-1-Spot 109	130	7	998143	0.054	1043.6	20.2	98.5	Fir-tree
16TG-143-1-Spot 030	114	7	330437	0.061	1043.7	19.0	98.5	Fir-tree
16TG-143-1-Spot 037	136	5	36787	0.037	1043.8	21.7	98.0	Fir-tree
16TG-143-1-Spot 064	135	6	45473	0.044	1044.4	31.5	99.4	Fir-tree
16TG-143-1-Spot 170	106	9	29780	0.085	1044.5	19.6	98.5	Fir-tree
16TG-143-1-Spot 081	133	6	19267	0.045	1044.8	20.2	100.4	Fir-tree
16TG-143-1-Spot 134	133	8	228304	0.060	1045.4	21.7	99.8	Fir-tree
16TG-143-1-Spot 127	228	10	20629	0.044	1045.9	22.6	100.5	Fir-tree
16TG-143-1-Spot 045	127	5	30455	0.039	1046.1	19.2	99.4	Fir-tree
16TG-143-1-Spot 103	213	5	30325	0.023	1046.1	20.1	100.3	Fir-tree
16TG-143-1-Spot 181	117	8	141724	0.068	1046.2	25.8	98.6	Fir-tree
16TG-143-1-Spot 040	129	13	281501	0.101	1046.3	20.0	98.9	Fir-tree
16TG-143-1-Spot 066	150	6	57619	0.040	1046.9	20.9	98.0	Fir-tree
16TG-143-1-Spot 076	139	6	41645	0.043	1047.0	20.2	98.9	Fir-tree
16TG-143-1-Spot 101	108	7	15000	0.065	1047.7	19.6	98.8	Fir-tree
16TG-143-1-Spot 233	129	8	67038	0.062	1047.7	17.3	98.7	Fir-tree
16TG-143-1-Spot 279	118	10	14843	0.085	1047.7	24.3	100.6	Fir-tree
16TG-143-1-Spot 271	130	5	149372	0.038	1048.6	23.5	99.9	Fir-tree
16TG-143-1-Spot 016	106	7	23314	0.066	1048.8	20.1	99.2	Fir-tree
16TG-143-1-Spot 095	149	8	57667	0.054	1049.1	23.0	99.5	Fir-tree
16TG-143-1-Spot 252	135	7	559043	0.052	1049.3	19.5	99.6	Fir-tree
16TG-143-1-Spot 141	128	7	57055	0.055	1049.3	20.4	99.4	Fir-tree
16TG-143-1-Spot 315	132	6	231594	0.046	1049.9	20.5	99.8	Fir-tree
16TG-143-1-Spot 272	115	8	41965	0.070	1050.9	20.1	99.4	Fir-tree

16TG-143-1-Spot 087	138	7	13613	0.051	1051.0	19.1	98.2	Fir-tree
16TG-143-1-Spot 287	144	10	67093	0.070	1051.3	21.5	98.6	Fir-tree
16TG-143-1-Spot 168	116	8	53133	0.069	1051.4	23.2	98.1	Fir-tree
16TG-143-1-Spot 283	122	8	15521	0.065	1051.5	20.6	98.4	Fir-tree
16TG-143-1-Spot 194	116	4	19556	0.035	1051.5	21.3	98.5	Fir-tree
16TG-143-1-Spot 200	141	8	146013	0.057	1052.1	23.4	98.6	Fir-tree
16TG-143-1-Spot 152	441	3	95572	0.007	1052.1	19.7	100.4	Fir-tree
16TG-143-1-Spot 056	142	6	36918	0.042	1052.2	22.2	99.9	Fir-tree
16TG-143-1-Spot 268	118	7	31292	0.059	1052.6	18.6	99.3	Fir-tree
16TG-143-1-Spot 135	128	6	34906	0.047	1053.1	21.4	99.6	Fir-tree
16TG-143-1-Spot 060	147	8	27123	0.054	1053.7	20.8	98.7	Fir-tree
16TG-143-1-Spot 262	115	6	22346	0.052	1053.8	20.4	99.7	Fir-tree
16TG-143-1-Spot 159	124	7	21958	0.057	1054.0	28.4	98.0	Fir-tree
16TG-143-1-Spot 088	129	9	65313	0.070	1054.7	16.8	98.1	Fir-tree
16TG-143-1-Spot 176	141	7	46860	0.050	1054.8	22.5	98.0	Fir-tree
16TG-143-1-Spot 199	130	8	57388	0.062	1055.0	19.2	100.5	Fir-tree
16TG-143-1-Spot 166	129	6	192493	0.046	1055.3	20.8	99.1	Fir-tree
16TG-143-1-Spot 284	113	7	129981	0.062	1055.7	19.9	99.5	Fir-tree
16TG-143-1-Spot 102	138	8	24098	0.058	1056.1	20.2	98.5	Fir-tree
16TG-143-1-Spot 309	145	6	71859	0.041	1056.8	16.1	99.7	Fir-tree
16TG-143-1-Spot 242	134	4	56201	0.030	1057.6	21.8	99.0	Fir-tree
16TG-143-1-Spot 286	141	6	22397	0.043	1058.5	20.6	98.1	Fir-tree
16TG-143-1-Spot 118	119	8	128161	0.067	1058.5	21.7	98.4	Fir-tree
16TG-143-1-Spot 265	120	6	58937	0.050	1061.1	26.7	99.0	Fir-tree
16TG-143-1-Spot 299	129	6	25272	0.046	1061.3	17.1	99.6	Fir-tree
16TG-143-1-Spot 261	101	7	35024	0.069	1061.9	17.8	98.3	Fir-tree
16TG-143-1-Spot 072	107	8	20836	0.074	1062.4	20.9	98.5	Fir-tree

16TG-143-1-Spot 230	137	5	1510624	0.037	1062.7	18.9	98.4	Fir-tree
16TG-143-1-Spot 306	143	5	136094	0.035	1063.7	24.7	98.1	Fir-tree
16TG-143-1-Spot 120	372	2	53730	0.005	1063.7	23.2	98.0	Fir-tree
16TG-143-1-Spot 217	123	6	26320	0.049	1063.9	26.3	98.0	Fir-tree
16TG-143-1-Spot 162	147	5	70987	0.034	1064.2	24.2	99.2	Fir-tree
16TG-143-1-Spot 119	121	6	78637	0.050	1064.4	16.3	98.9	Fir-tree
16TG-143-1-Spot 278	122	4	35100	0.033	1066.9	25.2	99.4	Fir-tree
16TG-143-1-Spot 115	215	5	14313	0.023	1068.4	22.6	98.2	Fir-tree
16TG-143-1-Spot 002	84	6	53388	0.072	1068.4	20.2	98.5	Fir-tree
16TG-143-1-Spot 003	116	6	202138	0.052	1068.8	17.7	99.5	Fir-tree
16TG-143-1-Spot 059	350	6	78303	0.017	1070.0	19.8	99.1	Bright CL/Fir-tree
16TG-143-1-Spot 001	87	6	69416	0.069	1075.8	18.2	98.5	Bright CL/Fir-tree
16TG-143-1-Spot 086	180	4	176561	0.022	1088.7	26.7	99.8	Bright CL
16TG-143-1-Spot 256	288	12	44851	0.042	1116.1	20.2	100.4	Core
16TG-143-1-Spot 213	239	21	77119	0.088	1137.3	17.9	98.0	Core
16TG-143-1-Spot 133	253	11	57038	0.043	1148.3	23.4	98.3	Core
16TG-143-1-Spot 050	251	27	22789	0.108	1175.8	18.6	100.8	Core
16TG-143-1-Spot 312	271	81	146681	0.299	1240.2	15.8	100.4	Core
16TG-143-1-Spot 083	345	96	193027	0.278	1286.4	16.9	100.0	Core

Table 4: Leucosome Zircon U/Pb Analyses

Analysis	U (ppm)	Th (ppm)	206Pb 204Pb	Th/U	206 Pb 207 Pb	± (Ma)	Conc (%)	Texture
In-situ								
16TG-143-5 Spot 7	330	7	107373	0.021	1030.8	22.0	99.4	Dark CL Rim
16TG-143-5 Spot 19	217	27	21926	0.125	1031.2	18.3	99.7	Fir-Tree
16TG-143-5 Spot 20	593	249	97454	0.420	1110.6	21.0	99.4	Core
16TG-143-5 Spot 13	496	185	43927	0.373	1150.7	22.9	98.8	Core
16TG-143-5 Spot 28	623	408	75892	0.655	1157.1	26.4	99.7	Core
16TG-143-5 Spot 22	339	58	33234	0.171	1158.7	16.4	99.3	Core
16TG-143-5 Spot 2	1009	617	171323	0.612	1167.8	17.2	98.4	Core
Separate								
16TG-143-2 Spot 20	452	56	31584	0.124	1050.0	20.3	97.5	Rim
16TG-143-2 Spot 24	452	59	68759	0.130	1050.5	18.1	99.1	Rim
16TG-143-2 Spot 22	892	290	219252	0.325	1117.7	21.0	100.6	Core
16TG-143-2 Spot 16	776	115	127444	0.148	1131.1	20.0	97.1	Core
16TG-143-2 Spot 19	1158	570	334403	0.492	1150.1	18.0	99.2	Core
16TG-143-2 Spot 30	678	272	183553	0.401	1161.2	22.9	99.2	Core
16TG-143-2 Spot 18	597	281	126981	0.471	1163.5	21.3	99.3	Core
16TG-143-2 Spot 10	471	191	85151	0.405	1164.5	19.9	99.0	Core
16TG-143-2 Spot 4	882	277	295575	0.314	1165.3	19.6	98.9	Core
16TG-143-2 Spot 7	1344	602	335639	0.448	1172.0	21.2	99.6	Core
16TG-143-2 Spot 12	784	266	211999	0.339	1173.5	19.5	98.0	Core
16TG-143-2 Spot 28	1674	808	186659	0.483	1176.1	22.2	98.3	Core
16TG-143-2 Spot 27	806	398	78644	0.494	1180.8	17.8	98.3	Core
16TG-143-2 Spot 14	1154	518	214894	0.449	1202.2	22.4	98.0	Core

APPENDIX C

MAJOR MINERAL COMPOSITIONS

The mineral composition for garnet, feldspar, plagioclase and biotite were identified using electron microprobe quantitative analysis (EMPA). Garnet, biotite, feldspar, and plagioclase were first mapped on the SX50 to observe any compositional differences prior to quantitative analysis. The thin-section 16TG-143-1 is the restite and thin-section 16TG-143-5 is the leucosome. The results for the mineral compositions are presented in the figures below.

GARNET

Figure 23: Comparison of the composition of garnet in all samples (restite and leucosome).

16TG-143-1-Garnet1

16TG-143-1-Garnet2

16TG-143-5-Garnet1

Figure 24: Calcium x-ray microprobe maps of the garnet grains analyzed in the restite.

16TG-143-5-Garnet2

16TG-143-5-Garnet3

Figure 25: Calcium x-ray microprobe maps of the garnet grains analyzed in the leucosome

K-FELDSPAR

Figure 26: Comparison of the composition of K-feldspar in the restite (143-1) and leucosome (143-5).

16TG-143-5-Kspar1

Figure 27: Potassium x-ray microprobe map of K-feldspar in the leucosome (143-5).

PLAGIOCLASE

Figure 28: Compositional comparison of plagioclase in the restite (143-1) and leucosome (143-5).

16TG-143-5-plag1

Figure 29: Calcium x-ray microprobe map of plagioclase in the leucosome (143-5).

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