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Structure and Geochronology of the Jurassic Pliny Range Caldera Complex: 7.5' Jefferson Quadrangle, Northern New Hampshire

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Structure and Geochronology of the Jurassic Pliny Range Caldera Complex: 7.5' Jefferson Quadrangle, Northern New Hampshire

Bates College Geology Honors Thesis

Presented to the Faculty of the Department of Geology, Bates College,
in partial fulfillment of the requirements for the Degree of Bachelor of Science

by
Jordan Cargill

Lewiston, Maine
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Abstract

The southern half of the Jefferson, NH 7.5' quadrangle was remapped for the USGS/NHGS StateMap program. The study area contains two key Appalachian lithotectonic elements: 1) Ordovician granitic orthogneisses of the Jefferson Oliverian Dome in the Bronson Hill Anticlinorium (BHA); and 2) Jurassic igneous intrusive rocks of the Pliny Range Caldera Complex (PRCC) that were emplaced by cone-sheeting associated with caldera collapse. Models for the formation of BHA domes call for arc (?) plutonism associated with the Taconic orogeny and elements of Gander followed by tectonism during the Salinic, Acadian and Neo-Acadian orogenies as the Oliverian Jefferson Dome diapirically rose through its younger cover.

This study used U-Th-Pb geochronology and detailed mapping of a ~6-acre clear-cut with 50% exposed bedrock located within the PRCC to address relative-age and structural ambiguities in the PRCC and BHA. Mapping in the quadrangle also revealed a previously unrecognized tuffaceous rhyolite, part of the PRCC. Zircons from the rhyolite and two PRCC granites were analyzed by LA-ICP-MS to determine U-Th-Pb crystallization ages. The granites are 187.3 ± 1.1 Ma and 188.3 ± 1.0 Ma with the latter cutting the former. Within error, the intrusions are essentially contemporaneous. The rhyolite yielded two grain-age populations with concordant ages of 184.9 ± 2.3 Ma and 430.6 ± 2.6 Ma. The younger age is believed to mark the crystallization of the rhyolite and the older the crystallization of a suite of xenocrystic zircons from the older coarse syenite country rock, cut by the rhyolite.

The syenite was thought to be Ordovician in age but the new zircon ages, although indirect, suggest a Silurian age. The syenite is not visibly deformed yet cuts strongly foliated Ordovician Oliverian orthogneisses suggesting that some deformation in the Jefferson Dome may actually be older (Ordovician?) than previously thought. Alternately, the syenites may be related to the Salinic Orogeny, have a rheology such that they are resistant to ductile deformation, and/or they are related to a separate plutonic suite (Highlandcroft?) from the foliated orthogneisses. Xenoliths of the Ordovician orthogneisses within the ring complex show consistent deflection of foliations with strike and dip averaging 304° , 62° relative to trends identified distal from the caldera (257° , 43°). The two distinct foliation trends combined with caldera-centric dipping, ring-parallel hornblende veins (278° , 61°) identified cutting only the Oliverian orthogneisses and Silurian syenites suggests a faulted relationship for re-orientation of foliations.

The granite ages confirm the Jurassic timing of the cone-sheets and identification of new relative age relationships amongst the PRCC units suggest two temporally separate phases of caldera collapse and intrusion. The combination of intense brecciation and consistent foliation among Oliverian orthogneisses within the ring complex suggests a less forceful yet complex pattern of cone-sheet intrusion during the second phase of collapse. The new rhyolite age suggests a third and final dominantly extrusive (?) phase of caldera collapse near contemporaneous with the intrusive cone-sheeting of the first and second phases.

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Contents

Abstract	ii
Acknowledgments	iii
1. Introduction	1
1.1 Overview	1
1.2 Previous mapping studies	3
1.2.1 Chapman (1942)	3
1.2.2 Eichelberger (1971) and Czamanske and others (1977)	5
1.2.3 Lyons and others (1997)	8
1.2.4 Devoe (2015), Oxman (2015), and Xiao (2015)	8
1.3 Basic Description and Mineralogy of Previously Identified Units	11
1.3.1 Jurassic Units	12
1.3.2 Ordovician Units	12
1.4 Previous Experimental Geochronology and Petrogenesis Studies:	13
1.4.1 Foland and Loiselle, 1981	14
1.4.1.1 Rb-Sr Geochronology	14
1.4.1.2 Petrogenesis of the Syenites	16
1.4.2 Randall and Foland, 1987	16
1.4.2.1 K-Ar Geochronology	16
1.4.2.2 Petrogenesis of the PRCC	19
1.5 Orogenic History of the Northern Appalachians	20
1.5.1 Taconic Orogeny (~495-450 Ma)	21
1.5.1.1 The BHA and Oliverian Plutonism	24
1.5.2 Salinic Orogeny (~420-423 Ma)	25
1.5.3 Acadian and Neo-Acadian Orogenies (~410-345 Ma)	26
1.5.3.1 Oliverian Jefferson Doming	26
1.5.4 Alleghanian Orogeny (~345-300Ma)	27
1.6 Extensional Tectonic History	27
1.6.1 White Mountain Magma Series (WMMS)	27
1.6.3 Caldera-Collapse	28
1.6.3.1 Number of Collapse Events	30
1.6.3.2 Collapse Geometry	30
1.6.3.3 The Presence or Absence of Resurgence or Other Deformation	32
1.6.3.4 The Dominant Composition of Erupting Magma	32
2. Methods	33
2.1 Field Mapping	33
2.2 Clear-Cut Mapping	35
2.3 Lab Work	37
2.3.1 7.5' Quadrangle Map	37
2.3.2 Clear-Cut Interpretive Map	37
2.3.2.1 Interpretive Cross-Section	37
2.3.3 Uranium-Thorium-Lead (U-Th-Pb) Geochronology	38

2.3.3.1 Principles of U-Th-Pb Geochemistry	38
2.3.3.2 Sample Collection	39
2.3.3.3 Heavy Mineral Separation and Sample Preparation	39
2.3.3.4 LA-ICP-MS Session Details	43
2.3.3.5 Data Analysis	43
2.3.4 Structural Analysis – Stereographic Projections	45
2.3.5 Mineralogical Analysis – Transmitted Light Microscopy	45
3. Results	47
3.1 Overview	47
3.2 Updated 1:24,000 Quadrangle Map	47
3.3 Unit Descriptions	51
3.3.1 Jurassic Igneous Rocks	51
3.3.1.1 Rhyolite (Jr)	51
3.3.1.2 Conway Granite (Jcg)	54
3.3.1.3 Pink Biotite Granite (Jpbg)	55
3.3.1.4 Quartz Monzodiorite (Jqmd)	56
3.3.1.5 Porphyritic Quartz Monzonite (Jpqm)	59
3.3.1.6 Hastingsite Quartz Syenite (Jhqs)	60
3.3.1.7 Diorite (Jd)	61
3.3.1.8 Basalt Dykes (Jb1)	61
3.3.2 Silurian Igneous Rocks	63
3.3.2.1 Medium Syenite (Sms)	63
3.3.2.2 Coarse Syenite (Scs)	63
3.3.3 Ordovician Rocks of the Jefferson Dome	66
3.3.3.1 Ordovician High Strain Amphibolite (Oa)	66
3.3.3.2 Porphyritic K-feldspar Orthogneiss (Oopkg)	67
3.3.3.3 Hornblende Granite Orthogneiss (Oo1h)	69
3.3.3.4 Biotite Granite Orthogneiss (Oo1b)	71
3.4 Clear-Cut Interpretive Map	71
3.4.1 Description of Units and Features in the Clear-Cut	74
3.4.1.1 Jurassic Rocks	74
3.4.1.1.1 Jurassic Conway Granite (Jcg)	74
3.4.1.1.2 Jurassic Pink Biotite Granite (Jpbg)	74
3.4.1.1.3 Jurassic Quartz Monzodiorite (Jqmd)	76
3.4.1.1.4 Basalt Dyke (Jb1) (Jpbg)	76
3.4.1.2 Ordovician Rocks of the Jefferson Dome	78
3.4.1.2.1 High Strain Amphibolite (Oa)	78
3.4.1.2.2 Porphyritic K-feldspar Orthogneiss (Oopkg)	78
3.4.2 Clear-Cut Cross-Section	79
3.4.2.1 Jurassic Conway Granite (Jcg)	80
3.4.2.2 Jurassic Pink Biotite Granite (Jpbg)	80
3.4.2.3 Quartz Monzodiorite (Jqmd)	80
3.4.2.4 Ordovician High Strain Amphibolite (Oa)	80
3.4.2.5 Porphyritic K-feldspar Orthogneiss (Oopkg)	81
3.5 Structural Geology	81
3.5.1 Foliations	81

3.5.2 Amphibolite High Strain Zones	83
3.5.2.1 Section 1	83
3.5.2.2 Section 2	85
3.5.2.3 Section 3	85
3.5.3 Hornblende veins	85
3.5.4 Joints	87
3.6 U-Th-Pb Geochronology	87
3.6.1 Jurassic Conway Granite (Jcg) (sample 504)	87
3.6.2 Jurassic Pink Biotite Granite (Jpbg) (sample 501)	87
3.6.3 Jurassic Rhyolite Jr (sample 286)	89
4. Discussion	91
4.1 Overview	91
4.2 Evolution of Structural Geology	91
4.2.1 Formation of Dome-related Foliations	91
4.2.3 Intrusion of the Silurian Syenites.	93
4.2.4 Localized High Strain Amphibolite	94
4.2.5 Intrusion of Hornblende Veins.	95
4.2.6 Fault Rotation of Dome-Related Foliations.	96
4.2.7 Intrusion of Basalts	99
4.2.8 Caldera-Collapse	100
4.2.8.1 PRCC Intrusive Geometry	100
4.2.8.2 PRCC Relative Age Subgroups	100
4.2.8.3 Origin of PRCC Units	101
4.2.8.4 Phase 1	103
4.2.8.5 Phase 2	105
4.2.8.6 Phase 3	106
4.2.8.6.1 Intrusion of the Conway Granite (Jcg).	78
4.2.8.6.2 Rhyolite Extrusion or Intrusion.	78
4.2.9 Late-stage Jointing.	108
4.3 Summary and Description of Caldera-Collapse	110
4.3.1 Number of Collapse Events and Geometry	110
4.3.2 Presence of Resurgence and Deformation	111
4.3.3 Dominant Composition of Erupting Magma	111
5. Conclusions	113
6. References	115
7. Appendices	121
7.1 Appendix A: GeoSep Services LLC. – Laboratory Procedures and U-Pb Dating Methodology	121
7.2.1 Jurassic Pink Biotite Granite (Jpbg) – Sample 501	129
7.2.2 Jurassic Conway Granite (Jcg) – Sample 504	133
7.2.3 Jurassic Rhyolite (Jr) – Sample 286	137

List of Figures

<i>Figure 1:</i> Location of the 7.5' Jefferson Quadrangle in New Hampshire and its associated lithotectonic orogenic units (modified from: Granit.com; Hibbard et al., 2010)	2
<i>Figure 2:</i> The 161 sq km (100 sq mi) region, including the Pliny Range, mapped by Chapman (1942). The region that overlaps the southern half of the Jefferson Quadrangle is outlined in red (modified from: Chapman, 1942).	4
<i>Figure 3:</i> The 113 sq km (70 sq mi) region including the Pliny range mapped by Eichelberger (1971) and published by Czamanske and other (1977). The region that overlaps the southern half of the Jefferson Quadrangle is underlain by the USGS topographic map of the quadrangle (modified from: Czamanske et al., 1977).	6
<i>Figure 4:</i> The relative ages of the units pertinent to this study as determined by Czamanske and others (1977) (modified from: Czamanske et al., 1977).	7
<i>Figure 5:</i> The Northern half of the New Hampshire State Bedrock Geology map compiled by Lyons and others (1997). The Pliny region is blown up in the bottom left corner and a legend of the units pertinent to this study is in the upper left corner (modified from: Lyons et al., 1997).	9
<i>Figure 6:</i> The neighboring Mount Dartmouth 7.5' Quadrangle mapped by Eusden and others (2015). The quadrangle contains granitic rocks from the Oliverian Plutonic Series and structural features that are correlated to units and features in the Jefferson quadrangle (Eusden et al., 2015).	10
<i>Table 1:</i> A description of units mapped in the southern half of the Jefferson quadrangle and evolution of their nomenclature through previous mapping efforts.	11
<i>Figure 7:</i> A plot of number of publications per year of a number of radioisotopic dating methods including the U-Th-Pb technique. Curves were made by counting all publications per year with the dating method listed in the title (Schoene, 2014; www.webofknowledge.com).	14
<i>Figure 8:</i> The Rb-Sr isochron diagram showing the regression line of the coarse and medium syenites yielding an age of 441+5 Ma (modified from: Foland and Loiselle, 1981).	15
<i>Table 2:</i> A summary of ages determined through $^{40}\text{Ar}/^{39}\text{Ar}$ for units pertinent to this study from the PRCC. The summary includes cooling ages for biotite and amphibole, where appropriate, for each unit as well as the average cooling age for all units (modified from: Randall and Foland, 1987).	18
<i>Figure 9:</i> An example of age spectra, calculated through the $^{40}\text{Ar}/^{39}\text{Ar}$ technique, from the PRCC unit quartz monzodiorite. These results indicate the concordance of amphibole and biotite from an early intrusive phase. The graph illustrates not only the internally concordant spectra, but also the concordance of ages for “end members” of the emplacement sequence. T_p and T_{tg} represent plateaus and total-gas (sum of all fractions) $^{40}\text{Ar}/^{39}\text{Ar}$ ages, respectively. The patterned blocks represent + 1 sigma uncertainties without an uncertainty in the J value of the isochron equation. The arrows indicate the average $^{40}\text{Ar}/^{39}\text{Ar}$ for the complex (Randall and Foland 1987).	19
<i>Figure 10:</i> An Rb-Sr isochron plot for 25 whole-rock samples of felsic PRCC units including granite porphyry and hastingite biotite granite not mapped in this study. The significant heterogeneity of the Rb/Sr ratios can be observed by the spread of the samples along the regression line (Randall and Foland, 1987).	20

<i>Figure 11:</i> The Lithotectonic units of the Appalachian orogeny. The study site is most strongly affected by the accretion of Gander, Avalon, and Meguma related to the Devonian Acadian, Devonian-Carboniferous Neo-Acadian, and Permian Alleghanian orogenies. The deformation from these events is resultant from compressional and transpressional stress (modified from: Hibbard et al., 2010) . . .	21
<i>Figure 12:</i> Tectonic models produced by Van Staal and others (2009) depicting the evolution of Taconic 1 into the initiation of Taconic 2. a) Taconic 1: Formation of the Lush Bight oceanic tract terrane through subduction initiation and rapid hinge retreat of the east-dipping Dashwoods plate. b) Taconic 2: The arc-arc collision of the Baie Verte oceanic tract and Notre Dame arc (Shelburne Falls arc) from the stepping back of the subduction zone in the Humber Seaway. This collision slowed down convergence in the Humber Seaway potentially leading to the initiation of west-directed subduction outboard of Dashwoods. This subduction lead to the formation of the Annieopsquotch ophiolite belt (modified from: Van Staal et al., 2009).	22
<i>Figure 13:</i> Tectonic models produced by Van Staal and others (2009) depicting the termination of Taconic 2 into Taconic 3. a) Taconic 2: Collision of Dashwoods with the Humber Margin leading to east-directed thrusting at its boundary with the Annieopsquotch ophiolite belt (AOB). Thrusting lead to the closure of the AOB and accretion of parts of the Red Indian Lake arc. b) Taconic 3: Collision and accretion of the Popelogan-Victoria (the leading edge of Gander) closing the main Iapetan oceanic tract (modified from: Van Staal et al., 2009).	23
<i>Figure 14:</i> Tectonic model developed by Macdonald and others (2014) depicting a similar mechanism as illustrated in Van Staal and other's (2009) model of Taconic 3. Plutonism and creation of the Bronson Hill Anticlinorium follows the convergence of west Gander (Popelogan-Victoria arc) with composite Laurentia (modified from Macdonald et al., 2014).	24
<i>Figure 15:</i> A schematic model showing peri-Laurentian migration of the southeasterly dipping subduction zone attached to the western margin of the Popelogan-Victoria Arc (PVA), leading to back-arc rifting of the PVA into a series of ribbon continents. The rift margin between the southern Tetagouche ribbon and the PVA marks the future sight of Salinic subduction (circled in red) eventually leading to the orogenic merger of the ribbons with composite Laurentia prior to the main extent of Gander (modified from: Van Staal, et al., 2015).	25
<i>Figure 16:</i> The location of the White Mountain Igneous Province and the Jefferson Quadrangle within it (modified from: Creasy et al., 1993).	28
<i>Figure 17:</i> A basic model showing the four (a-d) general phases of caldera formation. a) Establishment of a volcano. b) Increased magmatic activity with small-scale eruptions. c) Cataclysmic explosive eruption. d) Subsidence of central crater along circular ring faults and intrusion of magma along the ring fault planes as ring-dykes or cone-sheets (modified from: Fossen, 2008).	29
<i>Figure 18:</i> Four end member mechanisms of caldera collapse: a) piston/plate, b) piecemeal, c) trapdoor, d) downsag (Cole et al., 2005).	31
<i>Figure 19:</i> The USGS topographic map of the 7.5" Jefferson Quadrangle showing the locations of the clear-cut used for high resolution mapping and collection locations for the U-Th-Pb geochronology samples of Jurassic Conway granite (Jcg), Jurassic pink biotite granite (Jpbg) and Jurassic rhyolite (Jr) (modified from: USGS).	34
<i>Figure 20:</i> A panorama of the exposures at the clear-cut. Images were captured through b) drone aerial photography and stitched together on Adobe Photoshop by Matt Duvall, Manager of the Bates College Imaging Center (Photo credit: Matt Duval).	36

<i>Figure 21:</i> Outcrops of the samples collected for U-Th-Pb geochronology. From top to bottom: Jurassic rhyolite (Jr), Jurassic Conway granite (Jcg), Jurassic pink biotite granite (Jpbg).	40
<i>Figure 22:</i> A flow diagram depicting the five general steps in the heavy mineral separation process: 1) Initial pulverizing of the samples using a sledge hammer; 2) crushing down to sub 5 mm size using the Spex 4200 Jaw Crusher at the Maine Mineral Museum (MMM) followed by pulverization to sub 1 mm size using a ceramic disk-mill grinder at Bates College; 3) Preliminary separation of the dense minerals using a Rogers Gemini Gold Table; 4) Heavy fluid separation samples using Lithium Metatungstate (approximate specific gravity = 2.95); 5) search for datable zircons using optical microscopy (Photo credit: J. Dykstra Eusden)	41
<i>Figure 23:</i> a) A method used by GeoSep Services to map spot locations on individual grains prior to ablation. b) The epoxy wafers containing grains from each sample as well as a set of standards.	42
<i>Figure 24:</i> a) Model describing the basic principles in the LA-ICP-MS technique (Schoene. 2014). b) An example of a concordia plot where the ratio of $^{207}\text{Pb}/^{235}\text{U}$ is plotted on the x-axis vs. $^{206}\text{Pb}/^{238}\text{U}$ on the y-axis. This technique allows for the determination of multiple ages types even when the plotted U/Pb ratios fall off of the parametric curve indicating when the two ratios correspond to the same age (Schoene. 2014).	44
<i>Figure 25:</i> A photograph of the Olympus BH-2 microscope used for transmitted light microscopy analysis of thin sections.	46
<i>Figure 26:</i> Baker's (2016) map and cross-sections of the southern half of the Jefferson 7.5' quadrangle.	48
<i>Table 3:</i> Correlation of the the unit nomenclature from previous mapping efforts to the nomenclature used for this study	49
<i>Figure 27:</i> A QAP IUGS ternary classification of the felsic igneous rocks within the southern half of the Jefferson Quadrangle (modified from: Winter, 2001).	50
<i>Figure 28:</i> a) A high resolution scan of the welded tuffaceous variety of the rhyolite (Jr) thin section alongside a photograph of an outcrop where it can clearly be seen cutting the Silurian coarse syenite (Scs) (hammer for scale). b) The very-fine grained porphyritic variety of Jr seen in contact with Scs in the high resolution scan to the left and the phenocrysts clearly visible in the cross-polarized photomicrograph in the center. Myrmekitic texture can also be observed in this variety of Jr in the photomicrograph to the far right. c) The very-fine grained Jr variety (thin section scan to the left) demonstrating spherulitic texture in the photomicrograph to the right.	52
<i>Figure 29:</i> A TAS diagram of four rhyolite samples representing the textural variability within the unit. Data for the plot was collected through X-ray Fluorescence as a part of Baker's (2016) Thesis. All four samples plot with near identical total alkali and SiO_2 content well within the rhyolite range.	53
<i>Figure 30:</i> a) An outcrop of the clear-cut variety of Jurassic Conway granite (Jcg) (Brunton compass for scale). b) A hand-sample of the plug variety of Jcg (no outcrop-photo available). c) Plane and cross-polarized photomicrographs of the clear-cut variety of Jcg.	55
<i>Figure 31:</i> a) An outcrop of Jurassic Pink biotite granite (Jpbg) with mineral mode representative plane and cross-polarized photomicrographs. b) An outcrop clearly showing the cross-cutting of Jpbg and Jurassic quartz monzodiorite (Jqmd) through a xenolith of Ordovician porphyritic K-feldspar orthogneiss (Oopkg) (hammer for scale). c) A blown-up photograph demonstrating co-mingling between a mafic rich variety of Jqmd and Jpbg from the same outcrop (hammer for scale).	57

<i>Figure 32: a) An outcrop of Jurassic quartz monzodiorite (Jqmd) (hammer for scale). b) Plane and cross-polarized photomicrographs of representative mineral mode and an example of plagioclase feldspar zoning outlined and blown-up 200% in red.</i>	<i>58</i>
<i>Figure 33: A hand sample of Jurassic porphyritic quartz monzonite (Jpqm) (outcrop photo not available)..</i>	<i>59</i>
<i>Figure 34: Outcrop photo of Jurassic hastingsite quartz syenite (Jhqs) (hammer for scale)..</i>	<i>60</i>
<i>Figure 35: A hand sample of Jurassic hastingsite quartz syenite (Jhqs) (outcrop photo not available).</i>	<i>61</i>
<i>Figure 36: a) A photograph of Jurassic basalt (Jb1) cutting Silurian coarse syenite (Scs) (hammer for scale). b) An equal area projection displaying the average strike of the 10 measured basalt dykes within the southern half of the Jefferson quadrangle.</i>	<i>62</i>
<i>Figure 37: a) A hand sample of Silurian medium syenite (Sms) (outcrop photo not available). b) Mineral mode representative plane and cross-polar light photomicrographs of Sms.</i>	<i>64</i>
<i>Figure 38: a) A xenolithic outcrop of Silurian coarse syenite (Scs) within a Jurassic pink biotite granite and quartz monzodiorite co-mingled shatter zone (hammer for scale). b) Plane and cross-polarized light photomicrographs of Scs; c) Scs truncating the foliation (direction of foliation indicated by red arrows) of Ordovician K-feldspar orthogneiss (Oopkg) (hammer for scale).</i>	<i>65</i>
<i>Figure 39: A xenolithic outcrop of Ordovician high strain amphibolite (Oa) displaying a foliation of 4 (on the relative scale) within Jurassic pink biotite granite (Jpbg) and quartz monzodiorite (Jqmd) “shatter.” Direction of foliation indicated by red arrows.</i>	<i>67</i>
<i>Figure 40: a) An outcrop of Ordovician K-feldspar orthogneiss (Oopkg) with a foliation of 3 on the relative scale (direction indicated by red arrows) cut by a dyke of Jurassic pink biotite (Jpbg) granite (hammer for scale). b) Plane and cross-polarized photomicrographs, representing the mineral content of Oopkg.</i>	<i>68</i>
<i>Figure 41: a) An outcrop of hornblende granite orthogneiss with foliation, of intensity 3 on the relative scale, and dip indicated by the north-arrow card scale card. b) Plane and cross-polarized photomicrographs depicting regions of representative mineral abundance within the unit.</i>	<i>70</i>
<i>Figure 42: Hand sample of Ordovician biotite granite orthogneiss (Oo1b) (outcrop photo not available).</i>	<i>71</i>
<i>Figure 43: An interpretive map the bedrock geology of the clear-cut.</i>	<i>72</i>
<i>Figure 44: An interpretive cross-section illustrating the bedrock geology of the clear-cut map in figure 43.</i>	<i>73</i>
<i>Figure 45: a) two examples of Jurassic Conway granite (Jcg) cutting Jurassic pink biotite granite (Jpbg) within the clear-cut (hammer for scale left, Brunton for scale right). b) Jcg clearly cutting the prominent basalt dyke within the clear-cut (Jb1) (Brunton for scale). c) Jcg with extremely shallow dip (less than 10°) in contact with Ordovician K-feldspar orthogneiss (Oopkg) (Brunton for scale).</i>	<i>75</i>
<i>Figure 46: The phenocrystic texture of the clear-cut basalt dyke (Jb1) and a phosphate nodule at the tip of the cat-paw crow-bar.</i>	<i>76</i>
<i>Figure 47: a) The phenocrystic hornblende and fine-grained varieties of high strain amphibolite (Oa) (foliation of 4 on the relative scale) in contact within the clear-cut and both cut by a Jurassic pegmatite vein (Brunton for scale). Foliation direction is shown by red arrows. b) Blown-up photograph of the fine-grained variety (left) and the porphyritic variety (right) (Brunton for scale).</i>	<i>77</i>

<i>Figure 48:</i> Ordovician porphyritic K-feldspar orthogneiss (Oopkg) with foliation of 3 on the relative scale in contact with Jurassic Conway granite (Jcg) in the clear-cut. The foliation direction is indicated by red-arrows.	79
<i>Figure 49:</i> a) foliations from the southern half of the Jefferson quadrangle plotted in an equal area projection as planes (top) and the contours to those planes with an extrapolated average strike and dip plane of 257°, 43° (bottom). b) Foliations from the clear-cut plotted in an equal area projection as planes (top) and the contours to those planes with an extrapolated average strike and dip of 304°, 62° (bottom).	82
<i>Figure 50:</i> a) The sampled outcrop of high strain amphibolite with foliation at 5 on the relative scale indicated by the red arrow. b) A high resolution scan of the thin section divided into sections 1, 2, and 3 and foliation indicated by the red arrows. c, d, e) Plane and cross polarized photomicrographs of sections 1, 2, and 3 respectively.	84
<i>Figure 51:</i> a) An outcrop photo of hornblende veins cutting the Silurian coarse (Scs) (hammer for scale). b) An equal area projection of hornblende veins as planes, no trends are apparent besides consistent steep dip towards the center of the caldera. c) Hornblende veins from the clear-cut plotted in an equal area projection as planes (top) and the contours to those planes with an extrapolated average strike and dip of 278°, 61° (bottom).	86
<i>Figure 52:</i> A rose plot of the 66 joints measured within the southern half of the Jefferson quadrangle. A trend was observed striking 170°.	87
<i>Figure 53:</i> A Concordia plot for Jurassic Conway granite (Jcg) showing a unanimously concordant population of zircons at a crystallization age of 188.3±1.0 Ma.	88
<i>Figure 54:</i> A Concordia plot for Jurassic Conway pink biotite granite (Jpbg) showing a unanimously concordant population of zircons at a crystallization age of 187.3±1.1 Ma. Within error, Jpbg is contemporaneous with Jurassic Conway granite (Jcg).	88
<i>Figure 55:</i> a) A concordia plot developed from all 22 analyzed zircons indicating two distinct concordant populations. b) A Concordia plot of the 17 grains in the older population giving a concordant age of crystallization at 430.6±2.5 Ma. c) A Concordia plot of the 5 grains in the younger population giving a concordant age of crystallization at 184.9±2.3 Ma. d) An example of a subhedral zircon grain, likely belonging to the older population, as it undergoes ablation.	90
<i>Figure 56:</i> a) Emplacement of the Ordovician Oliverian Plutonic Series (OPS) units, porphyritic K-feldspar orthogneiss (Oopkg), hornblende granite orthogneiss (Oo1h), and biotite granite orthogneiss (Oo1b) under cover of the Ordovician Ammonoosuc volcanics (see section 1.5.3.1 for theories regarding the unconformity between the Ammonoosuc volcanics and younger OPS units). Emplacement of basalt (?) sills or flows later metamorphosed and sheared into the high strain amphibolite zones. b) Emplacement of the Silurian syenites. c) An equal area projection from Devoe (2015; Devoe et al., 2015) showing the limbs of the Jefferson dome in the neighboring Mount Dartmouth quadrangle to the south. The northern limb, believed to be correlative to foliations in the Jefferson quadrangle, is highlighted in red. d) Oliverian doming in the Devonian from the late Acadian to early Neo-Acadian orogenies, followed by isolated dextral shearing yielding the high strain amphibolites in the Permian Alleghanian orogeny.	93

<i>Figure 57:</i> a) Oblique thrusting from pre-caldera collapse Tumescence of the magma chamber(s) leading to re-orientation of the dome foliations, in close proximity to the caldera, to ring parallel. b) The motion involved in re-orientation of the foliations. c) Reversal of the thrusts to normal faults during the first two phases of caldera collapse.	97
<i>Figure 58:</i> A model of magma chamber tumescence leading to oblique thrusting in the cover rock. The top of the magma chamber is dominated by vertical uplift and the lateral zones are a combination of rotational strain and vertical uplift leading to oblique thrusting. These thrusts create weaknesses along which cone-sheets can propagate during collapse (modified from: Tribaldi, 2015)	98
<i>Figure 59:</i> The relative ages of the units mapped in the southern half of the Jefferson quadrangle (modified from: Czamanske et al., 1977)	102
<i>Figure 60:</i> The first phase of collapse marked by Intrusion of the Jurassic diorite (Jd) and hastingsite quartz syenite (Jhqs) as cone-sheets along the reactivated fault plane (now with normal slip) created during oblique thrusting prior to collapse. B) The second phase of collapse marked by Intrusion of the commingled Jurassic pink biotite granite and quartz monzodiorite as cone-sheets along the normal-slip reactivated fault plane distal from the center of the caldera. C) Intrusion of the Jurassic Conway granite as circular plugs with sill-like off-shoots as a final intrusive pulse followed by extrusion (?) of the rhyolite. These events mark the third and final phase of caldera-collapse.	105
<i>Figure 61:</i> The current relationships and geometry of the Oliverian Plutonic Series (OPS), Silurian Syenites, and Jurassic Pliny Range Caldera Complex (PRCC) marking the culmination of the structural evolution outlined in figures 55, 56, and 59.....	109

1. Introduction

1.1 Overview

The Pliny Range, located in the USGS 7.5' Jefferson quadrangle in Northern New Hampshire records geologic events from both Ordovician and Silurian plutonism associated with the orogenic tectonics of the Appalachians and plutonism associated with the Jurassic break-up of Pangea (figure 1). Granitic orthogneisses, deformed during Oliverian Jefferson doming in the Devonian through the Carboniferous, and significantly less-deformed Silurian syenites make-up the older country rock of the southern half of the quadrangle (Hibbard et al., 2010; Lyons et al., 1997; Macdonald et al., 2014). The Pliny Range is formed from an igneous ring complex (Pliny Range Caldera Complex – PRCC) that was emplaced during ring-dyking associated with caldera collapse in the Jurassic about 180 Ma (Chapman, 1942; Czamanske et al., 1977; Eichelberger, 1971; Randall and Foland, 1987). The ring complex consists of several near contemporaneous intrusions with complex structural and relative age relationships. An extensive range of field mapping, mineralogical, and geochronological analyses have taken place in this region to map formations and determine their tectonic and petrologic origins. Czamanske and others (1977), Foland and Loiselle (1981), and Randall and Foland (1987) performed exhaustive investigations into the region's petrology and orogenic tectonics respectively and these areas have been sufficiently studied to date. However, mapping efforts by Chapman (1942) and Eichelberger (1971) were executed at a small-scale, 1:62,500, using less precise techniques than are available today leading to the persistence of relative age and structural ambiguities within the PRCC and between the PRCC and Oliverian Jefferson Dome features. Larger scale, higher resolution mapping at 1:24,000 using modern GPS-enabled techniques conducted as part of the USGS StateMap EdMAP initiative, an ongoing component of the National Cooperative Geologic Mapping Program (NGCPM), during the summer of 2015, yielded new cross-cutting relationships between two members of the PRCC and the discovery of a mappable extrusive/intrusive tuffaceous rhyolite unit. This study also identifies textural and mineralogical variations in the orthogneissic component of the Oliverian Jefferson Dome significant enough to separate the orthogneiss into two separate units. These discoveries indicate that additional investigation into the PRCC's structure, emplacement history and geochronology are necessary. The purpose of this study is use modern techniques of geochronology and detailed field mapping to constrain the relative ages and structural ambiguities of the PRCC and older Ordovician and Silurian rocks. This information is used to extrapolate a better understanding of caldera collapse and ring-dyke emplacement and the effects of these two

GRANIT 7.5' Quad Tile Index

38 New England - Quebec Igneous Suite; alkalic granite, syenite, and gabbro with minor felsic volcanic rocks. White Mountain Magma Series

13 Lower to upper Ordovician Ophiolitic, suprasubduction-zone, and rifted volcanic-arc magmatic rocks.

June, 2005

Figure 1: Location of the 7.5' Jefferson Quadrangle in New Hampshire and its associated lithotectonic orogenic units (modified from: Granit.com; Hibbard et al., 2010)

processes on the Oliverian Jefferson Dome features.

1.2 Previous mapping studies

The Pliny region of Northern New Hampshire has undergone two bedrock field mapping studies prior to mapping performed in this study. The region was first mapped by Randolph W. Chapman in the summers of 1939 and 1940 with a published map showing bedrock contacts and pertinent topography produced in 1942 (Chapman, 1942). John Charles Eichelberger performed the second round of mapping in 1971 as part of his Master's Thesis for the Massachusetts Institute of Technology. The map produced by Eichelberger (1971) was honed and published by his advisor Gerald Czamanske and others (1977).

1.2.1 Chapman (1942)

Chapman mapped an area of approximately 259 square kilometers (100 square miles) between latitudes $44^{\circ}30'30''$ and $44^{\circ}23'40''$ and longitudes $71^{\circ}15'$ and $71^{\circ}30'$. This area includes the majority of the modern-day 7.5' Jefferson quadrangle and portions of four neighboring quadrangles. Chapman's (1942) published map can be seen in figure 2. Reconnaissance and field-mapping were conducted by Chapman with assistance from Marland Billings, a prolific and key contributor to the first series of bedrock maps produced for the White Mountains of New Hampshire. Chapman's 1942 effort utilized enlarged photostatic copies of the Mount Washington quadrangle from the United States Topographic atlas as base maps. Field stops were plotted by means of aneroid barometer to determine elevation.

Chapman was able to establish a foundational understanding of the regional geology as well as provide a detailed mineralogical description of each mapped rock unit. All of the mapped units are of an igneous intrusive origin. The Jurassic rocks exist today unaltered or minimally altered from their original emplacement whereas the Ordovician units underwent significant tectonism and are now variably foliated orthogneisses. He parsed out the Pliny region into two major formation groups differentiated by age of emplacement. Chapman identified the older of the two groups as members of the Oliverian magma series (OMS), which Billings (1937) believed to be Devonian in age. This group consists of six separate formations as mapped by Chapman (1942), but only two of the formations, the coarse syenite and the biotite gneiss, are pertinent to this study. Chapman identifies the mechanism that produced the foliation in the biotite gneiss as post-emplacement doming of the OMS; however, as this hypothesis was pre-

Overlap with the Southern Half of the Jefferson Quadrangle

Figure 2: The 259 sq km (100 sq mi) region, including the Pliny Range, mapped by Chapman (1942). The region that overlaps the southern half of the Jefferson Quadrangle is outlined in red (modified from: Chapman, 1942).

tectonic theory the mechanism of doming remained unknown for several decades.

The second group consists of eight members of the White Mountain Magma Series (WMMS). Williams and Billings (1938) believed the WMMS was originally emplaced during the Mississippian to early Pennsylvanian Carboniferous. This hypothesis was pre-plate tectonics and it took several decades before a more accurate mechanism and time of emplacement could be determined. Chapman defined the relative age of these formations through contact relationships and correlation with rocks in other regions where relative ages were identified. The seven WMMS members mapped by Chapman (1942) form the prominent ring structure that makes up the Pliny Range. Five of the WMMS members identified by Chapman (1942) are pertinent to this study and they are from youngest to oldest (relative ages identified by Chapman (1942)): Conway granite, pink biotite granite, hastingsite quartz syenite, quartz monzodiorite, and quartz monzonite. Chapman (1942) identified that the quartz monzodiorite and quartz monzonite appear to grade into each other and are essentially the same formation. The Conway granite is the only member of the WMMS that does not follow the general trend of ring-dyke intrusion and instead intrudes as ‘stocks’ or plugs cutting the older WMMS members. Chapman (1942) also identified what he called a ‘shatter zone’ in the southeastern part of the ring-dyke where the pink biotite granite intrudes the older OMS rocks as dikes and irregular masses.

1.2.2 Eichelberger (1971) and Czamanske and others (1977)

In the summer of 1970 John Eichelberger remapped the Pliny Region at a scale of approximately 181 square kilometers (70 square miles), slightly smaller than the extent of Chapman’s (1942) map. This map was published by Czamanske and others (1977) and is shown in figure 3. Eichelberger used Chapman’s map and stratigraphy as a guide and an altimeter to pinpoint outcrop locations and sample collection sites. With an increased general knowledge of regional geology than that of Chapman’s (1942) era and new outcrops produced by logging activity Eichelberger (1971) was able to map two new units, provide greater detail for the ring-dyke structures and highlight new structural and relative age relationships between members of the WMMS and OMS, now referred to as the Oliverian Plutonic Series (OPS).

The two new formations Eichelberger (1971) identified are the porphyritic quartz monzonite and medium syenite, members of the WMMS and the OPS respectively. The porphyritic quartz monzonite makes up the ring-dyke on the western flanks of the range. Eichelberger mapped a medium grained syenite, which he observed cutting the coarse syenite to the south and east of the range. He asserts

Figure 3: The 181 sq km (70 sq mi) region including the Pliny range mapped by Eichelberger (1971) and published by Czamanske and other (1977). The region that overlaps the southern half of the Jefferson Quadrangle is underlain by the USGS topographic map of the quadrangle (modified from: Czamanske et al., 1977).

Figure 4: The relative ages of the units pertinent to this study as determined by Czamanske and others (1977) (modified from: Czamanske et al., 1977).

that the two syenites have origins distinct from both the WMMS and the OPS. His evidence for this designation is that the syenites exhibit little to no foliation or lineation and truncate the foliation of the orthogneisses separating them from the foliated orthogneisses known to be part of the OPS and they are well off the compositional trend of the WMMS. Page (1968) suggests that there was a late Devonian post-tectonic phase of igneous activity in New England and Eichelberger hypothesizes that the emplacement of the syenites is related to this activity. However, in publishing Eichelberger's (1971) map Czamanske and others (1977) place the syenites within the WMMS but separate from the PRCC.

In comparison to Chapman's (1942) map the ring-dyke geometry is more precisely delineated and Eichelberger eliminated the "Shatter Zone," instead mapping that area as pink biotite granite. The more detailed relative age relationships defined by Eichelberger (1971) allowed Czamanske and others (1977) to produce a model showing their interpretation of the relative ages of the mapped units (figure 4).

1.2.3 Lyons and others (1997)

The most contemporary map of the Pliny Region is the Bedrock Geology Map of New Hampshire, compiled by Lyons and others (1997) (figure 5). Since the scale is such that it encompasses the entirety of New Hampshire bedrock (1:250,000) the resolution of the Pliny Region is low. Lyons and others (1997) parse out the region of the Southern Half of the Jefferson Quadrangle into polygons of Ordovician hornblende quartz monzonite (Oo4Ch) and Jurassic Conway granite (Jc1b), hornblende-biotite quartz monzodiorite (J5), and hornblende and alkalic quartz syenite (J4h). The pink biotite granite, mapped by Chapman (1942) and Czamanske (1997), is lumped in with Jc1b by Lyons and others (1997). The Jurassic units make up the basic ring geometry of the PRCC and the Ordovician unit dominates the area to the south of the complex. The correlation of these units to those mapped by Czamanske (1977) and Chapman (1942) can be seen in table 1.

1.2.4 Devoe (2015), Oxman (2015), and Xiao (2015)

In the summer of 2014 Bates College Students Michelle Devoe, Graham Oxman, and Sarah Xiao, in conjunction with Professor J. Dykstra Eusden, mapped the Mount Dartmouth 7.5' USGS quadrangle, located immediately south of the Jefferson quadrangle (figure 6). Eusden, and others (2015) produced the final bedrock map submitted to the NHGS as required by their funding from the STATEMAP and NGCPM initiatives. The bedrock geology of their study site is dominated by formations related to the OPS and Jefferson Dome. The northern reaches of the Dartmouth quadrangle are dominated by a series

Figure 5: The Northern half of the New Hampshire State Bedrock Geology map compiled by Lyons and others (1997). The Pliny region is blown up in the bottom left corner and a legend of the units pertinent to this study is in the upper left corner (modified from: Lyons et al., 1997).

of granites with varying levels of foliation. The deformation history of these granites is the subject of a thesis by Devoe (2015). The granites are defined by the nomenclature Oo1b, Oo1h, and Oolbx. Formation designations are demarcated by amount of biotite, hornblende, and the coarse grained phase of the biotite rich member, respectively. The map by Eusden and others (2015) also includes a series of northeast-southwest striking silicified shear zones and a significant mafic dike known as the Mill Brook Dike Zone striking roughly north-south. A detailed analysis of the Mill Brook Dikes Zone's origin and mineralogy can be found in Oxman's (2015) thesis. The identification of these features is important for this study because the northern contact of Oo1h and Oolb project into the Jefferson quadrangle. Evidence of silicification and mafic intrusions related to the Mill Brook Dike Zone may also be correlated to features mapped in the Jefferson Quadrangle.

1.3 Basic Description and Mineralogy of Previously Identified Units

Czamanske and others (1977) performed an in depth mineralogical analysis of the units mapped by Eichelberger (1971). This section will rely heavily on their findings to describe the basic mineralogy and traits of previously identified units. However, Randall and Foland (1987) and Foland and Loiselle (1981) provide data and analysis altering many of the relative ages assigned by Czamanske and others (1977). The updated relative ages will be used to order the following descriptions from youngest to oldest. Table 1 shows the evolution of unit classification

Unit Type	Contemporary Unit Description	Evolution of unit Nomenclature			
		Chapman (1942)	Eichelberger (1971)	Czmanske et al., (1977)	Lyons et al., (1997)
Igneous Extrusive	Rhyolite	-	-	-	-
Igneous Intrusive	Conway Granite	cg	cg	cg	Jc1b
	Pink Biotite Granite	-	pbg	pbg	Jc1b
	Hastingsite Quartz Syenite	hqs	mhg	hqs	J4h
	Porphyritic Quartz Monzonite	-	pqm	pqm	J4h
	Quartz Monzodiorite	qm	qmd	qmd	J5
	Diorite	qm	qmd	d	J5
	Medium Syenite	-	ms	ms	Oo4Ch
	Coarse Syenite	cs	cs	cs	Oo4Ch
	K-feldspar Orthogneiss	-	-	-	-
	Hornblende Granite Orthogneiss	hqm	hgn	hgn	Oo4Ch
	Biotite Granite Orthogneiss	-	-	-	Oo1b

Table 1: A description of units mapped in the southern half of the Jefferson quadrangle and evolution of their nomenclature through previous mapping efforts.

and nomenclature throughout the history of mapping in the Pliny Region.

1.3.1 Jurassic Units

All units are listed from youngest to oldest based on relative and analytical ages from Czamanske and others (1977), Foland and Loiselle (1981), and Randall and Foland (1987).

Conway Granite: This unit is typically coarser grained than the pink biotite granite and pale pink to white-tan in color. It contains subhedral quartz grains, prominent on weathered surfaces, flecks of biotite and amphibole, and both alkali feldspar and plagioclase (Czamanske et al., 1977).

Pink Biotite Granite: The pink biotite granite is typically medium-grained and contains pink perthite contrasting strongly with white plagioclase accompanied, in decreasing abundance, by clear quartz and biotite (Czamanske et al., 1977).

Porphyritic quartz monzonite: This unit has uniform texture and composition. It contains large intensely pink alkali feldspar phenocrysts and abundant quartz in small shattered aggregates. The intensity of the pink color is the major differentiating component in field observations between it and the coarse syenite (Czamanske et al., 1977).

Hastingsite quartz syenite: This unit is generally whitish orange-pink in color, which is derived from its predominant constituent, perthite. Quartz crystals are prominent, clear, and defined to the interstices of the feldspar grains. Hornblende and minimal biotite are also present (Czamanske et al., 1977).

Diorite: The diorite is coarse to medium-grained and typically uniform in hand-specimen. The unit contains approximately one third mafic minerals and negligible amounts quartz and alkali feldspars and has a ‘salt and pepper appearance’ (Czamanske et al., 1977).

Quartz monzodiorite: The quartz monzodiorite is nearly identical to the diorite except it contains a larger fraction of quartz (Czamanske et al., 1977).

1.3.2 Ordovician Units

Medium Syenite: This unit is very similar to the coarse syenite with major distinguishing features being its overall finer grain size and lower mafic content. In hand specimen the medium syenite appears to consist entirely of alkali feldspar except for minor fine-grained mafics, including magnetite, in the matrix (Czamanske et al., 1977).

Coarse Syenite: The coarse syenite ranges from coarse to very coarse grained with pink perthite phenocrysts up to 2 cm long. A minor abundance of plagioclase phenocrysts exist as well, but the dominant color is pink due to the predominance of perthite. Other constituents in the matrix, in order of decreasing abundance include quartz, amphibole, biotite, sphene, and magnetite (Czamanske et al., 1977).

Hornblende granite Orthogneiss: This unit is typically highly foliated and has a layered appearance with a light to dark ground mass. The light layers consist dominantly of plagioclase with minor contributions of quartz. The plagioclase crystals are typically elongated, tabular, and occasionally very coarse with phenocrysts reaching lengths of up to 3 cm. The dark layers are dominated by hornblende and oriented biotite crystals (Czamanske et al., 1977).

1.4 Previous Experimental Geochronology and Petrogenesis Studies

Radiometric decay systems are important tools for acquiring precise experimental control on the time-scales of events throughout terrestrial and extraterrestrial geologic time (Faure and Mensing, 2005). A number of different radiometric decay systems can be used to acquire experimental dates, three of which will be discussed in this study Rb-Sr, $^{40}\text{Ar}/^{39}\text{Ar}$ + K-Ar, and U-Th-Pb. Each of these techniques are foundationally based on the radiometric decay principles of decay half-life, time it takes for the radioactivity of a parent isotope to fall to half its original value, and secular equilibrium (Faure and Mensing, 2005; Schoene, 2014). In order for a method to be a useful radiometric dating technique the parent isotope must have a half-life that is greater than the age of the tested samples. ^{238}U has a half-life of approximately 4.5 billion years, conveniently the same age as the Earth making its decay system and ideal method for determining dates for samples in the millions to billions of years-old scale. Secular equilibrium is the process whereby one atom of parent isotope will decay into one atom of stable daughter isotope in a closed system, where no parent or daughter isotope is lost or gained. Before decaying to a daughter isotope with a significantly long half-life to reach stability the parent isotope will decay through a series of short-lived daughter isotopes. An example of secular equilibrium in ideal conditions is the decay of ^{238}U - ^{206}Pb .

The above mentioned decay systems can be used to determine sample ages by measuring the ratio of parent to daughter isotopes for a given sample. The ratio of daughter isotope to

Figure 7: A plot of number of publications per year of a number of radioisotopic dating methods including the U-Th-Pb technique. Curves were made by counting all publications per year with the dating method listed in the title (Schoene, 2014; www.webofknowledge.com).

a non-radiogenic isotope of the same element (i.e. $^{206}\text{Pb}/^{204}\text{Pb}$) is used as a normalization tool to establish the parent/daughter ratio rather than determining the molar concentrations of the relevant parent and daughter isotopes. Determining molar concentration is associated with much higher uncertainty than the ratio technique. With a known system decay constant the normalization ratio, and parent/daughter ratio can be run through standard isochron age equations to solve for a date at time t . There are a number of techniques that can be used to acquire these ratio measurements and manipulate the raw data into usable information (Faure and Mensing, 2005; Schoene, 2014). Those involving the Rb-Sr and $^{40}\text{Ar}/^{39}\text{Ar} + \text{K-Ar}$ decay systems will be discussed briefly in the sections 1.4.1.1 and 1.4.2.1 respectively. The techniques involved in the U-Th-Pb decay system will be discussed in-depth in section 2.3.3 of the methods. U-Th-Pb analysis was chosen in this study due to its reproducibility, accuracy, precision, and efficiency as indicated in figure 7 demonstrating the dramatic increase in the technique's prevalence in the literature relative to other dating techniques.

1.4.1 Foland and Loiselle, 1981

1.4.1.1 Rb-Sr Geochronology

In 1981 Foland and Loiselle published a study using Rb-Sr isotopic measurements to experimentally date the medium and coarse syenites mapped by Eichelberger (1971), who placed their relative ages as predating the WMMS and post-dating the OPS. Experimental dating through the Rb-Sr technique involves analysis of the molar concentration ratio of parent isotope ^{87}Rb to daughter isotope to ^{87}Sr using an isochron equation where λ is the decay constant of ^{87}Rb in (y^{-1}) and t is the time elapsed in years since the time of formation of the mineral (equation 1) (Faure and Mensing, 2005).

$$\text{Eq. (1): } ^{87}\text{Sr}/^{86}\text{Sr} = (^{87}\text{Sr}/^{86}\text{Sr})_0 + ^{87}\text{Sr}/^{86}\text{Sr}(e^{\lambda t} - 1)$$

The standard method for acquiring pertinent isotope ratio data is by isotope dilution and mass spectroscopy (Faure and Mensing, 2005). With known molar concentrations of the parent and daughter isotopes the raw data set can then be plotted on a 2d isochron plot where the ratio $^{87}\text{Rb}/^{86}\text{Sr}$ (the non-

Figure 8: The Rb-Sr isochron diagram of the coarse and medium syenites yielding an age of 441 ± 5 Ma (modified from: Foland and Loiselle, 1981).

radiogenic tracer isotope) is on the x-axis and the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is on the y-axis (Schoene, 2014). The Rb-Sr isochron plot Foland and Loiselle (1981) produced from analyzing six coarse syenite and four medium syenite samples is shown in figure 8. The data points fall on a linear trend therefore satisfying the conditions necessary for use of an isochron plot. The isochron regression line in the plot is for the syenites only and not the biotite quartz monzonite, which is a formation not relevant to this study. Using equation 1 the crystallization of the syenites was determined to be 441 ± 5 Ma. This age was used for the regional units in the Lyons and others (1997) bedrock map of New Hampshire. This experiment provides radiometric age control for the syenites, placing their origin on the Ordovician-Silurian boundary within error (entirely within the Ordovician based on their designation of geologic periodicity at the time) as members of the OPS, rather than post-OPS and pre-WMMS as thought by Eichelberger (1971) and within the WMMS and pre-PRCC as theorized by Czamanske and others (1977).

This study was performed over three decades ago. Since then the Rb-Sr technique was largely abandoned by experimental geochronologists in-lieu of more precise and efficient techniques such as those involving the U-Th-Pb system to be discussed in section 2.3.3 of the methods. A limitation of the Rb-Sr technique is that it is difficult to account for discordance in samples, therefore any instances of isotope loss or gain could contribute to error in the resulting measurement. In this study an unexpected younger Silurian age for the medium and coarse syenites acquired from xenocrystic country-rock zircons in a U-Th-Pb dated Jurassic rock will serve to update the Rb-Sr date acquired by Foland and Loiselle (1981).

1.4.1.2 Petrogenesis of the Syenites

Foland and Loiselle (1981) propose partial melting of eclogite, an alkali rich rock-type typically derived from high pressure metamorphism related to subduction, as the source for the coarse and medium syenites. This assertion is derived from the syenites' high alkali content and other geochemical similarities to monzonitic rocks of eclogitic origin examined by Hanson (1975), Miller (1977, 1978), and Simmons and Hedge (1978). Foland and Loiselle (1981) further delineate the source of the eclogite to either altered mid-oceanic ridge basalt (MORB) or island-arc tholeiite because of their chemical similarities to the syenites, unaltered MORB is infeasible based on the abundance of K, Sr, Ba, Rb, and other large-ion-lithophile elements. Based on Foland and Loiselle's (1981) age for the syenites of 441 ± 5 Ma this petrogenesis model may be related to tectonics associated with the waning third phase of the Taconic orogeny (see section 1.5.1 for details on the Taconic Orogeny).

1.4.2 Randall and Foland, 1987

1.4.2.1 K-Ar Geochronology

In 1987 Randall and Foland conducted a $^{40}\text{Ar}/^{39}\text{Ar}$ analysis to determine the cooling ages (time at which the samples moved past the blocking temperatures of the tested minerals) of seven members of the PRCC, six of which have relevance to this study: Conway granite, pink biotite granite, Hastingsite quartz syenite, porphyritic quartz monzonite, quartz monzodiorite, and diorite. The ages for all the tested units were determined to be between 182.6 to 184.0 Ma with errors ranging from ± 0.2 to ± 0.8 Ma, with a concordant spectrum of age for all units at 183.2 ± 1.8 Ma (table 2). From these ages Randall and Foland (1987) conclude that the PRCC intruded in rapid succession. In addition, the near identical ages for hornblende and biotite (different blocking temperatures) suggests rapid cooling and shallow depth of emplacement. The time span of emplacement was such that it could not be resolved analytically and appears to have been within ~ 1 m.y.

The $^{40}\text{Ar}/^{39}\text{Ar}$ technique is based on the formation of ^{39}Ar by irradiation of K-bearing minerals, biotite and amphibole in the case of the Randall and Foland (1987) study (Faure and Mensing, 2005). This technique was chosen over the conventional K-Ar technique due to the complex intergrowth and relict cores of biotite and amphibole within the PRCC units. K-Ar requires separate aliquots for K and ^{40}Ar measurements. $^{40}\text{Ar}/^{39}\text{Ar}$ can be used on complex samples and allows for analysis of potential resetting because biotite and amphibole have different blocking temperatures, 300°C and 500°C respectively (Randall and Foland, 1987; Faure and Mensing, 2005). Ratios of radiogenic ^{40}Ar to ^{39}Ar are used in the $^{40}\text{Ar}/^{39}\text{Ar}$ technique as opposed to molar concentrations in the K-Ar technique allowing for increased precision (Faure and Mensing, 2005). Randall and Foland (1987) utilized a stepwise induction heating method to release the argon allowing for separate analysis of the constituent minerals, biotite and amphibole. A detailed description of their method can be reviewed in the Argon analysis section of Randall and Foland (1987). The data is represented graphically with apparent age on the y-axis and cumulative percent of Ar released on the x-axis. The apparent age is calculated by equation 2, where J is a constant determined through irradiating a sample of known age (the flux monitor) together with samples of unknown age, λ is the decay constant of ^{40}Ar in (y^{-1}), and t is the time elapsed in years since the time of formation of the mineral (Faure and Mensing, 2005).

$$\text{Eq. (2): } t = 1/\lambda \ln((^{40}\text{Ar}^*/^{39}\text{Ar})J+1)$$

TABLE 1. SUMMARY OF $^{40}\text{Ar}/^{39}\text{Ar}$ AGES FOR MINERAL SEPARATES BY ROCK AND MINERAL TYPE AND FOR ALL WMMS UNITS OF PLINY COMPLEX

$^{40}\text{Ar}/^{39}\text{Ar}$ total-gas ages by unit and mineral	Number of analyses	Average total-gas age	Standard deviation	Standard deviation of the mean
CONWAY GRANITE				
Y O Biotite:				
U (183.1; 182.7; 182.4; 182.6; 181.7; 183.6)	6	182.7	0.6	0.3
N Amphibole:				
G (182.6; 183.2)	2	182.9	..	..
E Biotite, amphibole:	8	182.7	0.6	0.2
S				
T				
PINK BIOTITE GRANITE				
Biotite:				
(185.6; 183.2; 183.5; 183.3; 183.8; 182.3)	6	184.0	1.3	0.5
HASTINGSITE QUARTZ SYENITE				
Amphibole:				
(181.4; 182.1; 184.7; 182.8; 182.7; 182.4)	6	182.7	1.1	0.5
PORPHYRITIC QUARTZ MONZONITE				
Biotite:				
(182.3; 184.2; 184.8)	3	183.8	1.3	0.8
QUARTZ MONZODIORITE				
Biotite:				
(181.9; 181.7; 183.9; 183.1; 182.9; 183.2; 183.2; 180.6)	8	182.6	1.1	0.4
Amphibole:				
(181.9; 183.9)	2	182.9	..	..
Biotite, amphibole:	10	182.6	1.1	0.3
DIORITE				
O L Biotite:				
D (183.8; 182.6; 182.3; 184.9; 185.3; 183.5)	6	183.7	1.2	0.5
E S T				
A Biotite:	29	183.2	1.2	0.2
L Amphibole:	10	182.8	1.0	0.3
L Biotite plus Amphibole:	3	183.5	0.5	0.3
U N I T S				
ALL SAMPLES:	42	183.2	1.1	0.2

Note: the units are listed according to relative emplacement age determined on the basis of field relations. Ages and uncertainties at the one-sigma level are in millions of years.

Table 2: A summary of ages determined through $^{40}\text{Ar}/^{39}\text{Ar}$ for units pertinent to this study from the PRCC. The summary includes cooling ages for biotite and amphibole, where appropriate, for each unit as well as the average cooling age for all units (highlighted in red) (modified from: Randall and Foland, 1987).

Figure 9: An example of age spectra, calculated through the $^{40}\text{Ar}/^{39}\text{Ar}$ technique, from the PRCC unit quartz monzodiorite. These results indicate the concordance of amphibole and biotite from an early intrusive phase. The graph illustrates not only the internally concordant spectra, but also the concordance of ages for “end members” of the emplacement sequence. T_p and T_{tg} represent plateaus and total-gas (sum of all fractions) $^{40}\text{Ar}/^{39}\text{Ar}$ ages, respectively. The patterned blocks represent $+1$ sigma uncertainties without an uncertainty in the J value of the isochron equation. The arrows indicate the average $^{40}\text{Ar}/^{39}\text{Ar}$ for the complex (Randall and Foland 1987).

Concordant ages are identified by plateaus where the rate of argon released and the radiogenic $^{40}\text{Ar}/^{39}\text{Ar}$ ratio remain constant. An example of a plateau age from Randall and Foland (1987) can be seen in figure 9. This technique is well tested for reproducibility and precision and is capable of producing results with relative precision within ~ 1 M.y. or less (Randall and Foland, 1987; Faure and Mensing, 2005).

1.4.2.2 Petrogenesis of the PRCC

Randall and Foland conducted a whole-rock Rb-Sr isotopic analysis on 25 samples of the felsic units in the Pliny Range including Conway granite, hastingsite biotite granite (Jhbg), granite porphyry (Jgb), pink biotite granite, and hanstingsite quartz-syenite. Jhbg and Jgb were mapped by Eichelberger (1971) in areas of the Pliny Range beyond the extent of this mapping effort. When plotted on an isochron diagram, the whole-rock samples demonstrate considerable heterogeneity along the regression line (figure 10). This indicates that the $^{87}\text{Rb}/\text{Sr}^{86}$ ratio was heterogeneous when the magma chamber was first generated and the heterogeneity did not result from a mixing event prior to eruption. Furthermore, this indicates that the geochemical diversity of the PRCC magmas cannot be accounted for by simple crystal fractionation and are rather primarily mantle-derived magmas with considerable crustal-contamination. In summation, there

Figure 10: An Rb-Sr isochron plot for 25 whole-rock samples of felsic PRCC units including granite porphyry and hastingite biotite granite not mapped in this study. The significant heterogeneity of the Rb/Sr ratios can be observed by the spread of the samples along the regression line (Randall and Foland, 1987).

was likely extensive interaction between one or more magma chambers and country-rock melting within ~1 M.y. or less producing significant chemical and isotopic diversity within the PRCC (Randall and Foland, 1987). This finding indicates that PRCC magmatic diversity, stemming from different times of formation, is not as feasible an option (Czamanske et al., 1977).

1.5 Orogenic History of the Northern Appalachians

The bedrock geology of the northeastern United States records one of the most complex and longest lived mountain building events in geologic history: the Appalachian Mountains. Due to the complexity of this orogeny it is useful to study the tectonics in two sections: the Northern and Southern Appalachians.

Figure 11: The Lithotectonic units of the Appalachian orogeny. The study site is most strongly affected by the accretion of Gander, Avalon, and Meguma related to the Devonian Acadian, Devonian-Carboniferous Neo-Acadian, and Permian Alleghanian orogenies. The deformation from these events is resultant from compressional and transpressional stress (modified from: Hibbard et al., 2010)

A portion of this study will focus on northern Appalachian tectonics, which dominate the mountainous territory stretching from Newfoundland, Canada to the island of Manhattan, NY (Hatcher, 2010; Hibbard et al., 2010) (figure 11). Accretionary history of the Appalachians began with the formation of the Iapetus and Rheic Oceans and the paleo-continents Laurentia and Gondwana from the rifting of the supercontinent Rodinia 750 Ma. The oceans were separated by a series of peri-Gondwanan and peri-Laurentian ribbon continents and micro terranes that rifted from their respective parent continents. 500 Ma the passive margin of Laurentia developed into a subduction zone causing the accretion of peri-Laurentian terranes, followed by peri-Gondwanan terranes, and lastly the north-south zippering of Gondwana and Laurentia. This sequence can be partitioned into five major accretionary events: The Ordovician Taconic orogeny, the Silurian Salinic, the Devonian Acadian, the Devonian to Carboniferous Neo-Acadian, and ending with the Mississippian Permian Alleghanian orogeny. The Alleghanian marked the formation of Pangea and the completion of a full Wilson Cycle, initiated approximately 750 million years ago (Ma) with the break-up of Rodinia (Hatcher, 2010; Hibbard et al., 2010; Eusden et al., 2013.)

1.5.1 Taconic Orogeny (~495-450 Ma)

The Taconic orogeny marks the first accretionary event of the northern Appalachians. The orogeny is generally broken into three intermediate events, Taconic 1, 2, and 3, with the first two involving the collision of peri-Laurentian terranes and the third the accretion of the first in

Figure 12: Tectonic models produced by Van Staal and others (2009) depicting the evolution of Taconic 1 into the initiation of Taconic 2. a) Taconic 1: Formation of the Lush Bight oceanic tract terrane through subduction initiation and rapid hinge retreat of the east-dipping Dashwoods plate. b) Taconic 2: The arc-arc collision of the Baie Verte oceanic tract and Notre Dame arc (Shelburne Falls arc) from the stepping back of the subduction zone in the Humber Seaway. This collision slowed down convergence in the Humber Seaway potentially leading to the initiation of west-directed subduction outboard of Dashwoods. This subduction led to the formation of the Annieopsquotch ophiolite belt (modified from: Van Staal et al., 2009).

a series of peri-Gondwanan terranes (van Staal, 2005; van Staal et al., 2009). Taconic 1 (495 MA) involved the development of an east-dipping subduction zone on the eastern side of the Dashwoods Terrane. Rapid roll-back of this subduction zone produced the Lush Bight Oceanic Tract, a fledgling island-arc system. Subduction led to west-directed obduction of the Lush Bight Oceanic Tract (LBOT) onto Dashwoods (Figure 12a). During Taconic 1 Dashwoods was separated from the Laurentian passive margin by the Humber Seaway. Taconic 2 was initiated by the onset of east-dipping subduction at the western margin of the Humber Seaway (van Staal et al., 2009; Macdonald et al., 2014). East-dipping subduction generated the per-Laurentian

Notre Dame arc. Continued subduction eventually caused the closing of the Taconic seaway and the Notre Dame Arc and Dashwoods LBOT composite to collide with Laurentia 475 Ma (van Staal et al., 2009; Macdonald et al., 2014; Waldron and van Staal, 2001). Van Staal and others (2009) believe this impact slowed convergence generating a west-dipping subduction zone, which then lead to the production of the Annieopsquotch ophiolite belt (AOB) outboard of the Notre Dame arc and inboard of the new subduction zone (figure 12b). Emergence of the new subduction zone forced the eastward obduction of the AOB onto the western margin of the Notre Dame arc (480-464 Ma). The Notre Dame arc reached peak igneous activity as the Shelburne Falls arc following its accretion to Laurentia (van Staal et al., 2009; Macdonald et al., 2014). The final collision of Dashwoods with the Humber margin caused the westward thrusting of the AOB and generation of the Annieopsquotch oceanic tract coeval with plutonism in the accreted Notre Dame arc from slab break-off of the east-dipping subduction zone. Taconic 2 ended with the late Ordovician (470-460 Ma) initiation of a Molucca Sea-style subduction zone. Due to its

Figure 13: Tectonic models produced by Van Staal and others (2009) depicting the termination of Taconic 2 into Taconic 3. a) Taconic 2: Collision of Dashwoods with the Humber Margin leading to east-directed thrusting at its boundary with the Annieopsquotch ophiolite belt (AOB). Thrusting lead to the closure of the AOB and accretion of parts of the Red Indian Lake arc. b) Taconic 3: Collision and accretion of the Popelogan-Victoria (the leading edge of Gander) closing the main Iapetan oceanic tract (modified from: Van Staal et al., 2009).

complexity Taconic 2 is displayed as two cross-sections spanning two time intervals, 480Ma-470Ma and 470-460Ma respectively, displayed in figures 12b and 13a respectively. (Van Staal et al., 2009). Taconic 3 (460-450 Ma) involved arc-arc convergence between the Peri-Laurentian Red Indian Lake arc and peri-Gondwanan Popelogan Victoria arc (PVA), originating west and east of the Molucca Sea-style subduction zone respectively (figure 13b) (van Staal et al., 2009). This impact generated the mid-Ordovician growth of the Bronson Hill arc (BHA) (figure 13b) (van Staal et al., 2009; Macdonald et al., 2014; Moench and Aleinikoff, 2003).

1.5.1.1 The BHA and Oliverian Plutonism

The generation and subsequent plutonism associated with the BHA is of particular import to this study because it is believed to be the origin of the three Ordovician orthogneisses of the OPS, mapped in this study (Karabinos et al., 1998; Moench and Aleinikoff, 2003). There are many models that attempt to explain the tectonics of the BHA. The most recent literature, van Staal and others (2009), Hatcher (2010), and Macdonald and others (2014), favor a model where the BHA occurs after the accretion of the PVA to Laurentia (figure 14). The theories involve the existence of west and east dipping subduction zones and the accretion of west Gander (the PVA) following the subduction of the spreading ridge separating the subduction zones. The Molucca Sea-style collision and potential flat-slab subduction gave rise to contact crustal melting and the OPS around 458 Ma (Macdonald et al., 2014; Moench and Aleinikoff, 2003). Another theory of note involves the formation of the BHA off-shore of Laurentia as the volcanic arc accompanying a west-dipping subduction zone with eventual collision due to continued crustal shortening following the accretion of Dashwoods (Karabinos et al., 1998).

As indicated by the diversity of contemporary tectonic models considerable controversy still

Figure 14: Tectonic model developed by Macdonald and others (2014) depicting a similar mechanism as illustrated in Van Staal and other's (2009) model of Taconic 3. Plutonism and creation of the Bronson Hill Anticlinorium follows the convergence of west Gander (Popelogan-Victoria arc) with composite Laurentia (modified from Macdonald et al., 2014).

exists surrounding the source of the OPS. Dorais and others (2008) used isotopic analysis in an effort to identify the petrological origin of the OPS and to further constrain the tectonic environment of formation. Dorais and others (2008) found island arc isotopic signatures in the OPS. This finding is in contrast to the island-arc tholeiite signature of the slightly older overlying Ammonoosuc Volcanics (see section 1.5.3.1 on Jefferson doming) (Moench and Aleinikoff, 2003). In addition to these tectonic signatures, isotopic analysis indicates the derivation of OPS melt from mixing of both Gondwanan and Laurentian derived crust. This suggests proximity of the BHA to Laurentia during magma mixing and therefore, autochthonous growth of the Oliverian plutons (Dorais et al., 2008).

1.5.2 Salinic Orogeny (~420-423 Ma)

Of the five major accretionary sequences of the northern Appalachians, the existence of the Salinic orogeny is the most controversial. The event suggests the collision of East Gander with Laurentia on the trailing end of the PVA with the premise that Gander was divided into

Figure 15: A schematic model showing peri-Laurentian migration of the southeasterly dipping subduction zone attached to the western margin of the Popelogan-Victoria Arc (PVA), leading to back-arc rifting of the PVA into a series of ribbon continents. The rift margin between the southern Tetagouche ribbon and the PVA marks the future sight of Salinic subduction (circled in red) eventually leading to the orogenic merger of the ribbons with composite Laurentia prior to the main extent of Gander (modified from: Van Staal, et al., 2015)

east and west components separated by the Tetagouche-Exploits basin (van Staal et al., 2009; Hibbard et al., 2010). Van Staal and others (2015) suggest a peri-Laurentian migration of the southeasterly dipping subduction zone attached to the western margin of the PVA. This migration led to back-arc rifting and the formation of several ribbon terranes before the arc's collision with Laurentia (470-465 Ma). The rift zone marked the site of the future Salinic subduction zone, which would eventually lead to the collision of the peri-PVA ribbons with composite Laurentia prior to the main extent of Gander (figure 15) (Van Staal et al., 2015). Preceding this study the existence of Silurian meta-sedimentary rocks and subtle structures were the only indicators of the existence of the orogeny (Eusden, 2015; Eusden, 2010).

1.5.3 Acadian and Neo-Acadian Orogenies (~410-345 Ma)

The Acadian and Neo-Acadian orogenies were the dominant event in the formation of the New England and Canadian Appalachians. The orogenies are characterized by the north-south zippered closure of the Rheic Ocean and collision of the peri-Gondwanan superterranes Gander and Avalon with the northeastern coast of North America followed by Meguma, of which the deformational effects were felt most strongly in New Brunswick and Newfoundland. New England marks the overlap point of these two events and saw effects from both the accretion of Gander and Avalon associated with the Acadian and Neo-Acadian orogenies respectively, with the former occurring before the latter (Hatcher, 2010; Hibbard et al., 2010). These events are associated with poly-phase and high-grade metamorphism of wedge mélangé and marine clastic sediments and extensive plutonism. (Hatcher, 2010; Robinson et al., 1998).

1.5.3.1 Oliverian Jefferson Doming

The formation of the Oliverian Jefferson Domes, of which the Ordovician country-rock in this study is a part of, occurred during the Acadian and possibly into the Neo-Acadian orogenies. The mechanism for doming is two-fold with models supporting the combination of bimodal magma density differences and compressive forces of the Acadian and Neo-Acadian orogenies. The Ammonoosuc Volcanics, (461±8 Ma) deposited preceding Oliverian plutonism (454±5 Ma) and before doming, have a dense tholeiitic composition (Moench and Aleinikoff, 2003; Leo, 1991). Dorais and others (2012) suggest a faulted relationship between the Ammonoosuc Volcanics and the OPS where the former was obducted onto Laurentia during the late stages of the Taconic orogeny. The underlying Oliverian plutons possess a less-dense calc-alkaline composition. The bimodality of these melts are believed to be related to differences in magma

sources. Partial melting of the down-going slab is favored for the Ammonoosuc and contact melting of the continental crust for the Oliverian plutons (described in greater detail in section 1.5.1.1) (Dorais et al., 2008; Leo, 1991). These density differences combined with orogenic compressive forces caused the Oliverian plutons to rise diapirically through the Ammonoosuc Volcanics and other younger cover (Foley, 2009). This is evidenced by faint shear faulted contacts and the observation of fabrics such as S-C mylonites near the contact between the Ammonoosuc and Oliverian Plutons (Foley, 2009; Eusden et al., 2009).

1.5.4 Alleghanian Orogeny (~345-300Ma)

The Alleghanian orogeny marks the formation of Pangea and the completion of the Wilson Cycle initiated by the rifting of Rodinia 750 Ma. The coalescence of Pangea was completed with the closure of the Theic Ocean as Gondwana and Laurentia collided approximately 300 Ma (Hatcher, 2010; Stewart et al., 1997). A rotational transpressive regime is favored for the collision (Hatcher, 2010). Peak deformation and mountain-building is recorded in the central and southern Appalachians. Evidence of the event is also found in shearing and ductile deformation focused in coastal regions of New England and Canada (Hatcher, 2010; Hibbard et al., 2010; van Staal et al., 2009)

1.6 Extensional Tectonic History

Following its amalgamation Pangea entered a period of relative tectonic quiescence stretching almost 100 million years. Between 210 Ma and 65 Ma the supercontinent experienced a 3-phase rifting sequence. The first phase is most relevant to this study and involved the separation of Africa and North America and the opening of the Atlantic Ocean through a series of northeast-trending rifts (Stewart et al., 1997; LeTourneau and Olsen, 2003). The effects of rifting are recorded distal from the craton with increasing intensity towards the coastal margin. These effects manifest as oriented dike swarms, normal faulting, and small-scale plutonism occasionally associated with volcanism (Stewart et al., 1997).

1.6.1 White Mountain Magma Series (WMMS)

The WMMS was originally defined as a series of granitic plutons, mafic dykes, and caldera complexes thought to originate in the Permian by Billings (1934). It has since been redefined as the White Mountain Igneous Province (WMIP), a two-phase event associated with the opening of the Atlantic with the additional observation of overlapping caldera features

Figure 16: The location of the White Mountain Igneous Province and the Jefferson Quadrangle within it (modified from: Creasy et al., 1993).

(Creasy, et al., 1993; Eby, 1987). The source of the plutonism is ascribed to melting in the lower crust evidenced by contact aureoles or from hot-spot activity (McHone, 1992; McHone and Butler, 1984). The phases of activity are generally confined to two periods 200-165 Ma and 130-110 Ma (Eby et al., 1992). The PRCC is related to the earlier of the two phases. The WMIP follows a general north-northwest trend and is focused in central New Hampshire with minor additions to the North (figure 16).

1.6.3 Caldera collapse

Emplacement of the PRCC follows a model based on the collapse of an early Jurassic

Figure 17: A basic model showing the four (a-d) general phases of caldera formation. a) Establishment of a volcano. b) Increased magmatic activity with small-scale eruptions. c) Cataclysmic explosive eruption. d) Subsidence of central crater along circular ring faults and intrusion of magma along the ring fault planes as ring-dykes or cone-sheets (modified from: Ramxiaoberg, 2008).

caldera (Chapman, 1942; Czamanske et al., 1977). In their review of calderas and caldera structures Cole and others (2005) define a caldera as, “a volcanic structure, generally large, which is principally the result of collapse or subsidence into the top of a magma chamber during or immediately following eruptive activity (figure 17).” Calderas are wide-spread geologic features occurring in a variety of tectonically active environments. Due to the diversity in the processes that create caldera-complexes it is infeasible to sort calderas into distinct end-member categories. Based on the complexity and individuality of calderas Cole and others (2005) suggest describing each locality based on the number of collapse events, collapse geometry, the presence or absence of resurgence or other deformation, and the dominant composition of the erupting magma. The elements of these four categories are described below.

1.6.3.1 Number of Collapse Events

A single caldera can experience multiple collapse events. Collapse is theorized to be caused by one of two mechanisms, underpressure or overpressure of a magma chamber (Geyer and Marti, 2014; Gudmundsson and Nilsen, 2006). The validity of both mechanisms are still debated with the primary-shortcomings of the former being that the eruptive conduit should close before necessary underpressure conditions are reached, and for the latter, inconsistencies between the volume of erupted material and the magnitude of collapse. (Pinel and Jaupart, 2004; Gudmundsson and Nilsen, 2006). Following an initial collapse event it is possible for the magma chamber to experience resurgence and ensuing tumescence of the caldera (Tribaldi, 2015). This can then lead to conditions suitable for a second collapse event. Resurgence can occur several times within the same chamber (Cole et al., 2005). Additionally, collapse of chambers adjacent to the original collapsed chamber can create complexes of nesting or overlapping calderas of different ages (Cole et al., 2005).

1.6.3.2 Collapse Geometry

The faulting leading to caldera collapse can manifest in four end-member mechanisms each producing unique geometries (figure 18). The four end-members are piston/plate, piecemeal, trapdoor, and downsag. The piston/plate mechanism (figure 18a) involves near-vertical fracturing along a prominent ring fault and the subsidence of a coherent block into an evacuating chamber. This typically leads to circular, symmetric calderas with one distinct ring-dyke, or cone-sheet if it dips towards the collapse center (Cole et al., 2005; Tribaldi, 2015). Piecemeal (figure 18b) refers to the near-vertical fracturing and asymmetric collapse of multiple

Figure 18: Four end member mechanisms of caldera collapse: a) piston/plate, b) piecemeal, c) trapdoor, d) downsag (Cole et al., 2005).

floor blocks and/or the production of multiple collapse centers (Branney and Kokelaar, 1994; Cole et al., 2005). This typically generates asymmetric and uneven caldera-floor geometry with multiple overlapping or independent ring-dykes. A subset of the piecemeal mechanism is funnel collapse. This geometry is produced by the production and collapse of megabreccia with increasing magnitude of faulting towards the collapse center. The geometry of funnel mechanisms manifest in symmetric calderas with deep central craters. The trap-door (figure 18c) mechanism is used to explain an instance of incomplete ring-dyking where part of the ring-fracture is hinged. In map-view this creates an asymmetric ring-dyke that does not fully connect. Downsag (figure d), the final end member, is envisioned to explain instances where the ring-fracture does not form or does not penetrate to the surface producing a depression with no visible ring-dyke. It is common for multiple collapse end-member mechanisms to be present in a single collapse event (Cole et al., 2005).

1.6.3.3 The Presence or Absence of Resurgence or Other Deformation

Evidence for resurgence or other deformation events is usually closely tied to the number of collapse events. Fault over-printing or reversal and the intrusion of multiple geochemically distinct ring-dykes are all indicators of deformation and/or resurgence (Cole et al., 2005; Tribaldi, 2015).

1.6.3.4 The Dominant Composition of Erupting Magma

The dominant composition of erupting magma is generally indicative of the tectonic environment of caldera-formation. The end-member compositions include basaltic, peralkaline, andesite-dacitic, and rhyolitic calderas. Basaltic calderas can be either effusive or explosive and are associated with shield volcanoes and hotspots such as Hawaii and the Galapagos (Walker, 1988; Cole et al., 2005). Peralkaline calderas are typically correlated to rift-zones and the production of shield-like volcanoes. The collapse of these volcanoes into calderas is typically in response to explosive eruption of tuffaceous material (Marti and Gudmundsson, 2000; Cole et al., 2005). Andesitic-dacitic magma is typically associated with calderas derived from the destruction of stratocones. Crater Lake, Utah is a prime example of this composition end-member (Bacon, 1983; Cole et al., 2005). Rhyolitic calderas typically have the largest collapse depressions at approximately 10 Km or more in diameter and are associated with the largest pyroclastic deposits. They are usually found in areas that have experienced considerable volcanism through an extended time-period before the caldera-forming event (Cole et al., 2005).

2. Methods

2.1 Field Mapping

Field mapping the southern half of the 7.5' Jefferson Quadrangle, as part of the StateMap/NGCPM program, was conducted over a five-week period from early June to mid-July of 2015. The study area has varied topography and land-use. Elevations range from around 330 m (1,080 ft) in Jefferson Valley to the summit of Mount Waumbek at around 1,221 m (4,006 ft). Land-use varies from forested to small-scale development (i.e. paved and dirt roads, residential homes, small businesses and agriculture) centered around the town of Jefferson and in the valley to the southwest. The study area contains 10-15% exposed bedrock with the remainder dominated by glacial deposits such as lake and flood plain deposits and till.

In order to effectively locate and map a variety of diverse outcrop exposures, previous studies, the USGS topographic map of the quadrangle (figure 19), and local resources were consulted. Marked exposures and contacts on Chapman's (1942) and Eichelberger's (1971) maps were revisited and the maps were analyzed for trends in outcrop exposure to plan traverses. The topographic map of the study site was consulted to find areas likely to contain exposure such as south to western facing ridgelines and both active and paleo-stream beds. The portion of the study site that is within the White Mountain National Forest has one meter resolution LiDAR data (collected from 2010-2012 and processed in 2013 by Photo Science Geospatial, contracted by the United States Geological Service). An ArcGIS hillshade of this data was used as an additional tool to find outcrop. An azimuth of 315° and angle 45° was used for the hillshade to best illuminate bedrock features. Google satellite images were used to find sites likely to contain exposure such as areas of recent logging and paleo/contemporary roads and trails. Community members, including the Randolph, NH town Forester Walter Wintturi, were consulted to find outcrops not likely to be discovered from other methods. There is a hiking trail network located on the ridgeline of the Pliny Range that was utilized for traverses, but the majority took place as off-trail bush-whacks.

Once an outcrop was discovered its location and pertinent information were recorded. A Juno Trimble was used to procure GPS points of outcrop locations and spatially locate them on a georeferenced digital and paper versions of the topographic map of the quadrangle. Pertinent data was entered into the TerraSync program on the Trimble including unit, mineralogy, and

[illegible]

- Figure 19: The USGS topographic map of the 7.5' Jefferson Quadrangle showing the locations of the clear-cut used for high resolution mapping and collection locations for the U-Th-Pb geochronology samples of Jurassic Conway granite (Jcg), Jurassic pink biotite granite (Jpbg) and Jurassic rhyolite (Jr) (modified from: USGS).

structural data. If present and measurable, the structural data could include the strike and dip of joints, foliations, veins, and dikes. All strike and dip measurements were made with a Brunton compass using the Right-Hand-Rule. In addition photographs of features such as cross-cutting relationships were taken. The information entered into the Trimbles was also entered into a field notebook to ensure a back-up copy of notes and for more extensive comments and sketches than possible through the digital medium. Samples were collected in an effort to assemble a representative suite of the mapped units and for further lab analysis of mineralogy, cross-cutting relationships and other microstructures of interest. In some cases, such as a sample from a shear zone, collecting an oriented sample was necessary. This involves marking the unit with a permanent marker to indicate the in-situ top of the sample and direction of foliation and lineation (where visible) relative to the top. A total of 290 stops were made in this manner.

2.2 Clear-Cut Mapping

On a routine traverse (06/29/15) a clear-cut of approximately 6 acres in area was discovered on the southern ridge of Mount Joseph Whipple (figure 19). The clear-cut was produced from recent logging by a private landowner, Bob Lottero and contained about 50% exposed bedrock. After initial discovery the clear-cut was re-visited several times in order to produce a large-scale (1:1,500) map to maximize the information that could be gleaned from this rare glimpse at the complexities of the PRCC and OPS interactions.

Matt Duval, of the Bates College imaging center, visited the clear-cut and collected a series of aerial photographs (from an approximate height of 30-90 m (100-300 ft) above ground-level) using a remote controlled drone (figure 20b). The photographs were merged on Photoshop to produce a panorama of the bedrock exposures (figure 20a). The panorama was used as a base-map to perform detailed hand-drawn mapping of the clear-cut. Mapping was performed on a series of northwest-southeast traverses beginning at the northern extent of the clear-cut. The clear-cut was roughly gridded with each grid corresponding to a data and location log in the Juno Trimble and field book. Strike and dip measurements were taken of observed foliations in the outcrops of Ordovician amphibolites and orthogneisses and of Jurassic granitic, pegmatitic, and basaltic intrusions that were observed throughout the clear-cut. Photographs were taken to document the many structural intricacies.

Figure 20: A panorama of the exposures at the clear-cut. Images were captured through b) drone aerial photography and stitched together on Adobe Photoshop by Matt Duvall, Manager of the Bates College Imaging Center (Photo credit: Matt Duval).

2.3 Lab Work

2.3.1 7.5' Quadrangle Map

Field mapping of the study site was undertaken with fellow Bates College geology student Sarah Baker, Professor J. Dykstra Eusden, and Dr. Dwight Bradley (USGS). Professor Eusden participated in field work for the first two weeks of mapping and Dr. Bradley acted in an advisory role for the remaining three weeks of mapping. Preliminary mapping of hand-drawn contacts was performed in collaboration, and Baker (2016) will produce the finalized map on ArcGIS as a primary component of her thesis.

2.3.2 Clear-Cut Interpretive Map

The hand-drawn contacts of the clear-cut and the strike and dip data collected in the field were used to produce an interpretive bedrock map. The contact interpretations for the Ordovician amphibole (Oa) and porphyritic k-feldspar orthogneiss (Oopkg) were made using foliation trends observed in the strike and dip data. The interpretations for the Jurassic Conway granite (Jcg) and Jurassic pink biotite granite (Jpbg) were made using outcrop exposure control and the most prevalent orientations of the exposed intrusions. The southern boundary between the Jurassic quartz monzodiorite (Jqmd) and Oopkg units was delineated by exposures of Jqmd recorded just south of the clear-cut during a traverse associated with the whole-quadrangle mapping effort. Drafts of the map were hand drawn and the final product was scanned, uploaded to ArcGIS as a two color .GIF file, and georeferenced. While in edit mode the .GIF image was converted to polyline features using the “Generate Features Inside Area” tool on the “Arcscan” toolbar. The polylines were then converted to polygons using the “Construct Polygons” tool on the “Advanced Editing” toolbar.

2.3.2.1 Interpretive Cross-Section

An interpretive cross-section drawn northeast-southwest across the center of the clear-cut map was produced based on field-relationships and map patterns. The purpose of the cross-section is to illustrate the interactions and characteristics of the clear-cut units along a vertical profile. To make the cross-section the “Interpolate Line” tool was used to produce a graph showing the cross-section relative to an elevation profile. The graph was manipulated to allow for no vertical exaggeration and uploaded to Adobe Illustrator as a PDF. The PDF was then

blown-up to ~500% and printed to allow drawing of the cross-section by hand using transparent mylar and correlation to a printed version of the clear-cut map. Once drawn by hand the cross-section was scanned and digitized in Adobe Illustrator.

2.3.3 Uranium-Thorium-Lead (U-Th-Pb) Geochronology

Thanks to a contact afforded by Dr. Dwight Bradley (USGS) an opportunity to do an experimental geochronological analysis on some of the mapped units from this study became available through GeoSep Services Inc. and Dr. Paul O’Sullivan. The utilized technique was Laser ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS), which involves the stable isotope geochemistry of the U-Th-Pb system and the collection and calculation of parent and daughter isotope ratios. This analysis method was chosen because the U-Th-Pb method yields an age of crystallization of tested zircon grains. This contrasts the $^{40}\text{Ar}/^{39}\text{Ar}$ analyses that yielded the time at which the temperature moved past the blocking temperatures of amphibole and biotite, as conducted on the PRCC by Randall and Foland (1987). The U-Th-Pb method is also the current standard for experimental geochronology with considerable published literature and experimentation supporting its accuracy and reproducibility (figure 7) (Schoene, 2014). Due to cost constraints only three units were analyzed using the U-Th-Pb method. Two of the units chosen were the Jurassic Pink biotite granite (Jpbg) and Jurassic Conway granite (Jcg) because of previously unidentified cross-cutting relationships observed at the clear-cut. The third unit was the rhyolite (Jr) and it was chosen because it was first mapped in this study and has yet to be dated experimentally.

2.3.3.1 Principles of U-Th-Pb Geochemistry

U-Th-Pb geochronology is based on the principles of radiogenic isotope geochemistry. Pb has four naturally occurring stable isotopes, Pb^{204} , Pb^{206} , Pb^{207} , and Pb^{208} , of which the latter three have a radiogenic component produced through the independent decay of ^{238}U , ^{235}U , and ^{232}Th respectively. Pb^{204} is the only nonradiogenic Pb isotope (Schoene, 2014; Faure and Mensing, 2005). By determining the ratio of parent isotope (U or Th) to daughter product (Pb) it is possible to pinpoint the date at which radiogenic decay of the parent isotope began through age equations 3-5 (Schoene, 2014).

$$\text{Eq. (3): } (^{206}\text{Pb}/^{204}\text{Pb}) = (^{206}\text{Pb}/^{204}\text{Pb})_0 + (^{238}\text{Pb}/^{204}\text{Pb})(e^{\lambda_{238}t} - 1)$$

$$\text{Eq. (4): } (^{207}\text{Pb}/^{204}\text{Pb}) = (^{207}\text{Pb}/^{204}\text{Pb})_0 + (^{235}\text{Pb}/^{204}\text{Pb})(e^{\lambda_{235}t} - 1)$$

$$\text{Eq. (3): } (^{208}\text{Pb}/^{204}\text{Pb}) = (^{208}\text{Pb}/^{204}\text{Pb})_0 + (^{232}\text{Th}/^{204}\text{Pb})(e^{\lambda_{232}t} - 1)$$

λ_{238} , λ_{235} , and λ_{232} are the radiogenic decay constants for the parent isotopes ^{238}U , ^{235}U , and ^{232}Th respectively. The subscript 0 follows the isotopic ratio of Pb when the system is closed (e.g., crystallization of the tested zircon grain where there is no Pb loss or gain) and t is the time since the system closed. In most isotopic geochronological analyses a stable isotope of the daughter element is chosen for normalization, Pb^{204} (AKA common Pb or nonradiogenic Pb) fills that role in this situation. Normalization allows for the removal of systematic uncertainty involved in calculating the molar concentration of both parent and daughter isotopes allowing, instead, for their ratios to be utilized, which can be measured very precisely compared to their concentrations.

In some mineral systems the contribution of common Pb is negligible compared to the radiogenic component. This is the case for zircon crystals thus equations 3-5 can be modified to equations 6-8 below, where the * indicates that the isotopes are radiogenic (Schoene, 2014).

$$\text{Eq. (6): } (^{206}\text{Pb}^*/^{238}\text{U}) = (e^{\lambda_{238}t} - 1)$$

$$\text{Eq. (7): } (^{207}\text{Pb}^*/^{235}\text{U}) = (e^{\lambda_{235}t} - 1)$$

$$\text{Eq. (8): } (^{208}\text{Pb}^*/^{232}\text{Th}) = (e^{\lambda_{232}t} - 1)$$

These equations are used for the basis of Concordia analysis described in section 2.3.3.5.

2.3.3.2 Sample Collection

Samples of the three experimentally dated units were collected during summer field work. Locations of each sampled outcrop were recorded in the Juno Trimble and before and after pictures of the outcrops were taken during sample extraction. Outcrops were chosen based on the purity of the desired sample, i.e. a significant distance from contacts and complex structural elements if possible. Figure 21 shows outcrop pictures of the field-collected samples and figure 19 shows the collection locations on the quadrangle topographic map.

2.3.3.3 Heavy Mineral Separation and Sample Preparation

In order to perform the U-Th-Pb method zircon grains were separated from the whole-rock samples collected in the field. Zircon grains were utilized for analysis because they contain U, are resistant to chemical and physical weathering, and tend to be present in extractable

Collection Outcrops for U-Th-Pb Geochronology Samples

Jurassic Rhyolite (Jr)

Jurassic Conway granite (Jcg)

Jurassic pink biotite granite (Jpbg)

Figure 21: Outcrops of the samples collected for U-Th-Pb geochronology. From top to bottom: Jurassic rhyolite (Jr), Jurassic Conway granite (Jcg), Jurassic pink biotite granite (Jpbg).

concentrations in most felsic intrusive and extrusive rock types. Figure 22 depicts a flow diagram of the separation process where boxes outlined in orange where performed with assistance of Dr. Alexander Falster from the Maine Mineral Museum in Bethel, ME, USA and boxes outlined in green where performed using facilities at Bates College in Lewiston, ME, USA

The zircon separation process began with a series of grain-size reduction steps involving rock crushing with an eight pound sledge-hammer, a Spex 4200 Jaw Crusher with minimum jaw separation set to 2-3 mm, and lastly, a ceramic disk-mill grinder. The crushed samples were then sieved through either 1 mm or 60 μm mesh and rinsed in tap-water to remove fine clay-sized grains. One set of separations underwent only crushing via the Spex 4200 Jaw Crusher and sieving through 1 mm mesh in addition to heavy fluid separation. This set was not utilized for mounting

Heavy Mineral Separation

Figure 22: A flow diagram depicting the five general steps in the heavy mineral separation process: 1) Initial pulverizing of the samples using a sledge hammer; 2) crushing down to sub 5 mm size using the Spex 4200 Jaw Crusher at the Maine Mineral Museum (MMM) followed by pulverization to sub 1 mm size using a ceramic disk-mill grinder at Bates College; 3) Preliminary separation of the dense minerals using a Rogers Gemini Gold Table; 4) Heavy fluid separation samples using Lithium Metatungstate (approximate specific gravity = 2.95); 5) search for datable zircons using optical microscopy (Photo credit: J. Dykstra Eusden)

zircons because the final product was too coarse and remained as mineral aggregates rather than individual grains. The 60 μm sieved samples were put through a Rogers Gemini Gold Table to concentrate the dense grains in each sample. The less dense grains were discarded. After drying, samples were transported to the Maine Mineral Museum and Lithium Metatungstate (LMT), a heavy fluid with a specific gravity of 2.95, was added to each sample to further separate and concentrate the heavy minerals. The ratio of sample to LMT was approximately 1:1. The three sample solutions were centrifuged for approximately sixty seconds to float off the grains with specific gravities less than 2.95 such as feldspar and quartz. The less dense grains were removed manually and the LMT was decanted out of the centrifuge vials. Each sample was rinsed with tap-water five times and the water was decanted into a LMT reclamation set-up. The samples were rinsed five additional times in tap-water to be sure that all impurities were removed. After drying, a hand-magnet was used to remove the magnetic grains from each sample. Lastly, the final heavy-mineral-separates were analyzed under microscope to ensure that they had usable populations of zircons for the mounting process to be described next.

After zircon separation, the samples were mailed to GeoSep Services LLC. in Moscow,

Figure 23: a) A method used by GeoSep Services to map spot locations on individual grains prior to ablation.
b) The epoxy wafers containing grains from each sample as well as a set of standards.

Idaho, USA to be mounted for LA-ICP-MS analysis. Epoxy wafers (~ 1 cm x 1 cm) containing zircon grains from each of the three sample separates were polished manually using 3.0 μm and 0.3 μm Al_2O_3 slurries to expose internal zircon grain surfaces. In order to clean zircon grain surfaces prior to introduction into the laser system vacuum chamber the mounts were washed in 5.5 M HNO_3 for 20 seconds at 21°C. Figure 23 shows sample mounts (two unknowns and a set of standards) about to be placed into the laser ablation chamber alongside a sheet used to map spot locations on individual grains prior to ablation. Section 7.1 of the appendices describes the GeoSep Services LLC final mineral separation and LA-ICP-MS session preparation methods in detail.

2.3.3.4 LA-ICP-MS Session Details

LA-ICP-MS data collection was performed at the Geoanalytical laboratory, Washington State University, Pullman, Washington, USA. The systems used in the laboratory include a New Wave YP213 213 nm solid state laser ablation system and ThermoScientific Element2 magnetic sector mass spectrometer. Figure 24a shows the basic processes involved in ablating the zircon grains and carrying the resulting U, Pb, and other elemental aerosols into the mass spectrometer for isotope analysis. The specific processes and parameters of this session are described in detail in section 7.1 of the appendices.

2.3.3.5 Data Analysis

The procedure for analysis of the data collected in the LA-ICP-MS session are described in detail in section 7.1 of the appendices. In addition to the ages calculated by GeoSep Services LLC, Concordia plots of the data were plotted independently. The title Concordia is derived from concordant; a system is in concordance if it remains closed with no U or Pb loss or gain up to the time of analysis. Concordia diagrams plot radiogenic $^{206}\text{Pb}/^{238}\text{U}$ versus radiogenic $^{207}\text{Pb}/^{235}\text{U}$ from the same analyses (an example is shown in figure 24b) (Faure and Mensing, 2005; Schoene, 2014). A parametric concordia curve can be drawn as a set of solutions to equations 6 and 7. The curve is non-linear because ^{238}U and ^{235}U have different half-lives, thus the Concordia curve represents the points at which radiogenic $^{206}\text{Pb}/^{238}\text{U}$ and radiogenic $^{207}\text{Pb}/^{235}\text{U}$ correspond to the same date. If plotted data points fall off the Concordia curve they are considered discordant and therefore have experienced some instance of open-system behavior, typically where lead is lost from the system. Analysis of discordant points can be useful to

a)

Laser ablation inductively coupled plasma mass spectrometry

b)

Figure 24: a) Model describing the basic principles in the LA-ICP-MS technique (Schoene, 2014). b) An example of a concordia plot where the ratio of $^{207}\text{Pb}/^{235}\text{U}$ is plotted on the x-axis vs. $^{206}\text{Pb}/^{238}\text{U}$ on the y-axis. This technique allows for the determination of multiple ages types even when the plotted U/Pb ratios fall off of the parametric curve indicating when the two ratios correspond to the same age (Schoene, 2014).

determine the origin of discordance, such as an event of metamorphic overgrowth. If the discordant points follow a linear trend the line-of-best-fit drawn through them will intersect the Concordia curve at the date of the lead-loss event (Schoene, 2014). An example of a Concordia plot from Schoene (2014) can be seen figure 23b.

Concordia plots were produced using the Berkley Chronology Center's Isoplot program on a computer that supports Microsoft Office Excel 2003. The corrected Pb^{207}/U^{235} and Pb^{206}/U^{238} ratios with corresponding 2 sigma error and error correlation values, produced by Geosep Services LLC., were selected and input into the Isoplot program. This process was performed five times. Once for each of the three samples and the fourth and fifth times for sample 286 (the Jurassic rhyolite) in order isolate the two distinct age populations identified in the Concordia plot containing all tested zircons.

2.3.4 Structural Analysis – Stereographic Projections

Structural data collected during summer field work were exported via ArcGIS into an excel file for stereographic manipulation. Once in excel, the data were copied into Dr. Richard Allmendinger's Stereonet program version 9.3.2 and plotted as great planes sets based on the strikes and dips of hornblende veins, joints, basalt dykes, and foliations. These sets were then further segregated spatially by those measured within the clear-cut and the whole study-site. The data were then manipulated to create poles-to-plane, contour (a method of analyzing trends in the poles-to-planes conversion), and rose plot projections based on whichever manipulation best highlighted trends within each data set. When using the contour method, 1% area was used rather than the Kamb method because it is more accurate when there are fewer than 250 data points in a set (Allmendinger, 2016). The 1% area method is defined where the counting circle is constrained to 1% of the total net area, whereas the counting circle in the Kamb method is variable and based on the number of standard deviations from the uniform distribution of the points (Kamb, 1959). Rose plots show only strike not dip and are useful for looking at large-scale strike orientation patterns.

2.3.5 Mineralogical Analysis – Transmitted Light Microscopy

Ten thin sections, produced by Spectrum Petrographics Inc., were analyzed through transmitted light microscopy to ascertain mineral mode and identify micro-structures and unit textures. The units analyzed via this technique include four samples of the Jurassic rhyolite (Jr),

one sample of the Jurassic Conway granite (Jcg), Jurassic pink biotite granite (Jpbg), Jurassic quartz monzodiorite (Jqmd), an Ordovician amphibolite high strain zone (Oa), Silurian coarse syenite (Scs), Silurian medium syenite (Sms), Ordovician hornblende granite orthogneiss (Oo1h), and Ordovician porphyritic k-feldspar orthogneiss (Oopkg).

The microscope used to conduct analyses was the Olympus BH-2 (figure 25). This instrument is capable of magnifying samples at 2x, 4x, 10x, and 40x increments and displaying samples in plane-polarized and cross-polarized light (OlympusMicro.com, 2012). Plane-polarized light allows for observation of the optical mineral properties, relief and opacity. Using cross-polarized light the properties, birefringence, twinning, and extinction angle can be observed. These properties were used for the identification of minerals in thin section. Pertinent examples of mineral mode, unit texture, and microstructures were captured in photomicrographs using an Olympus DP21 system.

Figure 25: A photograph of the Olympus BH-2 microscope used for transmitted light microscopy analysis of thin sections.

3. Results

3.1 Overview

Several sets of analysis were performed on samples and quantitative data collected during field-mapping of the southern half of the Jefferson Quadrangle including transmitted light microscopy of thin sections, U-Th-Pb experimental dating, the development of a large-scale interpretive map of the spectacular exposures within the clear-cut at the edge of the PRCC, and stereographic projections of structural data. The purpose of the transmitted light microscopy is twofold. First it serves to assess the mineral mode of several of the PRCC and OPS units, originally established by Chapman (1942) Czamanske and others (1977) and secondly, to analyze the microstructures present (or lack-there-of) within an Ordovician amphibolite high strain zone. U-Th-Pb dating of the newly mapped Jurassic Rhyolite, Conway granite, and pink biotite granite serves to provide updated crystallization ages for the purpose of quantifying newly observed cross-cutting between the Jurassic pink biotite granite (Jcg) and Jurassic Conway granite (Jcg) and temporally constrain and establish the role of the rhyolite (Jr) within PRCC emplacement. These tests also provided a gratuitous Silurian crystallization age from the rhyolite, extrapolated to be indicative of the age of the medium and coarse syenites. Large-scale ArcGIS mapping of the clear-cut provides insight into the complex nature of caldera-collapse event(s) related to the emplacement of the PRCC and their interaction with the OPS country rock. Stereographic projection analysis of joints, hornblende veins, and foliations, serve to identify structural trends and sequences as they relate to emplacement and deformation of the OPS and PRCC.

3.2 Updated 1:24,000 Quadrangle Map

Baker (2016; Baker et al., 2016) produced an updated bedrock geology map of the southern half of the 7.5' minute Jefferson Quadrangle with field mapping contributions from Professor J. Dykstra Eusden, the author, and Dr. Dwight Bradley of the USGS (figure 26). This map redistributes a number of bedrock unit contacts, includes the addition of two new units unobserved in the previous map iteration produced by Czamanske (1977), and provides updated unit nomenclature and ages based on new experimental and relative age data for the medium and coarse syenites. The units in Baker's (2016; Baker et al., 2016) map are from youngest to oldest Jurassic rhyolite (Jr), Conway granite (Jcg), pink biotite granite (Jpbg), quartz monzodiorite

Figure 26: Baker's (2016) map and cross-sections of the southern half of the Jefferson 7.5' quadrangle.

Unit Ages	Unit Type	Contemporary Unit Description	Evolution of unit Nomenclature					
			Chapman (1942)	Eichelberger (1971)	Czmanske et al. (1977)	Lyons et al. (1997)	Current (2015)	Map/figure color
Jurassic	Igneous Extrusive	Rhyolite	-	-	-	-	Jr	
	Igneous Intrusive	Conway Granite	cg	cg	cg	Jc1b	Jcg	
		Pink Biotite Granite	-	pbg	pbg	Jc1b	Jpbg	
		Quartz Monzodiorite	qm	qmd	qmd	J5	Jqmd	
		Porphyritic Quartz Monzonite	-	pqm	pqm	J4h	Jpqm	
		Hastingsite Quartz Syenite	hqs	mhg	hqs	J4h	Jhqs	
		Diorite	qm	qmd	d	J5	Jd	
		Basalt	-	-	-	-	Jb1	
	Silurian	Medium Syenite	-	ms	ms	Oo4Ch	Sms	
		Coarse Syenite	cs	cs	cs	Oo4Ch	Scs	
Ordovician		Amphibolite	-	-	-	-	Oa	
		K-feldspar Orthogneiss	-	-	-	-	Oopkg	
		Hornblende Granite Orthogneiss	hqm	hgn	hgn	Oo4Ch	Oo1h	
		Biotite Granite	-	-	-	Oo1b	Oo1b	

Table 3: Correlation of the the unit nomenclature from previous mapping efforts to the nomenclature used for this study

(Jqmd), porphyritic quartz monzonite (Jpqm), hastingsite quartz syenite (Jhqs), diorite (Jd), and basaltic (?) dykes (Jb1), Silurian medium syenite (Sms), coarse syenite (Scs), Ordovician porphyritic K-feldspar orthogneiss (Oopkg), hornblende granite orthogneiss (Oo1h), and biotite granite orthogneiss (Oo1b). Table 3 shows the updated unit nomenclature established by this study, which will be used through the remainder of this paper. Oo1h is used as nomenclature rather than Oo4ch because the mineral abundance classification of Oo1h fits a hornblende-granite, akin the Oo1h mapped in the adjacent Mount Dartmouth quadrangle by Eusden and others (2015), rather than a quartz monzonite as was the classification made by Lyons and others (1997). The two previously-unobserved units are the Jr and Oopkg. Oopkg was lumped in with the Oohg (referred to as Oo1h in this study) by Czmanske (1977). Through this study, Oopkg was deemed lithologically different from Oo1h due to the stark transition from coarse to porphyritic texture and plagioclase rich feldspar and quartz to dominantly K-feldspar. The Jr localities mapped in this study were included in zones of Jpbg and Scs by Czmanske (1977) and likely went unobserved during previous mapping efforts.

Figure 27: A QAP IUGS ternary classification of the felsic igneous rocks within the southern half of the Jefferson Quadrangle (modified from: Winter, 2001).

3.3 Unit Descriptions

The mineral assemblages of the mapped units vary considerably throughout the quadrangle. The Jurassic units span the end-members of igneous IUGS classification varying from monzonitic to granitic to dioritic in assemblage. The mineral assemblage of the Silurian and Ordovician units are dominated by feldspar, however the former are strongly syenitic and the latter vary from syenite to granite. Figure 27 reflects the diversity of mineral assemblages throughout the quadrangle and indicates igneous IUGS ternary classification of the units (besides Jr and Jb1 as they do not fall within felsic igneous intrusive classification) based on a combination of data from Czamanske and others (1977), Foland and Loiselle (1981), Randall and Foland (1987), Devoe (2015) and through hand sample and transmitted light microscopy analysis from this study. The Ordovician orthogneisses, Oopkg, Oo1h, and Oo1b are included in the igneous IUGS classification scheme as they were originally emplaced as igneous granitoids. The mode of mineral abundance is calculated with an error of $\pm 5\%$ when contemporary transmitted light microscopy data is available. This study assesses and slightly amends the mineral abundance classification of mapped units (conducted during previous studies) besides Jhqs, Jpqm, and Jd (classification is taken directly from previous studies) due to a lack of data. Special attention is given to Jr and Oopkg as they have not been identified by previous studies.

3.3.1 Jurassic Igneous Rocks

3.3.1.1 *Rhyolite (Jr)*

Jr was observed outcropping in three locations along the eastern flanks of the Pliny Range leading to the production of three map polygons. The most southerly and prominent of the three exists between the elevations of 550 m (1,800 ft) and 580 m (1,900 ft) and runs east-west along its long axis for approximately 1,880 m (6,170 ft) and increases in thickness to a maximum just greater than 305 m (1,000 ft) before it exits the quadrangle to the east. Excellent flat-lying exposures can be found in the bed of Big Ledge Brook which roughly bisects the polygon perpendicular the long axis. This polygon exhibits an arcuate trend roughly parallel to the topography of the Pliny Range and consistent with other adjacent PRCC units. Two small lenses (less than 30 m (100 ft) long and 15 m (50 ft) wide) exist to the north of the first prominent polygon. The southern of the two is approximately 620 m (2,000 ft) to the north of the large polygon at an elevation 675 m of (2,200 ft) and the other is to the south of Pliny Mountain Summit at an elevation of 1,005 m (3,300 ft). Both lenses are delineated by one outcrop each

Figure 28: a) A high resolution scan of the welded tuffaceous variety of the rhyolite (Jr) thin section alongside a photograph of an outcrop where it can clearly be seen cutting the Silurian coarse syenite (Scs) (hammer for scale). b) The very-fine grained porphyritic variety of Jr seen in contact with Scs in the high resolution scan to the left and the phenocrysts clearly visible in the cross-polarized photomicrograph in the center. Myrmekitic texture can also be observed in this variety of Jr in the photomicrograph to the far right. c) The very-fine grained Jr variety (thin section scan to the left) demonstrating spherulitic texture in the photomicrograph to the right.

showing direct contact with Scs. The southern of the two lenses is extremely well exposed as a ledge about 2 m (6 ft) feet high and 15 m (50 ft) long and clearly shows Jr cutting Scs as a dyke (figure 28a). This outcrop also demonstrates a contact with strike and dip 310° , 27° indicating dip towards the center of the PRCC.

Jr demonstrates significant textural variability. It varies from a welded tuffaceous texture to very fine-grained to very fine-grained with phenocrysts up to 4 mm along the long axis (figures 28). When present, the phenocrysts are quartz, k-feldspar, and/or plagioclase feldspar (figure 28b). The phenocrystic variety occasionally contains myrmekitic texture (Mackenzie et al., 1982). This was observed in a thin section of the northern-most lens (figure 28b). The non-welded varieties also demonstrated spherulitic texture indicating devitrification (figure 28c) (Mackenzie et al., 1982). Although the Jr was observed cutting Scs, thus displaying intrusive qualities, it is classified as a rhyolite based on the distinctly extrusive texture of the welded variety. These technically intrusive but texturally-looking extrusive rhyolites are common and observed in other WMMS calderas in New Hampshire (see for example: Kennedy and Stix,

Figure 29: A TAS diagram of four rhyolite samples representing the textural variability within the unit. Data for the plot was collected through X-ray Fluorescence as a part of Baker's (2016) Thesis. All four samples plot with near identical total alkali and SiO_2 content well within the rhyolite range.

2007) Mineral abundance calculation was not possible in hand-sample or thin section due to the glassy to very-fine grained texture of the unit. Baker (2016, Baker et al., 2016) performed an X-ray Fluorescence analysis (using facilities at the University of Maine Farmington) on all of the textural varieties of Jr. When plotted on a TAS diagram all of the varieties fall well within the rhyolite geochemical zone (figure 29) (Baker, 2016; Baker et al., 2016).

3.3.1.2 Conway Granite (Jcg)

The PRCC member Jcg outcrops in eight locations between the elevations 700 m (2,300 ft) and 1,190 m (3,900 ft) throughout the Pliny Range and cuts all intrusive members of the PRCC, the Silurian syenites, and the OPS. Jcg intrusions typically manifest as circular plugs rather than arcuate ring-dykes as is consistent with other members of the PRCC. The plugs are concentrated in the Jhqs ring and upper reaches of the PRCC near the crest of Pliny Ridge. Outcrops are rare and can range from 2-3 meter high cliff-bands to flat or low angle ledge exposures. An Excellent exposure exists as a ledge approximately 3 m (10 ft) high and 15 m (50 ft) long at an elevation of 945 m (3,100 ft) just below the summit of Mount Joseph Whipple. There are eight mapped plugs that vary in length along the long axis from approximately 125 m (410 ft) to 3,000 m (9,850 ft) and from 50 m (165 ft) to 865 m (2,840 ft) along the short axis. Another subgroup of Jcg outcrops in the clear-cut and displays analogous mineralogical characteristics to the plug variety but with the marked difference that the clear-cut variety is finer grained with contact dips less than 15° (nearly parallel to topography) indicating sill-like intrusion (figure 29a). This variety was also classified as Jcg because it was observed distinctly cross-cutting Jpbg. The clear-cut variety will be discussed in greater detail in section 3.4.1.1.2.

The plug variety of Jcg is medium to fine-grained with light brown to pink (from the presence of alkali feldspar) and some rust coloration on weathered surfaces and white to gray on non-weathered surfaces with darker spots (less than 3 mm along the long axis) representing the mafic mineral components (figure 30b). The mineral assemblage and mode, as determined through transmitted light microscopy of sample 504 (the clear-cut variety), is 40% K-feldspar, 35% quartz, 20% plagioclase, and 5% or less of biotite, opaque minerals, zircon and other trace minerals. Approximately half of the biotite grains display significant chlorite weathering. A large proportion of the opaque minerals are likely magnetite based on magnetism detected by hand magnet analysis of hand samples. Figure 30c demonstrates a mineral-mode representative area of the sample 504 thin section with the mineral assemblage identified under plane and cross-

Figure 30: a) An outcrop of the clear-cut variety of Jurassic Conway granite (Jcg) (Brunton compass for scale). b) A hand-sample of the plug variety of Jcg (no outcrop-photo available). c) Plane and cross-polarized photomicrographs of the clear-cut variety of Jcg.

polar light exposure. The largest grains are 4 mm along the longest axis. Quartz grains tend to be among the largest, rounded and with consistent dimensions along all axes.

3.3.1.3 Pink Biotite Granite (Jpbg)

Jpbg is a prominent granite member of the PRCC and forms one of the most conspicuous rings. One zone forms a continuous arcuate ring along the mid-elevations of the Pliny Range, with a maximum elevation at 975 m (3,200 ft) and minimum at 580 m (1,900 ft). The semi-circle circumference of the ring is approximately 10.4 km (6.45 mi) with a maximum thickness of 865 m (2,840 ft) and minimum of 200 m (650 ft). A secondary lens, separated from the main ring by a partial ring of Jqmd, exists on the southwestern flanks of the Pliny Range spanning

from 520 m (1,700 ft) to 640 m (2,100 ft) in elevation. The lens is 380 m (1,255 ft) at its thickest and 50 m (165 ft) at its thinnest. Jpbg zones are associated with significant igneous brecciation involving xenoliths of Sms, Scs, and Oopkg. Commingling of the Jqmd and Jpbg also exists in the region of the Jpbg ring closest to contact with the Jqmd semi-ring (figure 31c). Commingling is defined by multiple instances where each unit appears to cut the other and the observation of mixing between the units along contact margins. Baker (2016; Baker et al., 2016) label the zones of commingling and brecciation, “shatter” zones in their half-quadrangle map (figure 31b). A superb outcrop to observe Jpbg, brecciation, and shatter is the clear-cut (the site of detailed mapping in this study) located on the western Ridge of mount Starr King at an elevation of 685 m (2,250 ft).

Jpbg can vary from medium to fine-grained but is predominantly medium-grained with a strong pink coloration due to the presence of alkali feldspar, some minor rust-colored weathering is possible, and black spots (less than 2 mm along the long axis) representing the minor mafic components of the unit (figure 31a). The mineral assemblage and mode, as determined through transmitted light microscopy of sample 501, is 60% K-feldspar, 20% quartz, 10% plagioclase, 5% biotite with trace amounts of chlorite weathering, 5% or less of sphene, magnetite and other opaque minerals, zircon, and other trace minerals. Figure 31a demonstrates a mineral-mode representative area of the sample 501 thin section with the mineral assemblage identified under plane and cross-polar light exposure. The largest grains are typically K-feldspars at 2-3 mm along the longest axis and 2 mm or less along the shortest. The quartz grains are small at 2 mm or less along both axes and tend to be more interstitial compared to quartz grains in Jcg.

3.3.1.4 Quartz Monzodiorite (Jqmd)

Jqmd dominates the western region of the PRCC and forms one prominent arcuate semi-ring along the western flanks of the Pliny Range. The ring is approximately 5.8 km (3.60 mi) along the long axis with a maximum thickness of 765 m (2505 ft) and minimum of 440 m (1,440 ft). As with the Jpbg rings, there are significant areas of igneous brecciation involving xenoliths of Scs and Oopkg and commingling with Jpbg, labeled as “shatter” zones by Baker (2016; Baker et al., 2016), throughout the Jqmd ring (figure 31b/c). Excellent flat-lying outcrops of Jqmd, commingling between Jpbg and Jqmd, and xenoliths of Oopkg within Jqmd can be seen on a new dirt-road, privately owned by Bob Lottero. The road switch-backs up to the clear-cut from its start at the northern end of Cow Path Rd. off of Rt. 2.

Figure 31: a) An outcrop of Jurassic Pink biotite granite (Jpbg) with mineral mode representative plane and cross-polarized photomicrographs. b) An outcrop clearly showing the cross-cutting of Jpbg and Jurassic quartz monzodiorite (Jqmd) through a xenolith of Ordovician porphyritic K-feldspar orthogneiss (Oopkg) (hammer for scale). c) A blown-up photograph demonstrating co-mingling between a mafic rich variety of Jqmd and Jpbg from the same outcrop (hammer for scale).

Figure 32: a) An outcrop of Jurassic quartz monzodiorite (Jqmd) (hammer for scale). b) Plane and cross-polarized photomicrographs of representative mineral mode and an example of plagioclase feldspar zoning outlined and blown-up 200% in red.

Jqmd is medium to fine-grained and has a black and white speckled appearance averaging an equal ratio of black to white coloration due to the presence of dark mafic minerals and plagioclase feldspar (figure 32a). The mineral assemblage and mode, as determined through transmitted light microscopy of sample 506, is 40% plagioclase feldspar, 25% hornblende, 10% quartz, 10% k-feldspar, 10% biotite with trace amounts of chlorite weathering, and 5% or less of magnetite and other opaque minerals, zircon, and other trace minerals. Figure 32b demonstrates a mineral-mode representative area of the sample 506 thin section with the mineral assemblage identified under plane and cross-polar light. The largest grains are the hornblende grains at 3 mm along the long axis and 1 mm or less along the short axis. The biotite and quartz grains typically fill the interstices of the feldspars. A fraction of the plagioclase feldspar crystals demonstrate zoning (figure 32b).

3.3.1.5 Porphyritic Quartz Monzonite (Jpqm)

Figure 33: A hand sample of Jurassic porphyritic quartz monzonite (Jpqm) (outcrop photo not available).

Jpqm, a member of the PRCC, forms a single arcuate lens between the elevations of 740 m (2,400 ft) 825 m (2,700 ft) on the ridge below the summit of Mount Joseph Whipple. The lens is 875 m (2,870 ft) along its long axis and 240 m (780 ft) along its short axis. Sample 110 displays a strong pink coloration due to the large 2-3 cm porphyritic alkali feldspar crystals that characterize the unit. Minor pockets of gray quartz and mafic units, likely hornblende from hand sample analysis, are present in the interstices (figure 33). The contact of the lens is controlled by one instance of large angular float presumed to be detached from a nearby outcrop. The difficulty in finding outcrop and its similarity in mineralogy and appearance to Scs

made Jpqm difficult to map in the field and leaves many ambiguities with regard to its mapped contacts and whether or not it exists as an independent unit at all. Czamanske and others (1977) describes the unit as possessing uniform texture and composition throughout its ring with large, intensely pink alkali feldspar phenocrysts and abundant quartz in small shattered aggregates. Czamanske and others (1977) cite the intensity of the pink color as the major differentiating component in field observations between it and the coarse syenite

3.3.1.6 *Hastingsite Quartz Syenite (Jhqs)*

Jhqs forms a continuous PRCC ring in the upper elevations of the Pliny Mountains and is intruded by several plugs of Jcg. The ring spans from an elevation of 730 m (2,400) to 1,190 m (3,900 ft) and has a semi-circle circumference of 9.5 km (5.90 mi) with a maximum thickness of 1,675 m (5,495 ft) and minimum of 875 m (2,880 ft). A minor lens exists north of the primary ring at the summit of Mount Waumbek with long axis at 780 m (2,555 ft) and short axis at 115 m (380 ft). Outcrops are rare but were occasionally found in low cliff bands near the crests of ridgelines. Large angular float blocks are common. An excellent outcrop exists as a 10 m (35 ft) long by 2 m (6ft) high cliff approximately 200 meters down the Starr King Trail from the summit of Starr King. Jhqs has an orange to pink coloration, derived from the unit's dominant compositional mineral, perthite. Quartz crystals are prominent, clear, and confined to the interstices of the feldspar grains. Hornblende and minimal biotite are also present as black specs, less than 3 mm along the long axis (figure 34) (Czamanske et al., 1977).

Figure 34: Outcrop photo of Jurassic hastingsite quartz syenite (Jhqs) (hammer for scale).

3.3.1.7 *Diorite (Jd)*

Jd is the northern most element of the PRCC and encircles the summit of Mount Waumbek at 1,221 m (4,006 ft) and the Northern Flanks of the Pliny Range down to an elevation of 730 m (2,400 ft) where it extends beyond the mapped region. The Jd polygon in Baker's (2016; Baker et al., 2016) map is largely based on Czamanske's (1977) work as no outcrops were found during field work for this study, however, small, 1 m (3 ft) long, and 0.5 m (1.5 ft) thick angular chunks of float were discovered approximately 425 m (1,400 ft) to the east

Figure 35: A hand sample of Jurassic hastingsite quartz syenite (Jhqs) (outcrop photo not available).

of the summit of Mount Starr King in the saddle between it and Mount Waumbek. Czamanske and others (1977) show Jd continuing to the north of the extent mapped in this study. Future field-mapping efforts (slated for the summer of 2016) in this area will aid in confirming or updating Czamanske and others' delineation of Jd extent. The diorite is coarse to medium-grained and typically uniform in hand-specimen (figure 35). The unit contains approximately one third mafic minerals and negligible amounts quartz and alkali feldspars and has a 'salt and pepper appearance' (Czamanske et al., 1977).

3.3.1.8 Basalt Dykes (*Jb1*)

10 basalt dykes were mapped striking dominantly north-south with dips averaging 73° in areas dominated by the PRCC, Silurian syenites, and OPS alike (figure 36b). These dykes are between 1 to 4 m (3 -13 ft) wide with the largest dyke observed in the clear-cut with a thickness of 30 m (100 ft) (described in detail in section 3.4.1.1.6). The dykes were observed cutting OPS units and the Silurian syenites (figure 36a) and being cut by PRCC units, principally Jpbg (figure 45b). To a lesser extent, there were instances of basalt being cut by PRCC units (undocumented by photograph), indicating a range of intrusion spanning temporally before and after PRCC intrusion. The dykes observed outside of the clear-cut are fine-grained and gray to black with a majority composed of mafic mineral constituents (figure 36a).

Figure 36: a) A photograph of Jurassic basalt (Jb1) cutting Silurian coarse syenite (Scs) (hammer for scale).
 b) An equal area projection displaying the average strike of the 10 measured basalt dykes within the southern half of the Jefferson quadrangle.

3.3.2 Silurian Igneous Rocks

3.3.2.1 *Medium Syenite (Sms)*

Sms exists as a large plutonic intrusion in the eastern half of the study site spanning from a minimum elevation of 610 m (2000 ft) to a maximum of 945 m (3,100 ft). It is 3.7 km (2.30 mi) along its long axis and 1,524 m (5,000 ft) along its short axis with decreasing thickness to the west leading to final termination at a point. There is an auxiliary lens of Sms 1,220 m (4000 ft) to the northwest of the main body at 1060 m (3,475 ft) along its long axis and 460 m (140 ft) along its short axis. Sms also exists as xenoliths in the Jpbg “shatter” zones to the south and east of where Sms contacts the ring. A good outcrop of Sms exists as a low 1 m (3 ft) high cliff band approximately 440 m (1440 ft) to the east of the drainage west of Pliny Mountain at an elevation of 650 m (2,140 ft).

Sms is medium-grained and appears in hand sample to have a massive texture. Its coloration is a strong pink, due to the abundance of alkali feldspar, with a very minor presence of black to green specs (less than 2 mm along the long axis) confined to the interstices (figure 37a). The mineral assemblage and mode, as determined through transmitted light microscopy of sample 55, is 90% k-feldspar, 5% or less of quartz, and 5% or less of hornblende, biotite with trace amounts of chlorite weathering, magnetite and other opaque minerals, zircon, and other trace minerals. Figure 37b demonstrates a mineral-mode representative area of the sample 55 thin section with the mineral assemblage identified under plane and cross-polarized light exposure. The largest grains are the K-feldspars which can be up to 6 mm along the long axis and 3 mm along the short axis. The remaining mineral assemblage fills the interstices between the K-feldspar grains.

3.3.2.2 *Coarse Syenite (Scs)*

Scs manifests as large plutonic intrusions throughout the mid-elevations of the Pliny Range. The Scs zones are discontinuous due to cross-cutting by younger PRCC units, which also acts to shape the Scs zones into arcuate polygons similar to the PRCC rings. The Scs extends to a maximum elevation of 1,090 m (3,580 ft), the summit of Pliny Mountain, and a minimum elevation of 425 m (1,400 ft) in the northwestern-most region of the mapped extent. The largest continuous zone of Scs is 7.3 km (4.53 mi) along its long axis and decreases in thickness to the west until pinching off southeast of Mount Starr King at an elevation of 825 m (2,700 ft). The

a)

b)

1 mm

Figure 37: a) A hand sample of Silurian medium syenite (Sms) (outcrop photo not available). b) Mineral mode representative plane and cross-polar light photomicrographs of Sms.

Figure 38: a) A xenolithic outcrop of Silurian coarse syenite (Scs) within a Jurassic pink biotite granite and quartz monzodiorite co-mingled shatter zone (hammer for scale). b) Plane and cross-polarized light photomicrographs of Scs; c) Scs truncating the foliation (direction of foliation indicated by red arrows) of Ordovician K-feldspar orthogneiss (Oopkg) (hammer for scale).

smallest polygon of Scs, located near the base of the eastern Starr King ridge-line at elevations between 610 m (2,000 ft) and 640 m (2,100 ft) is 1,240 m (4,065 ft) along its long axis and 120 m (400 ft) along its short axis. In total, there are seven mapped polygons of Scs. Scs also exists as xenoliths in and around the Jpbg and Jqmd “shatter” zones (figure 38a). Scs can clearly be seen truncating the foliation of Oopkg in figure 38c. This cross-cutting combined with cross-cutting of Scs by Sms, as observed by Czamanske and others (1977), and a U-Th-Pb Silurian crystallization age helps to constrain this unit as the oldest of the two Silurian syenites and younger than the presently accepted age of the OPS (figure 55b). Due to the textural and mineralogical similarities between Scs and Jpqm the two are often confused during field identification, typically the latter for the former since outcrops for it are far more widespread. Excellent outcrops of Scs can be found on the southern part of the unnamed hill, from elevations 640 m (2,100 ft) to 670 m (2,200 ft), leading to the prominent welded tuff outcrop of Jr at the far western extent of the quadrangle. At this locality Scs outcrops as cliff-bands of 2 m (6 ft) to 5 m (16 ft) in height.

Scs is coarse-grained with a dominant pink coloration from the presence of alkali feldspar and minor interstitial green to black streaks of sub cm length indicating the mafic components of the unit (figure 38a). The mineral assemblage and mode, as determined through transmitted light microscopy of sample 502, is 90% K-feldspar, 5% biotite with significant chlorite alteration, and 5% or less of hornblende, quartz, magnetite and other opaque minerals, and trace amounts of plagioclase and zircon. Figure 38b demonstrates a mineral-mode representative area of the sample 502 thin section with the mineral assemblage identified under plane and cross-polar light exposure. The K-feldspar crystals, reaching up to 2 cm along the longest axis, and approximately 0.5 cm along the short axis, give the unit its coarse texture.

3.3.3 Ordovician Rocks of the Jefferson Dome

3.3.3.1 Ordovician High Strain Amphibolite (Oa)

Several high strain amphibolite zones were mapped interbedded along foliation of Oo1h and Oopkg. These zones are characterized by high strain (4 or 5 out of 5 on a relative scale where 5 is very well-developed and 1 is enough consistent crystal orientation to identify a trend) and are typically 2 m (6 ft) or less in width (figure 39). They contain considerable textural variability, but most commonly appear as a fine-grained green amphibolite matrix. Its secondary

Figure 39: A xenolithic outcrop of Ordovician high strain amphibolite (Oa) displaying a foliation of 4 (on the relative scale) within Jurassic pink biotite granite (Jpbg) and quartz monzodiorite (Jqmd) "shatter." Direction of foliation indicated by red arrows.

manifestation is a gray matrix filling the interstices of highly aligned medium to coarse-grained mafic minerals, likely hornblende (see sections 3.4.1.2.1 and 3.5.2 for outcrop photos and photomicrographs respectively)

3.3.3.2 Porphyritic K-feldspar Orthogneiss (Oopkg)

Oopkg contacts the Oo1h zone on its northeast border and forms one continuous arcuate band at the base of the Pliny Range extending from a minimum elevation of 335 m (1,100 ft) and maximum of 610 m (2,000 ft). The arcuate nature of the band is established by intrusions of the Silurian syenites and PRCC rings. The semi-circle circumference of the band is 11.3 km (7.02 mi) and the thickness reaches a maximum of 1,130 m (3,710 ft) in the northwestern extent of the band and a minimum of 90 m (290 ft) before pinching off in contact with the southern-most Jr polygon. Oopkg exists as abundant xenoliths in the Jpbg and Jqmd "shatter" zones (figure 31b). Outcrops of intact Oopkg, and outcrops Oopkg "shatter" along with Jpbg and Jqmd, can be observed in the clear-cut, and the new road leading up to it, as recently exposed prominent flat-lying ledges.

Oopkg is porphyritic with pink k-feldspar crystals along foliation, with minor interstitial green to black streaks consisting of the mafic components of the unit. The majority of outcrops

1 mm

Figure 40: a) An outcrop of Ordovician K-feldspar orthogneiss (Oopkg) with a foliation of 3 on the relative scale (direction indicated by red arrows) cut by a dyke of Jurassic pink biotite (Jpbg) granite (hammer for scale). b) Plane and cross-polarized photomicrographs, representing the mineral content of Oopkg.

exhibit foliation in the 2-4 range on the relative scale (figure 40a). No macro or microstructures indicating shear direction were observed. The mineral assemblage and mode, as determined through transmitted light microscopy of sample 24, is 75% K-feldspar, 15% biotite with approximately a quarter of the population exhibiting chlorite alteration, 5% plagioclase feldspar, and 5 % or less of quartz, magnetite and other opaque minerals, hornblende, zircon and other trace minerals. This assemblage represents the unit's IUGS classification prior to metamorphism as a syenite (figure 27). Figure 40 demonstrates a mineral-mode representative area of the sample 24 thin section with the mineral assemblage and foliation fabric identified under plane and cross-polar light exposure. Feldspar crystals were commonly observed reaching up to 3 to 4 cm in length and up to 1 cm in thickness.

3.3.3.3 Hornblende Granite Orthogneiss (Oo1h)

Oo1h is a member of the OPS and forms the most substantial bedrock zone in the study site, dominating the low-lying areas to the south and west of the Pliny Range and reaching a maximum elevation of 550 m (1800 ft) and minimum of 335 m (1,100 ft). The Oo1h zone is continuous besides two lenses of Oo1b towards the southern border of the quadrangle. Good flat-lying outcrops of Oo1h can be found at an elevation of 465 m (1,520 ft) in the stream-bed of Priscilla Brook as it crosses Hyfield Lane. The majority of outcrops exhibit moderate foliation of 2 to 4 on the relative scale (figure 41a). The foliation of Oo1h mirrors the level of foliation and variability found in Oopkg. No macro or microstructures indicating shear direction were found.

Oo1h is dominantly coarse-grained with alternating pinkish-white and black to dark green streaks, the former representing the equal plagioclase and K-feldspar content, and the latter the mafic mineral content (figure 41a). The streaks are 2 cm or less in length and up to 0.5 cm in thickness. The mineral assemblage and mode, as determined through transmitted light microscopy of sample 24 is 30% quartz, 25% hornblende, 15% K-feldspar, 15 % plagioclase feldspar, 10% biotite with approximately half of the population demonstrating chlorite alteration, and 5% or less of magnetite and other opaque minerals, zircon, and other trace minerals. This assemblage represents the unit's IUGS classification prior to metamorphism as a granite. Figure 41b demonstrates a mineral-mode representative area of the sample 24 thin section with the mineral assemblage and foliation fabric identified under plane and cross-polar light exposure. Feldspar crystals were occasionally observed reaching greater than 2 cm in length creating

Figure 41: a) An outcrop of hornblende granite orthogneiss with foliation, of intensity 3 on the relative scale, and dip indicated by the north-arrow card scale card. b) Plane and cross-polarized photomicrographs depicting regions of representative mineral abundance within the unit.

a porphyritic texture. The higher abundance of quartz and plagioclase feldspar and the less porphyritic nature of Oo1h relative to Oopkg are the primary differences between the two.

3.3.3.4 Biotite Granite Orthogneiss (Oo1b)

Two lenses of Oo1b exist within the Oo1h polygon. They are located on the southwestern border of the map and within 210 m (680 ft) of the south-central border of the map. The southwestern lens is located at an elevation of 365 m (1,200 ft) and is roughly circular with a maximum diameter of 830 m (2,715 ft). The South-central lens is located at an elevation of 365 m (1,200 ft) and is 1,525 m (5,000 ft) along its long axis and 220 m (725 ft) along its short axis. Outcrop control for Oo1b is poor with

Figure 42: Hand sample of Ordovician biotite granite orthogneiss (Oo1b) (outcrop photo not available).

only angular blocks of float, up to 2 m (6 ft) long and 1 m (3 ft) thick, observed. This float can be observed along the flanks of the hill located within the southwestern lens. Oo1b manifests as both an orthogneiss with a foliated texture and a non-deformed granite with gray and brownish-white coloration respectively. The foliated variety can vary from weak to well-developed (1-4 on the relative scale) and parallel to the foliations in Oo1h. The unit is composed of 50% quartz, 35% feldspars varying from alkali to plagioclase varieties, 10% biotite and chlorite altered biotite, and 5% opaque minerals (as seen through transmitted light microscopy) (Devoe, 2015; Lyons et al., 1997). This mineralogy provides the IUGS classification of the unit as a granite prior to metamorphism rather than a quartz syenite as was Lyons and other's (1997) and Devoe's (2015) classification of the unit (figure 27). A hand sample of Oo1b can be observed in figure 42.

3.4 Clear-Cut Interpretive Map

A large-scale (1:1,500) map of a bedrock dominated ~6-acre clear-cut on the southern ridge of Mount Joseph Whipple was produced from data collected through field measurements and drone georeferenced aerial photography (figure 20). The clear-cut is located near the southern boundary of the PRCC and provides a unique opportunity to better understand contact relationships and unique unit features and variation within the PRCC and OPS. Outcroppings of Jcg, Jpbg, Jqmd, Jb1, Ordovician amphibolite (Oa), and Oopkg were identified and mapped in the clear-cut (figure 43).

Clear-Cut Bedrock: 7.5' Jefferson Quadrangle, NH (southern half)

Legend

Figure 43: An interpretive map the bedrock geology of the clear-cut.

Figure 44: An interpretive cross-section illustrating the bedrock geology of the clear-cut map in figure 43.

3.4.1 Description of Units and Features in the Clear-Cut

3.4.1.1 *Jurassic Rocks*

3.4.1.1.1 Conway Granite (Jcg)

Jcg was observed as shallow-dipping (near parallel to topography – figure 45c) lenses throughout the clear-cut generally striking northeast-southwest. There are seven polygons mapped from well-exposed outcrops. the largest is located in the center of the map at 70 m (225 ft) along its long axis and 20 m (65 ft) along its short axis and the smallest is located in the southern corner of the map and oriented roughly east-west at 10 m (33 ft) along its long axis and 1.5 m (4.5 ft) along its short axis. The inferred polygons drawn without outcrop control are primarily drawn as lenses striking northeast-southwest as is the dominant strike of the outcrop controlled regions. Some variations to this trend are drawn to demonstrate the semi-random nature of intrusion. The grain-size of clear-cut Jcg is finer than that of outcrops observed at other localities. However, the clear-cut variation maintains the mineral proportions consistent with other Jcg localities where tan to gray circular quartz crystals with average diameters of 3 to 4 mm are the largest grains and visually dominate the unit (see section 3.3.1.2 for a more detailed description non-clear-cut Jcg) (figure 30). Observations of Jcg cross-cutting Jpbg and Jb1 in the clear-cut places Jcg as the relative youngest unit in the clear-cut (figure 45a/b).

3.4.1.1.2 Pink Biotite Granite (Jpbg)

Clear-cut Jpbg demonstrates a general northwest-southeast strike with erratic but dominantly shallow dip (15° to 35°) along contacts. In the clear-cut the Jpbg polygon represents the ring parallel strike of the dominant Jpbg ring, in which, the clear-cut is located as illustrated by Baker's (2016; Baker et al., 2016) map. This leads to the Jpbg zone mapped from exposed outcrop to be continuous at 370 m (1,215 ft) along its long axis and 110 m (335 ft) at its thickest. This continuous polygon is punctuated by xenoliths of Oopkg, high strain amphibolite (Oa), intrusions of Jcg, and off-shoots of Jpbg into the Oopkg dominated zone to the south. The remaining polygons not controlled by outcrop exposures are drawn as lenses following the dominant strike of the exposed sections with a secondary portion demonstrating random-strikes indicating the semi-random nature of intrusion. The mineralogy of Jpbg is described in detail in section 3.3.1.3 and an outcrop photo can be seen in figure 31a.

Figure 45: a) two examples of Jurassic Conway granite (Jcg) cutting Jurassic pink biotite granite (Jpbg) within the clear-cut (hammer for scale left, Brunton for scale right). b) Jcg clearly cutting the prominent basalt dyke within the clear-cut (Jb1) (Brunton for scale). c) Jcg with extremely shallow dip (less than 10°) in contact with Ordovician K-feldspar orthogneiss (Oopkg) (Brunton for scale).

3.4.1.1.3 Quartz Monzodiorite (Jqmd)

No outcrops of Jqmd were identified in the clear-cut mapping effort, however Jqmd was observed clearly outcropping as a flat-lying ledge at the end of the road to the clear-cut approximately 35 m (110 ft) west from the western most outcrop in the clear-cut (an outcrop of Oa). This prominent outcrop extends over 100 m (330 ft) down the road and is predominantly Jqmd with minor occurrences of Oopkg and Oa xenoliths. This outcrop formed the impetus for drawing the Jqmd zone at the western edge of the clear-cut. The zone is 505 m (1,660 ft) along its long axis and 105 m (345 ft) at its widest. The polygon is drawn with xenoliths of Oopkg due to their presence in the outcrop along the road to the clear-cut. The mineralogy and other distinct unit characteristics of Jqmd are described in detail in section 3.3.1.4 and an outcrop photo can be seen in figure 32a.

3.4.1.1.4 Basalt Dyke (Jb1)

Figure 46: The phenocrystic texture of the clear-cut basalt dyke (Jb1) and a sulfide nodule at the tip of the cat-paw crow-bar.

A prominent basaltic dike was mapped in the southern central region of the clear-cut. Through a composite of several isolated localities of outcrop control the strike was determined to be north northwest to south southeast with a near vertical dip. The dyke extends into the center of the clear-cut for 85 m (275 ft) with a maximum thickness of 30 m (100 ft). The dyke has a background of black coloration from a fine-grained mafic matrix with prominent white (likely plagioclase feldspar) crystals reaching up to 1 cm in length and 0.5 cm along the short axis giving it a porphyritic texture (figure 46). It also has sporadic occurrences of coarse sulfide (?) phenocrysts of up to 2 cm along the long axis, which weather at a slower rate than the rest of the unit forming protruding nodules on exposed surfaces (figure 46). Jcg, Jpbg, and a

number of quartz and pegmatite veins cut the dyke indicating that it is the relative oldest Jurassic unit within the clear-cut (figure 45b). This relative age can likely be extrapolated and added to

Figure 47: a) The phenocrystic hornblende and fine-grained varieties of high strain amphibolite (Oa) (foliation of 4 on the relative scale) in contact within the clear-cut and both cut by a Jurassic pegmatite vein (Brunton for scale). Foliation direction is shown by red arrows. b) Blown-up photograph of the medium-grained phenocrystic variety (left) and the fine-grained variety (right) (Brunton for scale).

other extra-clear-cut examples of basalt being cut by pegmatites, quartz veins, and Jpb_g indicating that the majority of basaltic intrusions are the relative oldest Jurassic unit in the southern half of the Jefferson Quadrangle.

3.4.1.2 Ordovician Rocks of the Jefferson Dome

3.4.1.2.1 High Strain Amphibolite (Oa)

Oa outcrops in several localities with significant mineralogical and textural variation throughout the clear-cut, however, all manifestations are highly foliated (4 to 5 on the relative scale). The outcrops and foliation trends of Oa lead to the drawing of a continuous polygon intruding along strike of foliation in the northern portion of the Oopkg section. The sill-like intrusion is 325 m (1,065 ft) along the long axis and averages 10 m (30 ft) along the short axis. Oa most commonly appears as a fine-grained green amphibolite matrix (figure 47 a/b). Its secondary manifestation is a gray matrix filling the interstices of highly aligned medium-grained mafic minerals, likely hornblende (figure 47a/b). Oa was observed as composite xenoliths with Oopkg, where both units contain the same strike and dip of foliation (averaging 304°, 62°), and as independent xenoliths. The xenoliths are angular and span up to 5 m (15 ft) along the long axis and can vary from rectangular to polygonal in shape with dykes of Jcg, Jpb_g, and/or quartz and pegmatite veins cutting them. They can be any range of size smaller than the maximum dimensions of approximately 20 m (65 ft) by 15 m (50 ft). In addition Oa is cut by pegmatite and granite dykes stemming from the Jcg and Jpb_g intrusions indicating it is likely near-contemporaneous with the Oopkg and older than the Jurassic units (figure 47a/b). Oa was also seen in several other isolated localities within the OPS zones of the greater half-quadrangle study site displaying similar characteristics to those identified above (section 3.3.3.1).

3.4.1.2.2 Porphyritic K-feldspar Orthogneiss (Oopkg)

Oopkg outcrops as both xenoliths in the Jpb_g and Jqmd and as a nearly continuous zone in the center of the map striking northwest-southeast with a length of 355 m (1,170 ft) and maximum thickness of 130 m (420 ft). The zone is intruded by multiple discontinuous lenses of Jpb_g and Jcg as well as bisected by the Jb1 dyke. The Oopkg zone represents a “mega-breccia” within the greater Jpb_g ring. The morphology and geometry of the Oopkg xenoliths mirror that of the Oa and Oa/Oopkg composite xenoliths. The strike and dip of foliation also matches that of Oa averaging 304°, 62°. Oopkg is cut by all units in the clear-cut besides Oa (figure 48).

Figure 48: Ordovician porphyritic K-feldspar orthogneiss (Oopkg) with foliation of 3 on the relative scale in contact with Jurassic Conway granite (Jcg) in the clear-cut. The foliation direction is indicated by red-arrows.

3.4.2 Clear-Cut Cross-Section

An interpretive cross-section was produced to demonstrate the sub-surface interaction between the units identified in the clear-cut. The cross section is shown with an exaggerated scale, where the vertical and horizontal axes maintain the same relative scale, to show detail in figure 44. The vertical axis extends (30 m) 95 ft from an elevation of 715 m (2,345 ft) to 745 m (2,440 ft) and the cross-section line is drawn 145 m (480 ft) northeast-southwest from A to A'. The lighter area represents the inferred zone above the present day topography and the brighter area represents the inferred unexposed area beneath present day topography. The interactions between units are described beginning with the youngest unit (Jcg) and ending with the oldest unit (Oopkg) in the clear-cut based on the relative ages established in the cross-cutting relationships outlined in previous sections.

3.4.2.1 Jurassic Conway Granite (Jcg)

Jcg intrudes along topography as a discontinuous sill stretching approximately 95 m (310 ft) with a maximum thickness 3 m (10 ft). The sill cuts through all units besides Jqmd, however based on evidence of commingling between Jpbg and Jqmd the Jcg would likely cut/mingle with Jqmd as well. The Jcg sill contains many small (less than 5 m (16 ft) along the long axis) angular Oopkg and Oa xenoliths as was observed in the map. Four additional smaller discontinuous sills were drawn representing the likelihood that there are multiple Jcg sills like the one mapped at the clear-cut in the region and at all levels of the vertical axis of the PRCC.

3.4.2.2 Jurassic Pink Biotite Granite (Jpbg)

Jpbg passes through the cross-section twice. The most prominent zone of Jpbg is located in the northeastern half and contacts Oopkg and Oa. It is drawn dipping at 80° to the northeast based on the foliation measurement most proximal to intersection with the cross-section. Foliation measurements were used for the dip of the Jurassic units in lieu of contact measurements because the contacts were too chaotic and random to obtain an accurate measurement. The prominent Jpbg zone contains xenoliths of Jb1, Oa, and Oopkg and intrusions of Jcg. The xenoliths of Oopkg and Oa decrease in size as they near the contact based on observations when mapping and the likelihood that forces present near the contact margins lead to increased shattering. The xenoliths of Jb1 are drawn at depth with minimal break-up, indicating that the Jb1 dyke, observed outcropping at the clear-cut, likely continues at depth along the north northwest to south southeast strike identified in the map. The secondary instance of Jpbg is located just northeast of the border with Jqmd. It manifests as a dyke approximately 3 m (10 ft) thick dipping 60° indicating the intrusion of Jpbg throughout the region as dykes of varying scale as indicated by the “shatter” zone, within which, the clear-cut is located.

3.4.2.3 Quartz Monzodiorite (Jqmd)

Jqmd passes through the last 15 m (50 ft) of the southwestern portion of the cross-section. It exists in a continuous zone dipping 60° to the northeast parallel to the secondary Jpbg dyke. It contains xenoliths of Oopkg mirroring the morphology of those found in the primary Jpbg zone.

3.4.2.4 Ordovician High Strain Amphibolite (Oa)

Oa is present in the center of the cross-section dipping steeply at 80° to the northeast as a dyke of 3 m (10 ft) in thickness. It contacts Oopkg and is cut by Jcg and Jpbg. The contact

with Oopkg is consistent and straight based on the observation of matching foliation between the two units. Cross-cutting by Jpbg causes the contact between the two units to be uneven. This relationship is also shown by small (sub 2 m (6 ft)) xenoliths of decreasing abundance moving away from the Oa dyke into Jpbg zone and Jcg sill.

3.4.2.5 *Porphyritic K-feldspar Orthogneiss (Oopkg)*

Oopkg is present as a near continuous zone in the central southwestern region of the cross-section and as xenoliths in the Jpbg and Jcg. It is cut by all units except the Jb1 dyke, however cross-cutting between the two units is shown in the map. As was illustrated in the description of Oopkg in section 3.4.1.2.2, the zone of Oopkg likely represents “mega-breccia.” Therefore it likely has angular termini within a few hundred meters above and below the vertical extent of this cross-section.

3.5 Structural Geology

The strike and dip of joints, foliations, and hornblende veins were collected throughout the southern half of the Jefferson quadrangle. Separate data sets for each of these categories were also collected from the clear-cut. The following sections show a combination of equal-area projections and other structural field relationships for the previously mentioned data sets. This information serves to delineate the structural geology and provide a basis for generating a sequence of regional deformation events when combined with review of the literature.

3.5.1 Foliations

50 foliations were measured within the southern half of the Jefferson quadrangle. A 1% contour of the poles indicates one primary grouping of foliations with an average strike and dip of 257° and 43° (figure 49a). Devoe (2015) and Devoe and others (2015) identify two sets of foliations with average strikes and dips of 273°, 22° and 50°, 42°, respectively in the adjacent Mount Dartmouth Quadrangle. Using cylindrical best fit they identify the two sets as the northwestern, and southeastern limbs of the Jefferson Dome, a gently plunging, steeply inclined anticline with a hinge line trending 63° and plunging 11° (Devoe, 2015; Devoe et al., 2015). The foliation set 273°, 22° is analogous to the foliation set of 257°, 43° identified in this study indicating that the latter is likely an extension and slightly steeper dipping region of the Jefferson

Figure 49: a) foliations from the southern half of the Jefferson quadrangle plotted in an equal area projection as planes (top) and the contours to those planes with an extrapolated average strike and dip plane of $257^\circ, 43^\circ$ (bottom). b) Foliations from the clear-cut plotted in an equal area projection as planes (top) and the contours to those planes with an extrapolated average strike and dip of $304^\circ, 62^\circ$ (bottom).

Dome.

At the clear-cut an additional 32 foliations were measured. A 1% contour of the poles yielded a set with average strike and dip of 304° and 62° respectively (figure 49b). This set is oriented northwest and strikes more steeply than the whole-study-site set. Upon initial inspection the two sets appear to fit as two limbs of a separate dome but this is proven false upon attempt to run cylindrical best fit on a combination of both sets. When viewed in context of the Jurassic PRCC the clear-cut foliation set closely reflects the orientation of the neighboring PRCC rings. This indicates that a brittle Jurassic event, likely related to intrusion of the PRCC, was the probable mechanism for re-orientation of the foliations proximal to the caldera.

3.5.2 Amphibolite High Strain Zones

Devoe (2015) and Devoe and others (2015) identify two prominent dextral shear zones, the Appleby and the Mill Brook, within the neighboring Mount Dartmouth Quadrangle. They recognized that well developed foliation, from to 4-5 on the relative scale, was associated with shearing. Devoe (2015) and Devoe and others (2015) later extrapolated this shearing to be symptomatic of regional dextral transpression during the Permian Alleghanian Orogeny. Based on these observations, special care was taken to note and sample zones of high strain during the field-mapping efforts for this study to see if the transpressional influence within the Mount Dartmouth Quadrangle extends into the Jefferson Quadrangle.

Several amphibolite high strain zones, similar to those identified during clear-cut mapping, were observed throughout the study-site. All were within zones dominated by either Oopkg or Oo1h units. An oriented hand-sample was collected from one of these zones located in the southeastern lowlands of the quadrangle along Stag Hollow Brook (figure 50a). Transmitted light microscopy was used in an attempt to ascertain shear direction from micro-structures. None were observed. However, the test was useful in determining the mineralogical composition of the high strain zone, the results of which are described in sections 3.5.2.1 - 3.5.2.3. In thin section the sample has three sections designated by foliation parallel contacts, each with distinct mineralogy (figure 50b-e).

3.5.2.1 *Section 1*

The first section contains 60% highly-aligned needle-shaped hornblende crystals of 2 mm in length or less with quartz and sericite, a weathering product of feldspar, filling the interstices

Figure 50: a) The sampled outcrop of high strain amphibolite with foliation at 5 on the relative scale indicated by the red arrow. b) A high resolution scan of the thin section divided into sections 1, 2, and 3 and foliation indicated by the red arrows. c, d, e) Plane and cross polarized photomicrographs of sections 1, 2, and 3 respectively.

at 30% and 10% respectively. This is shown in plane and cross polarized light in figure 50c.

3.5.2.2 Section 2

The second section is nearly 100% massive quartz and in sharp contact with the upper and lower sections. A few xenocrystic slivers of hornblende are included in the quartz. This is shown in plane and cross polarized light in figure 50d. The sharp contacts and lack of cataclasis in the quartz indicates that quartz is likely cutting sections 1 and 2 making it the relative youngest age of the three sections. This indicates that the quartz vein is likely Jurassic and related to the intrusion of the PRCC.

3.5.2.3 Section 3

Section 3 displays a similar pattern to section 1 but with less consistent mineral distribution and slightly weaker crystal alignment. Section 3 consists of 40% strongly aligned hornblende crystals up to 3 mm in length, 40% K-feldspar crystals, 10% quartz, and 10% sericite. This is shown in plane and cross polarized light in figure 50e. The feldspars display tartan twinning which is indicative of the microcline variation (Klein and Hurlbut, 1993). This is in contrast to all other units analyzed through transmitted light microscopy where K-feldspar crystals displayed strong Carlsbad twinning.

3.5.3 Hornblende veins

32 hornblende veins were measured, 16 throughout the southern half of the Jefferson quadrangle and 16 at the clear-cut. They were likely originally emplaced as high temperature hydrothermal fluids along brittle fractures (figure 50a). The hornblende veins were only observed cutting the OPS units and Silurian Syenites proximal and within the ring complex. This indicates that their emplacement was before formation of the PRCC and after the foliation deformation that affected the OPS and Silurian syenites (to a much lesser degree). Those measured within the clear-cut show little consistency in strike, however the dips all face inwards toward the center of the caldera complex (figure 51b). A trend is identifiable within the hornblende veins of the southern half of the Jefferson quadrangle. This trend involves a group of 8 hornblende veins (half of the sample size) with an average strike of 278° and dip of 61° , roughly parallel to the central-southern portion of the PRCC rings (figure 51c). These trends, although weak, may indicate an event related to the collapse of the caldera before the

Figure 51: a) An outcrop photo of hornblende veins cutting the Silurian coarse (Scs) (hammer for scale). b) An equal area projection of hornblende veins as planes, no trends are apparent besides consistent steep dip towards the center of the caldera. c) Hornblende veins from the clear-cut plotted in an equal area projection as planes (top) and the contours to those planes with an extrapolated average strike and dip of $278^{\circ}, 61^{\circ}$ (bottom).

emplacement of the PRCC.

3.5.4 Joints

66 joints were measured in the southern half of the Jefferson quadrangle, all dipping steeply (averaging 79°). The steep dip is, in part, due to the preferential selection against measurement of ubiquitous shallow dip joints not related to tectonics. The joints cut all rocks and are hence the youngest structures in the southern half of the Jefferson Quadrangle. Besides the steep dip of the joints, a trend can be observed through analysis of a rose plot from equal area projection of great planes. The trend has an average strike of 170° (figure 52).

Figure 52: A rose plot of the 66 joints measured within the southern half of the Jefferson quadrangle. A trend was observed striking 170° .

3.6 U-Th-Pb Geochronology

From the three tested samples, Jcg, Jpbg, and Jr four concordant age zircon populations were determined.

3.6.1 Jurassic Conway Granite (Jcg) (sample 504)

Of 30 analyzed zircons 28 were found to occupy the same concordant population at 188.3 ± 1.0 Ma (figure 53). This indicates that the date determined through concordia analysis is likely the age of crystallization for the unit. The remaining two zircons failed on at least one of their spot tests.

3.6.2 Jurassic Pink Biotite Granite (Jpbg) (sample 501)

Similar to the analysis of Jcg 28 of 30 zircons were found to occupy the same concordant

Figure 53: A Concordia plot for Jurassic Conway granite (Jcg) showing a unanimously concordant population of zircons at a crystallization age of 188.3 ± 1.0 Ma.

Figure 54: A Concordia plot for Jurassic Conway pink biotite granite (Jpbg) showing a unanimously concordant population of zircons at a crystallization age of 187.3 ± 1.1 Ma. Within error, Jpbg is contemporaneous with Jurassic Conway granite (Jcg).

population at 187.3 ± 1.1 Ma (figure 54), again indicating that the date determined through concordia analysis is likely the age of crystallization for the unit. Like the Jcg, two of the zircon grains failed on at least one of their spot tests and the data were discarded. For both the Jcg and Jpbg analyses, the zircon grains selected for analysis were dominantly the same size (approximately less than $60 \mu\text{m}$ along the long axis and $10 \mu\text{m}$ along the short axis), clear, and subhedral to euhedral with minimal to no indication of deformation or metamorphic overprinting through observation under plane light.

3.6.3 Jurassic Rhyolite Jr (sample 286)

Within the 22 analyzed zircons two distinct age populations were recognized through Concordia analysis (figure 55a). The younger population contains 5 zircons at 184.9 ± 2.3 Ma (figure 55c) and the older population contains 17 zircons at 430.6 ± 2.5 Ma (figure 55b). The younger population likely represents the age of crystallization of the Jr based on cross-cutting relationships observed of it cutting Scs (figure 30a). The older zircons likely represent a xenocrystic population included from the Scs country rock that Jr cuts. This assertion is supported by the distinct difference in structure and appearance of the zircon populations yielding the two ages. The population that yielded the younger Jurassic age was similar in appearance, shape, and size to the grains analyzed for Jpbg. The population that yielded the older Silurian age was distinctly smaller (approximately less than $30 \mu\text{m}$ along the long axis), near equidistant along both axis, pinkish to orange in color, fractured, and subhedral to anhedral (figure 55d). This evidence indicates a Silurian age of crystallization at 430.6 ± 2.5 Ma for the Scs amending Foland and Loiselle's (1981) designation of Ordovician. The new Scs age also alters the age of Sms based on cross-cutting relationships. Sms was observed cutting Scs, thus updating the age designation of Sms from Ordovician to Silurian (Czamanske et al., 1977).

Figure 55: a) A concordia plot developed from all 22 analyzed zircons indicating two distinct concordant populations. b) A Concordia plot of the 17 grains in the older population giving a concordant age of crystallization at 430.6 ± 2.5 Ma. c) A Concordia plot of the 5 grains in the younger population giving a concordant age of crystallization at 184.9 ± 2.3 Ma. d) An example of a subhedral zircon grain, likely belonging to the older population, as it undergoes ablation.

4. Discussion

4.1 Overview

The focus of this study is to create a better understanding of the formation of the PRCC through caldera collapse and the effects of this emplacement on the OPS Oliverian Jefferson Dome units and Silurian syenites. In order to define this relationship a chronology of pertinent geologic events is established through a combination of field relationships, structural data, and U-Pb geochronology. This chronology begins with the deformation of the OPS through Oliverian Jefferson doming in the Ordovician and ends with late stage jointing post-caldera collapse. The data leading to the establishment of this chronology allows for modeling of the unique caldera collapse event(s) that lead to the current bedrock relationships observed in the southern half of the 7.5' Jefferson Quadrangle and in the clear-cut. Description of the caldera is based on these parameters: 1) number of collapse events; 2) collapse geometry; 3) the presence or absence of resurgence or other deformation; and 3) the dominant composition of the erupting magma. This descriptive sequence is recommended by Cole and others (2005) in their review of calderas and caldera structures.

4.2 Evolution of Structural Geology

4.2.1 Formation of Dome-related Foliations

The orthogneissic OPS units Oo1h and Oopkg distal from the caldera complex display foliations that follow trends identified by Devoe (2015) and Devoe and others (2015) in the gneissic Oo1h and Oo1bx (the coarse grained version of Oo1b) at the northern border of the 7.5' Mt. Dartmouth Quadrangle, located directly south of the Jefferson Quadrangle (Eusden, et al., 2015). Devoe (2015) and Devoe and others (2015) observed a foliation trend with average strike and dip of 273° , 22° identified through cylindrical best fit of lower hemisphere projections to be the northern limb of the Jefferson Dome (figure 56c). A similar foliation set far from the caldera complex in this study was observed with an average strike and dip of 257° , 43° (figure 49a). This foliation is striking slightly more southerly than the northern dome limb identified by Devoe (2015) and Devoe and others (2015). This is likely due to the position of these foliations at the far limit of the northern anticlinal limb of the Jefferson Dome (figure 56d).

Figure 56: a) Emplacement of the Ordovician Oliverian Plutonic Series (OPS) units, porphyritic K-feldspar orthogneiss (Oopkg), hornblende granite orthogneiss (Oo1h), and biotite granite orthogneiss (Oo1b) under cover of the Ordovician Ammonoosuc volcanics (see section 1.5.3.1 for theories regarding the unconformity between the Ammonoosuc volcanics and younger OPS units). Emplacement of basalt (?) sills or flows later metamorphosed and sheared into the high strain amphibolite zones. b) Emplacement of the Silurian syenites. c) An equal area projection from Devoe (2015) showing the limbs of the Jefferson dome in the neighboring Mount Dartmouth quadrangle to the south. The northern limb, believed to be correlative to foliations in the Jefferson quadrangle, is highlighted in red. d) Oliverian doming in the Devonian from the late Acadian to early Neo-Acadian orogenies, followed by isolated dextral shearing yielding the high strain amphibolites in the Permian Alleghanian orogeny.

The OPS units and Ammonoosuc Volcanics were emplaced in the Ordovician prior to the initiation of doming (Moench and Aleinikoff, 2003) (figure 56a). Both Laurentian and Gondwanan isotopic signatures have been identified in the OPS units (Dorais et al., 2012). The presence of both providential signals is given by the generation of magma in close proximity to the Laurentian margin by the Bronson Hill Arc, originally a component of west Gander and a micro-terrane of Gondwanan origin (Dorais et al., 2012; Karabinos, 2015). Following its emplacement the OPS rose diapirically through its younger cover, Silurian and Devonian meta-sedimentary rocks, and the older Ammonoosuc Volcanics during deformation in the Devonian late Acadian orogeny with possible continuation into the early Neo-Acadian (Figure 56d). This model is suggested based on the deformation sequence proposed by Eusden (2010) in the Presidential Range, neighboring the Pliny and Mount Dartmouth ranges to the southeast.

4.2.3 Intrusion of the Silurian Syenites

The syenites are taken to be early Silurian in age, given by the crystallization age of 430 ± 2.5 Ma acquired from U-Th-Pb analysis of Jr. This intrusion post-dates the Taconic Orogeny and tectonism that emplaced the OPS units, currently held to be ~ 458 Ma (figure 56b) (Macdonald et al., 2014; Moench and Aleinikoff, 2003). However, recent investigations by Merschhat (2016) suggest that plutonism related to emplacement of the OPS may have extended into the Silurian based on new U-Pb ages of crystallization for some of the Oliverian Domes south of the Jefferson Dome. The Silurian age for the syenites in this study may be added fuel to this argument or it may suggest new evidence for plutonism related to the next major tectonic sequence that affected the region, the Salinic Orogeny (420- 423 Ma) (van Staal et al., 2009; Hibbard et al., 2010). Existence of the orogeny is controversial and currently the only evidence to support it is the presence of Silurian meta-sedimentary rocks and cryptic structures (Eusden, 2015; Eusden, 2010). The plutonism that lead to the emplacement of the syenites may indicate an initiating event of the orogeny. Besides the Silurian age of the syenites there is no additional

evidence from this study to support the correlation of the emplacement of the syenites with the Salinic orogeny.

Another interpretation is that the syenites are a member of the Highlandcroft Plutonic suite (HPS). This suite exists throughout northern New Hampshire with plutons present in close proximity to the Jefferson quadrangle, the closest being in Whitefield, NH (the town and quadrangle neighboring Jefferson). The HPS overlaps temporally with the OPS, containing plutons ranging in crystallization ages from 441 to 452 ± 4 ma. The HPS is also related to the same BHA magmatic pulse as the OPS units. Notably, the Silurian syenites share mineralogical properties characteristic of the HPS such as medium to fine-grained texture, the presence of abundant pink alkali feldspars, and occasionally, strongly feldspar-porphyritic texture (Moench and Aleinikoff, 2003). The HPS is likely correlative with the Newtown gneiss dated to have crystallized between 456-436 Ma and containing inheritance ages of ~1121-1194 Ma indicating derivation from Grenville basement, a suggested origin for the entirety of the HPS (Sevigny and Hanson, 1995; Moench and Aleinikoff, 2003). U-Th-Pb experimental geochronology analysis of a sample taken directly from a coarse or medium syenite outcrop (rather than included zircons from the rhyolite sample), with special care to identify inheritance ages, may help to determine if the syenites have an origin related to partial melting of Grenville basement, and therefore closer connection the HPS rather than the OPS (Moench and Aleinikoff, 2003).

Regardless of which interpretation is favored the Silurian age is not particularly strong evidence because the age itself was extrapolated and assigned without direct collection and analysis of syenite samples. In order to create a better understanding of the available data it would have been useful to conduct a spatial analysis of where the spots were located on the zircon grains. This would aid in determining whether or not the Silurian age was derived from a complex crystal containing a combination such as a Jurassic rim with a Precambrian core averaging to a Silurian age rather than a grain crystallized in the Silurian that remained in a closed system until present analysis.

4.2.4 Localized High Strain Amphibolite

Several amphibolite high strain zones with exceptionally well-developed foliation were observed interlayered along foliation of the orthogneissic OPS units (figure 50a). Their original emplacement and associated deformation event is difficult to constrain due to limited outcropping and the lack of observed macro or micro shear-indicators. The PRCC units were

observed cutting several high strain amphibolites (figure 50a) and no zones were observed cutting the Silurian syenites. This indicates that original emplacement of the amphibolites were likely manifested as basaltic intrusions (sills?) or flows prior to Silurian plutonism.

Devoe (2015) and Devoe and others (2015) identified the Mill Brook and the Appleby dextral shear zones in the Mt. Dartmouth Quadrangle. Although no shear indicators were found at zones observed in this study Devoe (2015) and Devoe and others (2015) found a strong positive correlation between increased intensity of foliation and presence of shear indicators. This correlation and the dramatic increase in the intensity of foliation relative to the orthogneisses allows for the designation of the amphibolites as at least high strain zones. The Mill Brook shear zone in the Mount Dartmouth quadrangle shares many characteristics with the amphibolite high strain zones of this study. Both are narrow, less than 5 meters in width, and appear to exploit the foliation planes on the northern limb of the Jefferson Dome (Devoe, 2015; Devoe et al., 2015). These similarities may indicate that the Mill Brook and amphibolite shear zones are linked, but no direct evidence for this was observed during mapping.

The proximity and correlation of the Mill Brook Zone and amphibolite zones indicate that they likely share a mechanism for deformation. The dextral shear sense of the Mill Brook zone indicates a period of post-doming transpressional tectonism. The propagation of the Alleghanian orogeny led to the late middle Paleozoic initiation of the Norumbega fault zone, a major dextral transpressional system that dominated Alleghanian tectonics for 1,200 Km along the Laurentian margin from present day Connecticut to the Gulf of St. Lawrence (Ludman et al., 1999; Hooke and Winski, 2014). Since both the Mill Brook and amphibolite high strain zones are ductile, and dextral shear sense was observed in Mill Brook, their deformation could be contemporaneous to the Norumbega system (figure 56c) (Devoe, 2015; Devoe et al., 2015). If this is a viable interpretation of the amphibolite high strain zones, the transpressional effects must have been localized enough so that the neighboring Silurian Syenites, similar to the bulk of the OPS orthogneisses, escaped that pulse of deformation. It may also be possible that the rheology of the syenites was such that ductile shearing did not significantly deform them.

4.2.5 Intrusion of Hornblende Veins

Though some scatter exists in the southern half of the Jefferson quadrangle, equal area projections of hornblende veins show a strong trend with an average strike and dip 278° , 61° (figure 51b). This trend correlates to the strike of the southern-most portion of the ring-complex

(Figure 56). A key observation is that the hornblende veins were only observed cutting the OPS and Silurian syenites indicating their crystallization took place prior to primary caldera volcanism and magmatism (figure 51a). The veins also cut orthogonal to the foliation of the orthogneisses with dome-related foliations. Since the veins were only observed immediately proximal to and within the caldera complex they may mark the initiation of pre-caldera collapse brittle fault sequence reorienting the foliations of the Ordovician orthogneisses and amphibolites so that they change from a dome orientation to one parallel to the ring complex. Reorientation involves rotation of the dome-foliations from northeast-southwest striking to east-west increasing to northwest-southeast moving north along the PRCC rings. During this faulting process the foliations rotate their strike and slightly increase their dips (Figure 57b)

4.2.6 Fault Rotation of Dome-Related Foliations

Two major foliation trends exist within the study-site, one with dome-related foliations and the other with foliations parallel to the ring-complex (figure 57b). These foliations are also separated spatially with dome-related foliations located south and distal of the ring complex, and those parallel to the PRCC, immediately proximal or within the ring complex. An attempt was made to relate these groups through cylindrical best fit in stereographic projection. However, the shape of the fold produced through the cylindrical best fit model was an overturned fold rather than a symmetrical antiform analogous with the dome. Since the dome in the Mount Dartmouth quadrangle is not overturned (Devoe, 2015; Devoe et al., 2015) a more likely scenario is that the two foliation groups share a faulted relationship. Oblique thrusting associated with the inflation of the magma chamber prior to the caldera collapse event(s) could yield the current orientation of the two foliation groups (figure 57a and figure 58).

Tribaldi (2015) describes a mechanism that could produce oblique thrusting prior to the collapse of a caldera (figure 58). Tensional stress from increased pressure of a magma reservoir at depth could lead to the superposition of a tensional regime on the country rock that favors the formation of inward-dipping fractures. These fractures are then exploited as thrust faults as pressure in the magma chamber increases. The oblique nature of the thrusting is given by rotational strain that develops along the inward-dipping fault-planes restricting roof uplift relative to the immobile lateral regions. This scenario would also produce tensional orthogonal fractures nucleating steeply from the magma chamber, which may have been exploited by hydrothermal fluids producing the hornblende veins prior to the completion of faulting (Tribaldi,

Figure 57: a) Oblique thrusting from pre-caldera collapse Tumescence of the magma chamber(s) leading to re-orientation of the dome foliations, in close proximity to the caldera, to ring parallel. b) The motion involved in re-orientation of the foliations. c) Reversal of the thrusts to normal faults during the first two phases of caldera collapse.

Figure 58: A model of magma chamber tumescence leading to oblique thrusting in the cover rock. The top of the magma chamber is dominated by vertical uplift and the lateral zones are a combination of rotational strain and vertical uplift leading to oblique thrusting. These thrusts create weaknesses along which cone-sheets can propagate during collapse (modified from: Tribaldi, 2015)

2015). These tensional fractures and thrusts could later be exploited by cone-sheets intruding during the reversal of the faults at the onset of caldera collapse.

4.2.7 Intrusion of Basalts

Stereographic analysis of 10 basalt dykes indicate steep dip and dominantly north-south strike with minor deviance to the northeast-southwest and northwest-southeast (figure 36b). The basalts show no evidence of deformation and cut both the OPS and Silurian syenites indicating that these intrusions are likely Jurassic or younger. Two relative age sets are possible based on field-relationships. The basalt dyke in the clear-cut is cut by the PRCC pink-biotite granite (Jpbg) indicating that it intruded prior to caldera collapse and emplacement of the PRCC (figure 45b). Other outcrops of basalt (undocumented by photograph) were observed cutting PRCC units indicating emplacement post-caldera collapse. Two likely scenarios exist for the intrusion of the basalts. The older of the two can be correlated to the first phase of activity in the White Mountain Igneous Province (WMIP) spanning from 200-165 Ma (Eby et al., 1992). Intrusion within this event could be directly tied to the caldera system or more broadly associated with discrete dyke swarms following the general northeast-southwest trending tectonism of Atlantic rifting (Stewart et al., 1997; LeTourneau and Olsen, 2003). A second, younger phase of WMIP activity related to rifting occurred from 130-120 Ma (Eby et al., 1992). There may be a combination of dykes from both pulses of the WMIP. The dominant strike of the dykes can be correlated to the rift orientation during both WMIP pulses.

Oxman (2015) and Oxman and others (2015) identified a prominent basaltic dyke system known as the Mill Brook Dyke Zone in the adjacent Mount Dartmouth quadrangle. This zone contains four major dykes with spectacular exposure underneath the Mill Brook Bridge near the Intersection of Rt. 115 and Rt. 115A. The dyke zone shares many similarities to the clear-cut basalt dyke including a dominant north-south strike, a porphyritic phenocryst texture, and a width greater than 10 m (35 ft). However, this is where the similarities end. The Mill Brook Zone was observed cutting the Cherry Mountain Syenite, which has been relatively dated to Jurassic in age indicating that the Mill Brook Zone is younger than the Jurassic and likely Cretaceous (Oxman, 2015; Oxman et al., 2015). The clear-cut dyke is cut by Jurassic PRCC units indicating the intrusion of the two systems are temporally distinct. The clear-cut dyke also has distinct sulfide nodules lacking in the Mill Brook Dyke Zone. Due to these stark differences

the two systems are deemed unrelated.

4.2.8 Caldera collapse

4.2.8.1 PRCC Intrusive Geometry

Chapman (1942), Eichelberger (1971), Czamanske and others (1977), Foland and Loiselle (1981), and Randall and Foland (1986), define the majority of the ring features of the PRCC as ring-dykes intruded from the collapse of the caldera. However, Eichelberger (1971) and Czamanske and others (1977) cite an outcrop of the porphyritic quartz monzonite (Jpqm) with a sharp and regular contact dipping 50° towards the caldera center. They use this outcrop to classify the Jpqm as a cone-sheet or inclined sill dipping towards the magma chamber (Tribaldi, 2005). The present study goes a step further and uses this information, the faulted re-orientation of the OPS foliations to ring-parallel with centric-radial dips, and the dominant orientation of the hornblende veins as ring parallel with steep centric-radial dips as evidence that the PRCC consists dominantly of cone-sheets rather than ring-dykes.

A number of caldera structures have been identified within the region of New Hampshire dominated tectonically by the White Mountain Igneous Province during the Jurassic (Kennedy and Stix, 2007; Creasy, et al., 1993; Eby, 1987). Each of the described calderas contain a prominent, steep outwardly-dipping ring-dyke of porphyritic quartz syenite mapped as the Albany Quartz Syenite by Lyons and others (1997) for the bedrock geology map of New Hampshire. The PRCC contains no such unit, but rather several lithologically distinct ring intrusions. The PRCC's diversion from the standard lithology of other White Mountain caldera systems provides increased evidence that the PRCC are cone-sheets rather than ring-dykes.

4.2.8.2 PRCC Relative Age Subgroups

The subgrouping of the PRCC is based on a combination of field relationships observed in this study and evidence from previous studies. In their relative age delineation Czamanske and others (1977) place the quartz monzodiorite (Jqmd) as contemporaneous with the diorite (Jd). This assertion was based on the mineralogical similarity of the two units with the variation in quartz abundance being the only significant difference (figure 27). They also claim to observe “obvious cross-cutting” between the quartz monzodiorite (Jqmd) and the pink biotite granite (Jpbgr) indicating that the latter is the younger intrusion. In this study multiple outcrops were found displaying commingling of the units when in contact with each other (figure 31c).

This clearly indicates that the Jqmd and Jpbg are likely near-contemporaneous in age and co-magmatic. This modifies the relative age designation established by Czamanske and others (1977) placing the quartz monzodiorite (Jqmd) in the same relative age zone as the pink biotite granite (Jpbg) (figure 59). This study relies on the relative age designation of the hastingsite quartz syenite (Jhqs), porphyritic quartz monzonite (Jpqm), and diorite (Jd) established by Czamanske and others (1977) due to minimal outcrop control and lack-of cross-cutting observations. From these data two different PRCC subgroups can be defined based on relative ages. The older consists of the hastingsite quartz syenite (Jhqs), porphyritic quartz monzonite (Jpqm), and diorite (Jd) and the younger group is characterized by the quartz monzodiorite (Jqmd) and pink biotite granite (Jpbg) (figure 59). This subgrouping is further delineated qualitatively by the significant brecciation present in the younger group between two Jurassic units and the Silurian syenites and OPS units. Little to no brecciation was observed in the older subgroup, however, decreased abundance of outcrop relative to the younger group may have contributed to this observation.

4.2.8.3 Origin of PRCC Units

The significant mineralogical variation present in both PRCC subgroups indicate complex melt chamber conditions and/or multiple independent chambers (Czamanske et al., 1977). Without thorough geophysical and geochemical analysis it is difficult to classify the magmatic conditions that produced the PRCC cone-sheets. Identified here are models that could produce chamber conditions yielding the PRCC. During Intrusion of the older PRCC subgroup, magmatic conditions were such that near contemporaneous mafic (the diorite) and felsic (the hastingsite quartz syenite and porphyritic quartz monzonite) cone-sheets were intruded. One model can be defined by the existence of two or three magma chambers each containing one type of melt. A two chamber model would necessitate the fractionation of one containing the two felsic melts (Kennedy and Stix, 2007). The intrusion of the Jhqs from one of the chambers followed by the porphyritic quartz monzonite, in either the fractionated or independent chamber model, could then trigger intrusion from the secondary or tertiary magma chamber containing the diorite (Wiebe et al., 2004). A secondary model calls for a single complexly fractionated magma chamber. Density stratification would lead to the accumulation of dioritic melt on the bottom of the chamber and the felsic Jpqm and Jhqs melts near the middle and top. Further stratification of melt in the felsic zone could be produced by crystallization near the upper margin of the chamber and production of the porphyritic crystals in Jpqm (Kennedy and Stix, 2007; Tribaldi, 2015). In

Figure 59: The relative ages of the units mapped in the southern half of the Jefferson quadrangle (modified from: Czamanske et al., 1977)

plan view the Jhqs and Jpqm produce distinct ring features, whereas Jd produces what appears to be a plutonic feature occupying the center of the caldera (figure 3). Little outcrop has been observed in the center of the caldera to the north of Pliny Ridge, but if the diorite is a true pluton it could be the remainder of the exhumed and crystallized magma chamber from the first collapse event (Chapman, 1942; Eichelberger, 1971; Kennedy and Stix, 2007). This model is favored over the multiple chamber model because of the overall plan-view geometry of the caldera complex. The complex is nearly symmetric with regard to the center of the caldera and each set of cone-sheets from phases 1 and 2 (see sections 4.2.8.4 and 4.2.8.5 respectively) follows a similar arcuate path (figures 3 and 26). Multiple magma chambers and discrete intrusion events typically produce asymmetric and overlapping cone-sheets or ring-dykes due to nucleation from multiple points (Cole et al., 2005).

Models for the origin of the younger PRCC subgroup are similar to those presented above with the marked difference that only two distinct cone-sheets were intruded, Jpbg and the Jqmd. Again, the favored model calls for a single fractionated magma chamber with density stratification of the more mafic dioritic melt on the bottom of the chamber and the granitic melt on the surface (Kennedy and Stix, 2007). A single chamber yielding cone-sheets is also supported by the commingled textures observed between Jqmd and Jpbg (figure 31c). Two models are offered for whether or not the younger PRCC subgroup was derived from rejuvenation of the original chamber that held the older subgroup or activation of a separate chamber. If the Jd is a genuine pluton, inhibiting refill of the original chamber, the younger subgroup is likely derived from a separate magma chamber that may have been triggered by extrusion from the first event (Kennedy and Stix, 2007; Wiebe and Hawkins, 2004). A second magma chamber would have to be on or near the vertical axis of the first chamber in order to maintain a near symmetric caldera geometry to the older subgroup. If the diorite (Jd) is a cone-sheet similar to the remainder of its subgroup, and the original chamber was sufficiently depleted in the first event, the intrusion of the younger subgroup could be attributed to replenishment of the original chamber (Cole et al., 2005).

4.2.8.4 Phase 1

The division of the PRCC into two subgroups necessitates a two-phase model for intrusions directly related to caldera collapse followed by a third phase (section 4.3.8.6) marked by the post-collapse intrusion of Jcg and extrusion (?) of rhyolite (Jr). The first phase of caldera

Figure 60 - caption on next page

Figure 60: The first phase of collapse marked by Intrusion of the Jurassic diorite (Jd) and hastingsite quartz syenite (Jhqs) as cone-sheets along the reactivated fault plane (now with normal slip) created during oblique thrusting prior to collapse. B) The second phase of collapse marked by Intrusion of the commingled Jurassic pink biotite granite and quartz monzodiorite as cone-sheets along the normal-slip reactivated fault plane distal from the center of the caldera. C) Intrusion of the Jurassic Conway granite as circular plugs with sill-like off-shoots as a final intrusive pulse followed by extrusion (?) of the rhyolite. These events mark the third and final phase of caldera collapse.

collapse is defined by the intrusion of the older PRCC subgroup as three contemporaneous cone-sheets: 1) the outer Jpqm; the middle Jhqs, and 3) the inner Jd which may be a cone-sheet or a pluton (figure 60a). These are the northern-most ring features of the PRCC mapped in this study and are separated spatially from the younger subgroup by increased proximity to the center of the caldera relative to the younger group and by a distinct band of older rocks, principally the Silurian syenites. The first collapse event likely exploited the caldera-center proximal tension fractures and fault plane produced during the proposed oblique faulting model responsible for the rotation and thrusting of the OPS and Silurian Syenites (see section 4.2.6 and figures 57 and 58). The fault system was likely re-activated as a normal fault upon initiation of collapse (Cole et al., 2005; Tribaldi, 2015) (figure 58b). This may have been a strictly intrusive event with magma forced along the fault plane(s) and tension fractures from an over-pressurized magma chamber(s). For this event to be defined as true caldera collapse it had to be initiated by a volcanic event (Kennedy and Stix, 2007; Cole et al., 2005). The only preserved volcanics observed in the study site were dated to be 184.9 ± 2.3 Ma. This age is younger than the pink biotite granite at 187.3 ± 1.1 Ma, a member of the younger PRCC subgroup, indicating that the mapped volcanics are unrelated to the first collapse vent. However, this does not preclude an earlier event initiating the first caldera collapse phase that resulted in eruption of volcanics, where all eruptives are currently missing from the geologic record due to rapid exhumation and erosion.

4.2.8.5 Phase 2

The second phase of caldera collapse is defined by the intrusion of the younger PRCC subgroup consisting of Jpbq and Jqmd. These cone-sheets are distal to the center of the caldera relative to the older subgroup (figure 26). Two likely scenarios are possible based on the models described in section 4.2.8.3. If a single rejuvenated and later fractionated magma chamber is the source of intrusion than the caldera likely experienced tumescence as the magma chamber was reinflated (Cole et al., 2005; Marti, et al., 1994). Tumescence would lead to the propagation of new tension fractures that could be exploited during cone-sheet intrusion. If intrusion stemmed

from a magma chamber, secondary from that of the older PRCC subgroup, then the caldera likely collapsed further without any intermediate doming or resurgence between collapse events. The latter method is favored in this study with the added caveat that the thrust generated distal from the center of the caldera, during fault-re-orientation, was re-activated and utilized for intrusion of the second PRCC subgroup (Tribaldi, 2015) (Figures 57b and 60b)

Intense brecciation of orthogneissic OPS units and Silurian Syenites also occurred during the second phase of collapse as evidenced by the “shatter” zones throughout the Jpbg and Jqmd rings. A unique aspect of this brecciation event is that the foliated OPS units must have been fractured in place following their re-orientation because the foliations remain consistent among the xenoliths (figures 42 and 49b). This indicates that the Jpbg and Jqmd cone-sheets must have intruded in a relatively passive manner. If this phase of collapse exploited fractures generated during pre-collapse faulting (that resulted in the re-orientation of foliations) then the Jqmd and Jpbg cone-sheets would have a weakness to intrude along without introducing additional energy into the system forcing the erratic orientation of foliated xenoliths.

Like the first phase, this event must be preceded by volcanism in order to be classified as true caldera collapse (Kennedy and Stix, 2007; Cole et al., 2005). Again, the volcanics observed in the study site were found to be younger than any of the PRCC units. Although their discovery does not directly indicate pre-collapse volcanism they do indicate that volcanism was likely associated with the event. Punctuation by volcanism increases the possibility that a volcanic event was present at initiation, but direct evidence of this has yet to be discovered or may be entirely exhumed and eroded.

4.2.8.6 Phase 3

4.2.8.6.1 Intrusion of the Conway Granite (Jcg)

The youngest intrusive unit in the PRCC is the Conway granite (Jcg). Contrary to the intrusive morphology of the other PRCC units, Jcg dominantly intrudes as vertical plugs along the boundaries of the cone-sheets (Czamanske et al., 1977). This indicates that intrusion likely took place at or near the completion of caldera collapse and its magma source has a separate derivation than that of the two PRCC subgroups. Its youth relative to the rest of the PRCC is defined by cross-cutting of all cone-sheets, Silurian syenites, and OPS units observed in this study and by Chapman, (1942) and Czamanske and others (1977).

During mapping of the clear-cut a granitic unit determined to be texturally and mineralogically unique from the pink biotite granite (Jpb_g) was discovered. This granite was given the label of Jc_g due to its textural similarity and apparent mineralogical equivalence in hand-sample comparison to samples collected at outcropping Jc_g plugs. However, there does exist several distinct differences between the two subsets of Jc_g. The clear-cut variety is fine to medium grained and manifests in thin sheeted sill-like intrusions (figure 44). The plug variety is medium to coarse grained with slightly deeper brown to rust coloration (figure 30a/b). Although grain size difference between the two varieties is significant they still maintain the same crystal proportionality with rounded to spherical quartz grains as distinguishing characteristics. The clear-cut variety was also included with the other variety because it was observed cross-cutting Jpb_g placing it as one of the youngest PRCC members (figure 45a/b). The clear-cut variety of Conway granite was used as the U-Pb age dating sample. The crystallization ages of the clear-cut Jc_g and Jpb_g, 188.3 ± 1.0 Ma and 187.3 ± 1.1 Ma respectively, fall within error leaving cross-cutting as the only mechanism to define their relative ages. If the clear-cut and plug varieties of Jc_g are derived from the same intrusive event, the clear-cut variety likely represents small-scale off-shooting sills or shallowly dipping dykes from the main plugs as they migrated through the crust (figure 60c). The smaller scale (figure 44) of these off-shoots relative to the main plugs could explain the finer grain size due to increased cooling rates. The clear-cut variety of Jc_g may also be unrelated to the plug variety and exist as its own independent intrusive phase or as an intrusion related to caldera collapse given its age, the latter of which is more likely considering its age relative to Jpb_g.

4.2.8.6.2 Rhyolite: Extrusion or Intrusion?

Of the three mapping efforts in the Pliny Range (Eichelberger, 1971; Chapman, 1942) this was the first study to identify outcrop of the rhyolite (Jr). This find was important for several reasons. First, one prominent outcrop (the site of the tuffaceous rhyolite outcrop) represents a potential paleo-Indian quarry site (figure 28a). The validity of this theory is investigated in Baker (2016; Baker et al., 2015) study. Secondly and pertinent to this study, the rhyolite indicates that the PRCC is likely associated with volcanism, offering more evidence that the PRCC is a true caldera (Kennedy and Stix, 2007; Cole et al., 2005). However, contrary to expectation, the rhyolite yielded an age of 184.9 ± 2.3 Ma indicating that it is younger than all the PRCC intrusives. Also surprising was the observation of the rhyolite cutting the Silurian coarse syenite (Scs) at two separate outcrops suggesting intrusion rather than extrusion despite

clear extrusive volcanic textures in hand sample and thin section (figure 28a/b).

Several models are offered to explain the intrusive nature and age of Jr. Models call for post-caldera collapse volcanism from a vent system auxiliary to the primary vent. The presence of Jcg indicates that the caldera system still had active magmatism following collapse. The intrusive appearance of Jr at outcrop could indicate that an explosive event was arrested just before reaching the surface causing the intrusions to cool rapidly and maintain a fine-grained rhyolitic texture (Kennedy and Stix, 2007). These intrusions may have also reached the surface and produced an eruptive event and the bulk of the eruptive material has since been removed through exhumation and erosion exposing the upper most vent-fill that failed to erupt. The former two models are supported by the textural variability of the rhyolite (figure 28) where the coarser-grained and phenocrystic rhyolites represent crystallization of melt deeper in the vent system (Kennedy and Stix, 2007). However, The tuffaceous rhyolite does not fit this model well as the welding and flow-banding is a strong indicator of surficial flow (Chapin and Lowell, 1979). The collapse of mega-breccia into a high viscosity flow near the vent opening could explain the apparent intrusion of the tuffaceous rhyolite (Kennedy and Stix, 2007). Alternately the rhyolites may be related to another caldera entirely. The nearby Crescent Range is believed to be part of a separate caldera complex and the rhyolite (Jr) mapped in this study may be related to its collapse event. This is supported by a contact of 310° , 27° between the tuffaceous rhyolite and the coarse syenite (Scs). This contact is roughly perpendicular to the regional strike of the PRCC cone-sheets, such a deviation from uniformity may be strong evidence that the rhyolite is derived from a separate caldera. Additional evidence besides one contact measurement is needed to further investigate this theory.

4.2.9 Late-stage Jointing

The joints of the southern-half of the Jefferson quadrangle are the youngest structural feature based on their cross-cutting of all units. The brittle fracture history of the study site can be constrained through a combination of stereographic analysis and field observations. Plotting of the 92 measured joints in great circle projections indicate a dominant orientation of south and southeast strikes. The trend is probably derived from protracted rifting of the Atlantic in the Cretaceous (Hatcher, 2010; Stewart et al., 1997; LeTourneau and Olsen, 2003; Faure et al., 2006, 1996). The extensional forces from this event were approximately oriented east-west to southwest northeast.

Figure 61: The current relationships and geometry of the Oliverian Plutonic Series (OPS), Silurian Syenites, and Jurassic Pliny Range Caldera Complex (PRCC) marking the culmination of the structural evolution outlined in figures 55, 56, and 59.

During field mapping, measurement of shallow dip joints were intentionally selected against because they are ubiquitous and unrelated to tectonic events. However, they were observed regularly at outcrop. The shallow-dip joints are associated with slow-exhumation of the bedrock over time and glacial eustasy, to a minor extent. Figure 61 depicts a summary of the structural evolution and features within the southern half of the Jefferson quadrangle at the present level of exhumation and erosion.

4.3 Summary and Description of Caldera collapse

Cole and others (2005) assert that caldera collapse events seldom fall neatly into end-member categories and instead should be defined descriptively by number of collapse events, collapse geometry, the presence or absence of resurgence or other deformation, and the dominant composition of the erupting magma. This principle is used in the following summary of the PRCC.

4.3.1 Number of Collapse Events and Geometry

Based on the division of the PRCC into two relative age subgroups two collapse events are defined. The symmetry of the PRCC likely indicates similar collapse geometries for the two events. The brecciation present in the second collapse event and the generation of cone-sheets indicates a piecemeal funnel morphology (Cole et al., 2005) (figure 18b). Piecemeal morphology is generated by numerous floor blocks (mega-breccia) in the collapse-center. Funnel morphology is derived from the cohesive down-dropping of individual blocks, indicated by the symmetric-shape of the caldera and inward crater-centric dip of the cone-sheets in this study (Cole et al., 2005). Arguments can also be made for trap-door morphology. The map produced by Czamanske and others (1977) indicates a lack of continuation of many of the southern cone-sheets in the northern portion of the quadrangle. Both erosion and lack of emplacement would indicate asymmetric subsidence of the central collapse block(s), which is indicative of the trapdoor mechanism where collapse occurs on a hinge (figure 18c) (Cole et al., 2005). It is likely that piecemeal, funnel, and trapdoor fault mechanisms were present during collapse and contributed to the currently exposed geometry of the PRCC.

4.3.2 Presence of Resurgence and Deformation

The models described in sections 4.2.8.4 and 4.2.8.5 indicate the possibility of a variety of deformation and resurgence events. The subdivision of the PRCC into two relative age subgroups controlled by two collapse events provides evidence for at least one deformation event and a possibly resurgence event before final collapse. The precise nature of this event or events requires geophysical analysis of the caldera plumbing to generate evidence for quantitatively derived deformation and resurgence models.

4.3.3 Dominant Composition of Erupting Magma

The composition of the erupting magma is rhyolitic based on the observation of isolated Jr outcrops. However, the composition of the intrusive cone-sheets are dominantly peralkaline (figure 27) and the presence of the rhyolite is minimal. The peralkaline nature is demonstrated by the abundance of alkali feldspar in Jpbg, Jqmd, Jpqm, Jhqs and the presence of a riebecktite granite, mapped in the northeastern region of caldera by Czamanske and others (1977), indicative of a peralkaline magmatic environment (Winter, 2001). Based on the duality of the eruptive and intrusive magma, it is useful to describe this caldera through analysis of both the extrusive and intrusive melt rather than just the dominant composition of the erupting magma as is suggested by Cole and others (2005).

The rhyolitic nature of the erupting magma suggests a large amount of pyroclastic deposits relative to other compositional caldera varieties. Rhyolitic calderas are also defined by massive collapse depressions, extensive volcanic activity, and large crater diameters of up to 10 km (Cole et al., 2005). The PRCC crater is approximately 5 km (3.1 mi) in diameter as demarcated by the diameter of the central pluton or ring of Jd and there is no evidence of extensive pyroclastic deposits or volcanic activity, although evidence may have been exhumed and eroded. Peralkaline calderas are typically associated with zones of rifting (like the environment of PRCC emplacement) and less explosive volcanic activity and volume of eruptives relative to rhyolitic calderas. They are also typically characterized by the deposition of a tuffaceous material, similar to the welded tuff textural variety of Jr observed in this study, upon eruptive initiation of collapse (Cole et al., 2005). Based on these caldera-type characteristics it is likely that the morphology of the PRCC is dominantly controlled by the peralkaline magmatic environment of the cone-sheets. Despite the dominance of peralkaline magmas there is evidence of other magmatic environments indicated by the presence of the plagioclase feldspar rich Jqmd

and Jd cone-sheets. As with the preceding sections it is likely that the caldera is influenced by a combination of several varying magma compositions.

5. Conclusions

The Pliny Range Caldera Complex (PRCC) has seen multiple waves of study throughout the 20th century including three mapping efforts and two experimental geochronology and petrogenesis studies. Despite extensive efforts to delineate the complex events that led to intrusion of the PRCC and the effects of this intrusion on the older Silurian syenites and Ordovician orthogneisses of the Oliverian Plutonic Series (OPS) many ambiguities still exist. These ambiguities have three primary manifestations: 1) the relative ages of the PRCC units and the continued identification of new units; 2) the effect of PRCC intrusion through caldera-collapse on the OPS country rock resulting in two distinct foliation sets in those orthogneisses; and 3) the mechanisms surrounding caldera-collapse that lead to intrusion of the PRCC. This study addresses these ambiguities through the use of large-scale mapping of a well exposed ~6-acre clear-cut within the PRCC, U-Th-Pb geochronology of two PRCC units (Jurassic pink biotite granite (Jpbg) Jurassic Conway granite (Jcg)) and a previously unidentified Rhyolite unit (Jr), and analysis of structural data gathered through field mapping.

1. Commingling of Jpbg and Jurassic quartz monzodiorite (Jqmd) was identified during field mapping indicating co-magmatic intrusion of the two units. This updates relative ages established by Czamanske (1977) that suggested Jd and Jqmd and not Jpbg, intruded together due to mineralogical similarity. A fine to medium-grained variety of Jcg was observed cross-cutting Jpbg in the clear-cut reaffirming the assertion that Jcg is the youngest intrusive PRCC unit. Based on these updates to the relative ages of the PRCC units the complex is divided into an older and a younger group: 1) Jurassic diorite (Jd), Jurassic hastingsite quartz syenite (Jhqs), and Jurassic porphyritic quartz monzonite (Jpqm); and 2) Jqmd and Jpbg. The first is relatively older than the second and the designation of the two groups is additionally based on the spatial separation of the two groups and the presence of breccia as “shatter” zones in the younger group. Jcg was emplaced during a final intrusive phase separate from the events that led to the emplacement of the two groups. However, all of the PRCC units intruded in relatively rapid succession, likely within ~1 million years of each other (Randall and Foland, 1987). The U-Th-Pb crystallization age of 184.9 ± 2.3 Ma for the Jr places it as the youngest and only extrusive (?) member of the PRCC. Within the analysis of Jr a suggestive age of Silurian was acquired for the syenites by a suite of xenocrystic zircons from the coarse syenite which Jr cuts. The identification of

a new OPS unit, Oopkg, was made based on the porphyritic nature of the unit, and its PRCC intrusion-parallel geometry.

2. A faulted model is suggested for the re-orientation of OPS orthogneiss foliations from an earlier Jefferson dome-orientation to a later PRCC ring-parallel orientation. The proposed mechanism for re-orientation is oblique thrusting caused by tumescence of a magma chamber(s) prior to caldera collapse. Evidence for this event is limited to the re-orientation of foliations in mostly the Oopkg and the presence of hornblende veins that predominantly strike parallel to and dipping towards the center of the PRCC and that only are found cutting the OPS units and the Silurian syenites.

3. The existence of two PRCC groups necessitates a two-phased collapse model for the intrusion of the PRCC. The first collapse event features intrusion of Jd, Jpqm, and Jhqs and the second, intrusion of Jqmd and Jpbg. These intrusions are characterized as cone-sheets rather than ring-dykes due to their inward dip towards the center of the caldera. The cone-sheets from each group likely exploited a series of fractures or faults concentric to the caldera that were established in the oblique thrusting phase prior to collapse. This is evidenced by a consistent foliation strike and dip of 304° , 62° in the xenoliths of OPS orthogneisses within the Jpbg and Jqmd cone sheets. Lack of further reorientation of the foliations and blocks during the intrusion of Jpbg and Jqmd suggests a somewhat “passive intrusion” of those units.

Future studies should involve continued dating by the U-Th-Pb method of PRCC and OPS units to acquire crystallization ages and further constrain relative age relationships. Additional mapping of the upper half of the 7.5' Jefferson USGS Quadrangle, slated for the summer of 2016, will aid in further eliminating any remaining ambiguities that surround the emplacement of the PRCC units and help to constrain the areas mapped in this study with little outcrop-control including Jd and Jpqm.

6. References

- Allmendinger, R.W. Stereonet 9.5. ©2011-2016.
- Bacon, C.R. (1983) Eruptive history of Mount Mazama and Crater Lake caldera, Cascade Range, USA. *Journal of Volcanology and Geothermal Research*, 18(1), 57-115.
- Baker, S., Cargill, J., Eusden, J. D., Bradley, D., O'Sullivan, P., Boisvert, R. (2016) Bedrock Geology of the Jefferson 7.5' Quadrangle, New Hampshire: Geological Society of America Northeastern Section, 51st, New Hampshire, Abstracts, vol. 47, No. 2.
- Baker, S., Eusden, J. D. (2016) Bedrock Geology of the Jefferson 7.5' Quadrangle, New Hampshire [Undergraduate thesis]: Bates College.
- Billings, M. (1934) PALEOZOIC AGE OF THE ROCKS OF CENTRAL NEW HAMPSHIRE. *Science* (New York, NY), 79(2038), 55-56.
- Billings, M.P. (1937) Regional metamorphism of the Littleton-Moosilauke area, New Hampshire *Geological Society of America Bulletin*, 48(4), 463-566.
- Branney, M.J., and Kokelaar, P. (1994) Volcanotectonic faulting, soft-state deformation, and rheomorphism of tuffs during development of a piecemeal caldera, English Lake District. *Geological Society of America Bulletin*, 106(4), 507-530.
- Chapin C.E., Lowell G.R. (1979) Primary and secondary flow structures in ash-flow tuffs of the Gribbles Run paleovalley, central Colorado. *Geology Society of America Special Paper*. Vol 180, 137-154
- Chapman, R.W. (1942) Ring structures of the Pliny region, New Hampshire. *Geological Society of America Bulletin*, 53(10), 1533-1568.
- Cole, J., Milner, D., and Spinks, K. (2005) Calderas and caldera structures: a review. *Earth-Science Reviews*, 69(1), 1-26.
- Creasy, J.W., and Eby, G.N. (1993) Ring dikes and plutons: A deeper view of calderas as illustrated by the White Mountain igneous province, New Hampshire. *Field Trip Guidebook for the Northeastern United States: Amherst, Massachusetts*, Department of Geology and Geography, University of Massachusetts, Contribution (67), N1-N25.
- Czamanske, G.K., Wones, D.R., and Eichelberger, J. (1977) Mineralogy and petrology of the intrusive complex of the Pliny Range, New Hampshire. *American Journal of Science*, 277(9), 1073-1123.
- Devoe, Michelle, "Deformation Post-Doming: New mapping of the Oliverian Jefferson Dome, Mt. Dartmouth 7.5' Quadrangle, New Hampshire" (2015). *Honors Theses*. Paper 115.
- Devoe, M., Eusden Jr., J.D., Oxman, G., Xiao, S. (2015) Deformation Post-Doming of the Oliverian Jefferson Dome, Mount Dartmouth 7.5' Quadrangle, New Hampshire: *Geological Society of America Northeastern Section*, 50th, New Hampshire, Abstracts, vol. 47, No. 3. P.112.

- Dorais, M.J., Workman, J., and Aggarwal, J. (2008) The petrogenesis of the Highlandcroft and Oliverian Plutonic Suites, New Hampshire: Implications for the structure of the Bronson Hill terrane. *American Journal of Science*, 308(1), 73-99.
- Eby, G.N. (1987) The Montereian Hills and White Mountain alkaline igneous provinces, eastern North America. Geological Society, London, Special Publications, 30(1), 433-447.
- Eby, G.N., Krueger H.W., & Creasy, J.W., (1992) Geology, geochronology, and geochemistry of the White Mountain Batholith, New Hampshire: Special Paper - Geological Society Of America v. 268, 379-397.
- Eichelberger, J.C. (1971) Granites and syenites of the Pliny Range, New Hampshire. Masters Thesis. Massachusetts Institute of Technology.
- Eusden, J.D., (2015) Silurian stratigraphy revisited: Extensions from New Hampshire!: Geological Society of America Northeastern Section, 50th, New Hampshire, Abstracts, vol. 47.3, p. 61.
- Eusden J.D. (2010) The Presidential Range: Its geologic and tectonic history. Durand Press, Lyme, NH.
- Eusden, J.D., Foley, M., Roden-Tice, M., 2009, The Ordovician to Carboniferous bedrock geology and cooling history of the Bronson Hill and Central Main Belts, Presidential Range, New Hampshire, *in* NEIGC 2009 Guidebook, p. A3-3 to A3-8.
- Eusden, J.D., Thompson, W., Fowler, B., Davis, P., Bothner, W., Boisvert, R., and Creasy, J. (2013) The Geology of New Hampshire's White Mountains. Durand Press, Lyme, NH.
- Eusden, J. D., Xiao, S., Devoe, M., Graham, G.G., (2015) Mt. Dartmouth Quadrangle, New Hampshire – Bedrock Geology: U.S. Geological Survey, scale: 1:24,000.
- Faure, G., and Mensing, T.M. (2005) *Isotopes: principles and applications*. John Wiley & Sons Inc.
- Faure, S., Tremblay, A., and Angelier, J. (1996) State of intraplate stress and tectonism of northeastern America since Cretaceous times, with particular emphasis on the New England-Quebec igneous province. *Tectonophysics*, 255(1), 111-134.
- Faure, S., Tremblay, A., Malo, M., and Angelier, J. (2006) Paleostress analysis of Atlantic crustal extension in the Quebec Appalachians. *The Journal of geology*, 114(4), 435-448.
- Foland, K.A., and Loiselle, M.C. (1981) Oliverian syenites of the Pliny region, northern New Hampshire. *Geological Society of America Bulletin, Part I*, 92(4), 179-188.
- Foley, M.B., Contact relationships between the Ammonoosuc Volcanics and the Jefferson Dome, Northern Presidential Range, New Hampshire (2009) [Undergraduate thesis]: Bates College, 118 p.
- Geyer, A., and Martí Molist, J. (2014) A short review of our current understanding of the development of ring faults during collapse caldera formation.
- Gudmundsson, A. (2006) How local stresses control magma-chamber ruptures, dyke injections, and eruptions in composite volcanoes. *Earth-Science Reviews*, 79(1), 1-31.

- Hanson, G.N. (1978) The application of trace elements to the petrogenesis of igneous rocks of granitic composition. *Earth and Planetary Science Letters*, 38(1), 26-43.
- Hatcher, R.D. (2010) The Appalachian orogen: A brief summary. *Geological Society of America Memoirs*, 206, 1-19.
- Hibbard, J.P., van Staal, C.R., and Rankin, D.W. (2010) Comparative analysis of the geological evolution of the northern and southern Appalachian orogen: Late Ordovician-Permian. *Geological Society of America Memoirs*, 206, 51-69.
- Hooke, R.L., and Winski, D.A. (2014) Unroofing Maine: Relating pressure of crystallization, thermochronological data, tectonics, and topography. *Geomorphology*, 210, 36-47.
- Kamb, W.B. (1959) Ice petrofabric observations from Blue Glacier, Washington, in relation to theory and experiment. *Journal of Geophysical Research*, 64(11), 1891-1909.
- Karabinos, P., Samson, S.D., Hepburn, J.C., and Stoll, H.M. (1998) Taconian orogeny in the New England Appalachians: collision between Laurentia and the Shelburne Falls arc. *Geology*, 26(3), 215-218.
- Kennedy, B., and Stix, J. (2007) Magmatic processes associated with caldera collapse at Ossipee ring dyke, New Hampshire. *Geological Society of America Bulletin*, 119(1-2), 3-17.
- Klein C., Hurlbut C.S., Jr. (1993) *Manual of Mineralogy* 21st Edition. New York. John Wiley and Sons: 154
- Leo, G.W. (1991) Oliverian domes, related plutonic rocks, and mantling Ammonoosuc Volcanics of the Bronson Hill anticlinorium, New England Appalachians.
- LeTourneau, P.M., and Olsen, P.E. (2003) *The Great Rift Valleys of Pangea in Eastern North America: Sedimentology, stratigraphy, and paleontology*. Columbia University Press.
- Ludman, A., Lanzirotti, A., Lux, D., and Chunzeng, W. (1999) Constraints on timing and displacement of multistage shearing in the Norumbega fault system, eastern Maine. *Norumbega fault system of the northern Appalachians: Geological Society of America Special Paper*, 331, 179-194.
- Lyons, J.B., Tufts-Moore, S., Koozmin, E.D., Falk, T., Mathieux, D.P., and Hampshire, N. (1997) *Bedrock geologic map of New Hampshire*. The Survey.
- Macdonald, F.A., Ryan-Davis, J., Coish, R.A., Crowley, J.L., and Karabinos, P. (2014) A newly identified Gondwanan terrane in the northern Appalachian Mountains: Implications for the Taconic orogeny and closure of the Iapetus Ocean. *Geology*, 42(6), 539-542.
- Mackenzie, W.S., Donaldson C.H., Guilford C. (1982) "Atlas of igneous rocks and their textures" John Wiley and Sons. New York: 49; 54-56
- Merschat, A.J., Walsch, G.J., Holm-Denoma, C.S., McAleer R.J. (2016) Detrital Zircon Geochronology of the Bronson Hill Anticlinorium and Western Facies of the Central Maine Terraine, Southern NH-VT: *Geological Society of America Northeastern Section*, 51st, New Hampshire, Abstracts, vol. 48, No. 2.
- Marti, J., Ablay, G., REDSHAW, L.t., and Sparks, R. (1994) Experimental studies of collapse calderas. *Journal of the Geological Society*, 151(6), 919-929.

- Martí, J., and Gudmundsson, A. (2000) The Las Cañadas caldera (Tenerife, Canary Islands): an overlapping collapse caldera generated by magma-chamber migration. *Journal of Volcanology and Geothermal Research*, 103(1), 161-173.
- McHone, J.G. (1992) Mafic dike suites within Mesozoic igneous provinces of New England and Atlantic Canada. *Geological Society of America Special Papers*, 268, 1-12.
- McHone, J.G., and Butler, J.R. (1984) Mesozoic igneous provinces of New England and the opening of the North Atlantic Ocean. *Geological Society of America Bulletin*, 95(7), 757-765.
- Miller, C.F. (1977) Early alkalic plutonism in the calc-alkalic batholithic belt of California. *Geology*, 5(11), 685-688.
- Miller, C.F. (1978) Monzonitic plutons, California, and a model for generation of alkali-rich, near silica-saturated magmas. *Contributions to Mineralogy and Petrology*, 67(4), 349-355.
- Moench, R.H., and Aleinikoff, J.N. (2003) Stratigraphy, geochronology, and accretionary terrane settings of two Bronson Hill arc sequences, northern New England. *Physics and Chemistry of the Earth, Parts A/B/C*, 27(1), 47-95.
- OlympusMicro.com (2015) The Microscope Resource Center: olympusmicro.com (accessed January-March 2016)
- Oxman, Graham Gear, "Petrogenesis and Paleostress Analysis of the Mesozoic Mill Brook Dike Zone in the Mount Dartmouth 7.5' Quadrangle, New Hampshire" (2015). *Honors Theses*. Paper 116.
- Oxman, G., Eusden Jr., J.D., Xiao, S., Devoe, M. (2015) Petrogenesis and Paleostress analysis of the Mesozoic Mill Brook Dike Zone in the Mount Dartmouth 7.5" Quadrangle, New Hampshire: *Geological Society of America Northeastern Section*, 50th, New Hampshire, Abstracts, vol. 47, No. 3. P.112.
- Page, L.R. (1968) Devonian plutonic rocks in New England. Zen, E-an, White, WS, Hadley, JB, and Thompson, JB, Jr., Editors, *Studies of Appalachian Geology—Northern and Maritime*: New York, Interscience, 371-383.
- Photo Science Geospatial, Inc. (2013) White Mountain National Forest 2 Lidar Metadata (2013): Unpublished.
- Pinel, V., and Jaupart, C. (2004) Magma storage and horizontal dyke injection beneath a volcanic edifice. *Earth and Planetary Science Letters*, 221(1), 245-262.
- Ramberg, I. B. (2008) *The making of a land: geology of Norway*, Geological Society of London.
- Randall, K., and Foland, K. (1987) Age and time span of emplacement of the Pliny Range complex, northern New Hampshire. *Geological Society of America Bulletin*, 97(5), 595-602.
- Robinson, P., Tucker, R.D., Bradley, D., Berry IV, H.N., and Osberg, P.H. (1998) Paleozoic orogens in New England, USA. *GFF*, 120(2), 119-148.
- Schoene, B. (2014) 4.10–U–Th–Pb geochronology. *Treatise on geochemistry*, 341-378.

- Sevigny, J., and Hanson, G. (1995) Late-Taconian and pre-Acadian history of the New England Appalachians of southwestern Connecticut. *Geological Society of America Bulletin*, 107(4), 487-498.
- Simmons, E.C., and Hedge, C.E. (1978) Minor-element and Sr-isotope geochemistry of Tertiary stocks, Colorado mineral belt. *Contributions to Mineralogy and Petrology*, 67(4), 379-396.
- Stewart, D., Wright, B., Unger, J., Phillips, J., and Hutchinson, D. (1997) Global geoscience transect 8, Quebec-Maine-Gulf of Maine transect, southeastern Canada, northeastern United States of America. *US Geological Survey, Global Geoscience Transects*.
- Tibaldi, A. (2015) Structure of volcano plumbing systems: A review of multi-parametric effects. *Journal of Volcanology and Geothermal Research*, 298, 85-135.
- Van Staal, C. (2005) The Northern Appalachians. *Encyclopedia of geology*, 4, 81-91.
- Van Staal, C., Wilson, R., Kamo, S., McClelland, W., and McNicoll, V. (2015) Evolution of the Early to Middle Ordovician Popelogan arc in New Brunswick, Canada, and adjacent Maine, USA: Record of arc-trench migration and multiple phases of rifting. *Geological Society of America Bulletin*, B31253. 1.
- Van Staal, C.R., Whalen, J.B., Valverde-Vaquero, P., Zagorevski, A., and Rogers, N. (2009) Pre-Carboniferous, episodic accretion-related, orogenesis along the Laurentian margin of the northern Appalachians. *Geological Society, London, Special Publications*, 327(1), 271-316.
- Waldron, J.W., and van Staal, C.R. (2001) Taconian orogeny and the accretion of the Dashwoods block: A peri-Laurentian microcontinent in the Iapetus Ocean. *Geology*, 29(9), 811-814.
- Walker, G.P. (1988) Three Hawaiian calderas: an origin through loading by shallow intrusions? *Journal of Geophysical Research: Solid Earth*, 93(B12), 14773-14784.
- Wiebe, R., Manon, M., Hawkins, D., and McDonough, W. (2004) Late-stage mafic injection and thermal rejuvenation of the Vinalhaven granite, Coastal Maine. *Journal of Petrology*, 45(11), 2133-2153.
- Winter, J. D. (2001) "Classification and Nomenclature of Igneous Rocks: An Introduction to Igneous and Metamorphic Petrology". P. Lynch. New Jersey, Prentice Hall: 128-154.
- Xiao, Sarah Mei and Eusden, J. Dykstra, "Bedrock Geology of the Mt. Dartmouth 7.5' Quadrangle, New Hampshire" (2015). *Geology Theses*. Paper 19.

7. Appendices

7.1 Appendix A: GeoSep Services LLC. – Laboratory Procedures and U-Pb Dating Methodology

GENERAL

All laboratory procedures (mineral separation and grain mounting) were performed under the direction of Paul O’Sullivan and Joseph Hanson at GeoSep Services (GSS) laboratory, located in Moscow, Idaho. Paul O’Sullivan performed all analytical procedures, including grain selection and parameter measurement. All laser ablation of samples for age analyses were performed under the direction of Paul O’Sullivan, using the equipment at the Washington State University School of Earth and Environmental Sciences GeoAnalytical Laboratory in Pullman, Washington.

All sample material is stored by GSS until the analyses have been completed and the report submitted to the Client. If not determined previously, following the completion of each project, GSS will attempt to determine whether the Client wishes to have the remaining sample material returned or have it disposed of.

A general discussion of the methods undertaken to process and analyze samples by GSS is presented below. Please see Donelick et al. (2005), for a complete and detailed discussion of these particular methods and their justification.

SAMPLE PREPARATION AND FEASIBILITY ASSESSMENT

Apatite and zircon grains were isolated and prepared for LA-ICP-MS analysis using standard procedures combined with specific customized procedures described by Donelick et al. (2005). These customized procedures were designed to maximize recovery of: 1) all possible grain sizes present within a sample by minimizing the potential loss of smaller grain sizes through the use of water-table devices, and 2) complete grains with as close to full terminations by minimizing grain breakage and/or fracturing inherent with the standard procedures typically used to separate individual grains from the original rock material. Use of these procedures results in a significantly greater range of recovered grain sizes, as well as a higher percentage of

“complete” grains being retained during the mineral separation process (Fig. 1).

Whole rock samples were first crushed using a jaw crusher with the minimum jaw separation set to 2-3 mm. The crushed material was then sieved through 300 μm nylon mesh, and the <300 μm size fraction washed with tap water and allowed to dry at room temperature. Apatite and zircon grains were subsequently separated from other mineral species using a combination of lithium metatungstate (density $\sim 2.9 \text{ g/cm}^3$), Frantz magnetic separator, diiodomethane (density $\sim 3.3 \text{ g/cm}^3$), and hand-panning separation procedures.

Figure 1. Recovered zircon fraction for sample 027-18. Customized separation techniques designed by A2Z Inc., and now used by GSS, allow for a significantly greater range of recovered grain sizes, and a higher percentage of “complete” grains with full terminations being retained during the mineral separation process.

For each sample processed for either apatite fission-track analysis (AFT), or zircon UPb (ZrnUPb) analysis, at least one 1cm^2 grain mount, consisting of some quantity of apatite or zircon grains immersed in epoxy resin, was prepared. Each grain mount was subsequently cured at 90°C for at least 1 hour. Once cured, each grain mount was polished manually to a glass-like finish using $3.0 \mu\text{m}$ and $0.3 \mu\text{m}$ Al_2O_3 slurries to expose internal grain surfaces. After polishing, the grain mounts were immersed in 5.5N HNO_3 for 20.0 seconds (± 0.5 seconds) at 21°C ($\pm 1^\circ\text{C}$) to: 1) reveal all natural fission tracks that intersected the respective polished apatite grain

surfaces, or 2) acid-wash the zircon grain surfaces.

The feasibility of continuing each sample through to analysis was then assessed by quickly scanning the polished and etched grain mounts to determine if any dateable apatite grains (for AFT), or zircon grains (for ZrnUPb) were present. If more than one dateable grain was observed during this quick scan, continued analysis was considered feasible.

GENERALIZED PROCEDURES - ZrnUPb

ZrnUPb – Published Methods

Detailed descriptions of the methods followed by GSS to produce and process their ZrnUPb data have been presented in numerous peer-reviewed manuscripts. These include Bradley et al. (2009), Hults et al. (2013), and Moore et al. (2015).

ZrnUPb – LA-ICP-MS Session Details

LA-ICP-MS data collection was performed at the Geoanalytical Laboratory, Washington State University, Pullman, Washington, U.S.A. Individual zircon grains were targeted for data collection using a New Wave YP213 213 nm solid state laser ablation system using a 20 μm diameter laser spot size, 5 Hz laser firing rate, and ultra high purity He as the carrier gas. Isotopic analyses of the ablated zircon material were performed using a ThermoScientific Element2 magnetic sector mass spectrometer using high purity Ar as the plasma gas. The following masses (in amu) were monitored for 0.005 s each in pulse detection mode: 202, 204, 206, 207, 208, 232, 235, and 238. At time = 0.0 s, the mass spectrometer began monitoring signal intensities; at time = 6.0 s, the laser began ablating zircon material; at time = 30.0 s, the laser was turned off and the mass spectrometer stopped monitoring signal intensities. A total of 250 data scans were collected for each zircon spot analyzed comprising: approximately 55 background scans; approximately 20 transitions scans between background and background+signal, approximately 175 background+signal scans. A scheme was developed to check whether mass 238 experienced a switch from pulse to analog mode during data collection and a correction procedure was employed to ensure the use of good quality intensity data for masses 235 and 238 when such a switch was observed.

ZrnUPb – UPb Data Analysis

Previous LA-ICP-MS studies of UPb zircon dating used the so-called intercept method, which assumes that isotopic ratio varies linearly with scan number due solely to linearly varying isotopic fractionation (Chang et al., 2006; Gerhels et al., 2008). The data modeling approach favored here was the modeling of background-corrected signal intensities for each isotope at each scan. Background intensity for each isotope was calculated using a fitted line (for decreasing background intensity) or using the arithmetic mean (for non-decreasing background intensity) at the global minimum of selected isotopes (^{206}Pb , ^{232}Th , and ^{238}U) for the spot. Background+signal intensity for each isotope at each scan was calculated using the median of fitted (2nd-order polynomial) intensity values for a moving window (7 scans wide here) that includes the scan. The precision of each background-corrected signal intensity value was calculated from the precision of background intensity value and the precision of the background+signal intensity value.

Zircon UPb age standards used during analysis are summarized in Table 2, including the 1099±0.6 Ma FC zircon (FC-1 of Paces and Miller, 1993) used here as the primary age standard. Isotopic data for FC were used to calculate Pb/U fractionation factors and their absolute errors for each FC data scan at each FC spot; these fractionation factors were smoothed session-wide for each data scan using the median of fitted (1st-order polynomial) fractionation factor values for a moving window that includes the current FC spot and scan

Table 2. Zircon age standards.

Standard	Standard	U-Pb age ($\pm 2\sigma$)	Reference
FC	Duluth complex	1099.0 $\pm$ 0.6 Ma	Paces and Miller, 1993
F5	Duluth complex	1099.0 $\pm$ 0.6 Ma (assumed equal to FC-1)	Paces and Miller, 1993
IF	Fish Canyon Tuff	28.201 $\pm$ 0.012 Ma	Lanphere et al., 2001; Kuiper et al., 2008
MD	Mount Dromedary	99.12 $\pm$ 0.14 Ma	Renne et al., 1998
PX	Peixe	563.5 $\pm$ 1.6 Ma	Gerhels et al., 2008
T2	Temora2, Middledale gabbroic diorite	416.78 $\pm$ 0.33 Ma	Black et al., 2004
TR	Tardree Rhyolite	61.23 $\pm$ 0.11 Ma	Dave Chew, personal communication

Under the operating conditions of LA-ICP-MS sessions, fractionation factors are occasionally found to vary strongly with scan number, decreasing with increasing scan number (presumably due to increasing ablation pit depth and the effect this has on fractionation; e.g., Paton et al., 2010). The zircon crystal lattice is widely known to accumulate α -radiation damage

(e.g., Zhang et al., 2009 and references therein). It is assumed that increased α -damage in a zircon leads to a decrease in the hardness of the zircon; this in turn leads to a faster rate of laser penetration into the zircon during ablation leading to dependence of isotopic fractionation on the degree of zircon lattice radiation damage. Ages calculated for all zircon age standards, when those standards were treated as unknowns, were used to construct a fractionation factor correction curve (exponential form) in terms of accumulated radiation damage. The notion of matrix-matched zircon standard and zircon unknown has been proposed largely on the basis of trace element chemistry (e.g., Black et al., 2004). In this study, time and lattice damage, parameters invisible to instruments used to characterize trace element chemistry, were introduced and applied based on measured U and Th chemistries to effectively matrix-match standard and unknown zircons.

Uranium decay constants and the $^{238}\text{U}/^{235}\text{U}$ isotopic ratio reported in Steiger and Yäger (1977) were used in this study. Errors for the isotopic ratios $^{207}\text{Pb}/^{235}\text{U}_c$ ($^{235}\text{U}_c = 137.88^{238}\text{U}$), $^{206}\text{Pb}/^{238}\text{U}$, and $^{207}\text{Pb}/^{206}\text{Pb}$ at each scan included errors from the background-corrected signal values for each isotope, the fractionation factor error, and an additional relative error term required to force 95% of the FC ages to be concordant. Ages for the ratios $^{207}\text{Pb}/^{235}\text{U}_c$, $^{206}\text{Pb}/^{238}\text{U}$, and $^{207}\text{Pb}/^{206}\text{Pb}$ were calculated for each data scan and checked for concordance; concordance here was defined as overlap of all three ages at the 1σ level (the use of 2σ level was found to skew the results to include scans with any significant common Pb). If the number of concordant data scans for a spot was greater than zero, the more precise age from the concordant-scan-weighted ratio $^{207}\text{Pb}/^{235}\text{U}_c$, $^{206}\text{Pb}/^{238}\text{U}$ or $^{207}\text{Pb}/^{206}\text{Pb}$ was chosen as the preferred age. Asymmetrical negative-direction and positive-direction age errors were calculated by subtracting and adding, respectively, the isotopic ratio errors in the appropriate age equation (Chew and Donelick, 2012).

Moving-Median Smoothing

Moving-median smoothing (MMS) is applied here to a subset (window) of N data points x, y of width m values of x to which a polynomial of order n is fitted. For each value of x at each position of the data window, a value of y is calculated for the fitted polynomial. The window is positioned with the right-hand boundary at the left-hand x value and then shifted $N-1$ times until the left-hand boundary of the window is positioned at the right-hand x value. At each x position, m fitted values of y are calculated and the median of these fitted values is taken.

REFERENCES CITED

- Black, L.P., Kamo, S.L., Allen, C.M., Davis, D.W., Aleinikoff, J.N., Valley, J.W., Mundil, R., Campbell, I.H., Korsch, R.J., Williams, I.S., and Foudoulis, C. 2004. Improved $^{206}\text{Pb}/^{238}\text{U}$ microprobe geochronology by the monitoring of trace-element-related matrix effect; SHRIMP, ID-TIMS, ELA-ICP-MS and oxygen isotope documentation for a series of zircon standards. *Chemical Geology*, 205, p.15-140.
- Bradley, D., Haeussler, P., O'Sullivan, P., Friedman, R., Till, A., Bradley, D., and Trop, J., 2009, Detrital zircon geochronology of Cretaceous and Paleogene strata across the south-central Alaskan convergent margin, in Haeussler, P.J., and Galloway, J.P., *Studies by the U.S. Geological Survey in Alaska, 2007: U.S. Geological Survey Professional Paper 1760-F*, 36 p
- Burtner, R.L., Nigrini, A., and Donelick, R.A., 1994, Thermochronology of Lower Cretaceous source rocks in the Idaho-Wyoming thrust belt. *American Association of Petroleum Geologists Bulletin*, v. 78, no. 10, pp. 1613-1636.
- Carlson, W.D., Donelick, R.A., and Ketcham, 1999, Variability of apatite fission track annealing kinetics I: Experimental results. *American Mineralogist*, v. 84, pp. 1213-1223.
- Chang, Z., Vervoort, J.D., McClelland, W.C., and Knaack, C., 2006. UPb dating of zircon by LA-ICP-MS. *Geochemistry, Geophysics, Geosystems*, American Geophysical Union, v. 7, n. 5, 14 p.
- Chew, D.M. and Donelick, R.A., 2012. Combined apatite fission track and U-Pb dating by LA-ICP-MS and its application in apatite provenance analysis. *Mineralogical Association of Canada Short Course*, v. 42, 219-247.
- Donelick, R.A., 1993, A method of fission track analysis utilizing bulk chemical etching of apatite. U.S. Patent Number 5,267,274.
- Donelick, R.A., 1995, A method of fission track analysis utilizing bulk chemical etching of apatite. Australian Patent Number 658,800.
- Donelick, R.A. and Miller, D.S., 1991, Enhanced TINT fission track densities in low spontaneous track density apatites using ^{252}Cf -derived fission fragment tracks: A model and experimental observations. *Nuclear Tracks and Radiation Measurements*, v. 18, pp. 301-307.
- Donelick, R.A., Ketcham, R.A., and Carlson, W.D., 1999, Variability of apatite fission track annealing kinetics II: Crystallographic orientation effects. *American Mineralogist*, v. 84, pp. 1224-1234.
- Donelick, R.A., O'Sullivan, P.B., and Ketcham, R.A., 2005, Apatite fission-track analysis. *Reviews in Mineralogy and Geochemistry*, v. 58, pp. 49-94.
- Donelick, R. A., O'Sullivan, P. B., and Donelick, M. B., 2010, A Discordia-Based Method of Zircon U-Pb Dating from LA-ICP-MS Analysis of Single Spots. *Smart Science for Exploration and Mining*, v. 1 and 2, p. 276-278.
- Farley, K.A., 2000, Helium diffusion from apatite: General behavior as illustrated by Durango fluorapatite. *Journal of Geophysical Research*, v. 105(B2), pp. 2903-2914.

- Gehrels, G.E., Valencia, V.A., and Ruiz, J., 2008. Enhanced precision, accuracy, efficiency, and spatial resolution of UPb ages by laser ablation-multicollector-inductively coupled plasma-mass spectrometry. *Geochemistry Geophysics Geosystems*, American Geophysical Union, v. 9, 13 p. Hasebe, N., Barbarand, J., Jarvis, K., Carter, A., and Hurford, A.J., 2004, Apatite fission-track chronometry using laser ablation ICP-MS. *Chemical Geology*, v. 207, pp. 135-145.
- Hults, C.P., Wilson, .H., Donelick, R.A., and O'Sullivan, P.B., 2013. Two flysch belts having distinctly different provenance suggest no stratigraphic link between the Wrangellia composite terrane and the paleo-Alaskan margin Lithosphere, December 2013, v. 5, p. 575-594, first published on November 15, 2013, doi:10.1130/L310.1.
- Ketcham, R.A., Donelick, R.A., and Carlson, W.D., 1999, Variability of apatite fission track annealing kinetics III: Extrapolation to geological time scales. *American Mineralogist*, v. 84, pp. 1235-1255.
- Ketcham, R.A., Donelick, R.A., and Donelick, M.B., 2000, AFTSolve: A program for multi-kinetic modeling of apatite fission-track data. submitted to *Geological Materials Research*, v.2, n.1.
- Ketcham, R.A., 2005, Forward and inverse modeling of low-temperature thermochronology data. *Reviews in Mineralogy and Geochemistry*, v. 58, pp. 275-314. Ketcham, R.A., Carter, A.C., Donelick, R.A., Barbarand, J., and Hurford, A.J., 2007, Improved modeling of fission-track annealing in apatite. *American Mineralogist*, v. 92, pp. 799-810.
- Kuiper, K.F., Deino, A., Hilgen, P.J., Krijgsman, W., Renne, P.R., and Wijbrans, J.R., 2008. Synchronizing rock clocks of Earth history. *Science*, 320, p. 500-504.
- Lanphere, M.A. and Baadsraard, H., 2001. Precise K-Ar, $^{40}\text{Ar}/^{39}\text{Ar}$, Rb-Sr and U-Pb mineral ages from the 27.5 Ma Fish Canyon Tuff reference standard. *Chemical Geology*, v. 175, p. 653-671.
- Moore, T.E., O'Sullivan, P.B., Potter, C.J., and Donelick, R.A., 2015, Provenance and detrital zircon geochronologic evolution of lower Brookian foreland basin deposits of the western Brooks Range, Alaska, and implications for early Brookian tectonism: *Geosphere*, v. 11, p. 93-122, doi:10.1130/GES01043.1.
- Paces, J.B. and Miller, J.D., 1993. Precise UPb ages of Duluth Complex and related mafic intrusions, northeastern Minnesota: Geochronological insights to physical, petrogenic, paleomagnetic, and tectonomagmatic processes associated with the 1.1 Ga Midcontinent Rift System. *Journal of Geophysical Research*, v. 98, no. B8, p. 13997-14013.
- Paton, C., Woodhead, J.D., Hellstrom, J.C., Hergt, J.M., Greig, A., and Maas, R., 2010, Improved laser ablation U-Pb zircon geochronology through robust downhole fractionation correction, *Geochem. Geophys. Geosyst.*, 11, Q0AA06, doi:10.1029/2009GC002618.
- Renne, P.R., Swisher, C.C., Deino, A.L., Karner, D.B., Owens, T.L., and DePaolo, D.J., 1998. Intercalibration of standards, absolute ages and uncertainties in $^{40}\text{Ar}/^{39}\text{Ar}$ dating. *Chemical Geology*, v. 45, p. 117-152.
- Shuster, D.L., Flowers, R.M., and Farley, K.A., 2006, The influence of natural radiation damage on helium diffusion kinetics in apatite. *Earth and Planetary Science Letters*, v. 249, pp. 148-161.

- Steiger, R.H. and Jäger, E., 1977, Subcommittee on geochronology: Convention on the use of decay constants in geo- and cosmochemistry. *Earth and Planetary Science Letters*, v. 36, pp. 359-362.
- Sweeney, J.J. and Burnham, A.K., 1990, Evaluation of a simple model of vitrinite reflectance based on chemical kinetics. *American Association of Petroleum Geologists Bulletin*, v. 74, no. 10, pp. 1559-1570.
- Zhang, M., Ewing, R.C., Boatner, L.A., Salje, E.K.H., Weber, W.J., Daniel, P., Zhang, Y., and Farnan, I., 2009, Pb⁺ irradiation of synthetic zircon (ZrSiO₄): Infrared spectroscopic study – Reply. *American Mineralogist*, v. 94, pp. 856-858.

7.2 Appendix B: U-Pb Session Data and Calculations provided by GeoSep Services LLC.

7.2.1 Jurassic Pink Biotite Granite (Jpbg) – Sample 501

Mineral	Zrn						
Sample Name	#501						
GSS Name	084-01						
	Uranium and Thorium			Concordant Scans: Isotopic Ratios			
Analysis Name	[U] (ppm)	[Th] (ppm)	U/Th	207Pb/235Uc Ratio	2 sigma	206Pb/238U Ratio	2 sigma
0841AZ1_15	976	1291	0.76	0.24945	0.21480	0.02741	0.00580
0841AZ1_28	360	179	2.01	0.21221	0.01687	0.02829	0.00091
0841AZ1_27	503	249	2.01	0.20261	0.01696	0.02836	0.00076
0841AZ1_3	300	203	1.48	0.20921	0.02972	0.02851	0.00280
0841AZ1_16	245	145	1.69	0.20013	0.02510	0.02862	0.00089
0841AZ1_29	607	310	1.96	0.20362	0.01619	0.02875	0.00068
0841AZ1_5	420	385	1.09	0.20456	0.01891	0.02895	0.00076
0841AZ1_17	455	278	1.64	0.20913	0.01734	0.02916	0.00124
0841AZ1_4	778	1127	0.69	0.20567	0.01132	0.02922	0.00061
0841AZ1_25	579	385	1.50	0.20643	0.01784	0.02923	0.00083
0841AZ1_7	492	416	1.18	0.20940	0.01872	0.02943	0.00078
0841AZ1_24	730	398	1.83	0.20388	0.01256	0.02943	0.00098
0841AZ1_22	774	588	1.32	0.20714	0.01448	0.02944	0.00073
0841AZ1_13	598	461	1.30	0.20768	0.01674	0.02945	0.00079
0841AZ1_12	410	405	1.01	0.19624	0.02038	0.02948	0.00135
0841AZ1_9	492	379	1.30	0.21292	0.01873	0.02949	0.00135
0841AZ1_8	533	455	1.17	0.20891	0.01686	0.02956	0.00115
0841AZ1_20	868	714	1.22	0.21001	0.01351	0.02957	0.00080
0841AZ1_30	2106	2348	0.90	0.20781	0.01312	0.02967	0.00157
0841AZ1_1	600	105	5.74	0.21674	0.01964	0.02971	0.00128
0841AZ1_19	579	492	1.18	0.21080	0.01535	0.02976	0.00106
0841AZ1_23	826	749	1.10	0.20626	0.01138	0.02979	0.00075
0841AZ1_21	642	527	1.22	0.20272	0.01587	0.02982	0.00127
0841AZ1_10	233	137	1.70	0.21483	0.02457	0.02987	0.00092
0841AZ1_18	929	711	1.31	0.20908	0.01276	0.02989	0.00071
0841AZ1_14	447	267	1.67	0.20960	0.01863	0.02993	0.00123
0841AZ1_11	621	1227	0.51	0.21558	0.01966	0.03014	0.00194
0841AZ1_6	1555	1388	1.12	0.21498	0.00945	0.03121	0.00083
0841AZ1_2	247	276	0.89	0.00000	0.00000	0.00000	0.00000
0841AZ1_26	85	103	0.83	0.56739	0.07338	0.06730	0.00210

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Concordant Scans: Ages					
207Pb/206Pb Ratio	2 sigma	Error Correlation	207Pb/235Uc Age (Ma)	2 -sigma	2 +sigma
0.06600	0.05753	0.07	226.13	182.52	167.46
0.05440	0.00448	0.10	195.40	14.18	14.08
0.05181	0.00442	0.09	187.33	14.37	14.27
0.05322	0.00761	0.34	192.89	25.11	24.81
0.05071	0.00646	0.05	185.24	21.35	21.13
0.05136	0.00416	0.07	188.19	13.70	13.61
0.05125	0.00479	0.09	188.98	16.01	15.88
0.05201	0.00438	0.22	192.82	14.62	14.51
0.05105	0.00286	0.12	189.91	9.56	9.51
0.05121	0.00452	0.08	190.55	15.07	14.96
0.05160	0.00467	0.10	193.05	15.78	15.66
0.05024	0.00312	0.25	188.41	10.62	10.56
0.05103	0.00364	0.10	191.15	12.22	12.14
0.05114	0.00416	0.13	191.60	14.13	14.03
0.04827	0.00499	0.23	181.94	17.37	17.23
0.05237	0.00459	0.26	196.00	15.74	15.62
0.05126	0.00424	0.18	192.64	14.21	14.11
0.05151	0.00342	0.12	193.56	11.37	11.31
0.05079	0.00302	0.48	191.71	11.06	11.00
0.05291	0.00486	0.20	199.19	16.46	16.33
0.05137	0.00388	0.16	194.22	12.92	12.83
0.05021	0.00287	0.13	190.41	9.60	9.55
0.04930	0.00381	0.29	187.43	13.44	13.35
0.05217	0.00608	0.05	197.60	20.64	20.43
0.05074	0.00310	0.18	192.78	10.75	10.69
0.05079	0.00464	0.16	193.22	15.70	15.58
0.05188	0.00447	0.43	198.23	16.49	16.36
0.04996	0.00208	0.37	197.72	7.91	7.88
0.00000	0.00000	0.00	0.00	0.00	0.00
0.06114	0.00802	0.06	456.32	48.10	46.99

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						Preferred Age
206Pb/238U Age (Ma)	2 -sigma	2 +sigma	207Pb/206Pb Age (Ma)	2 -sigma	2 +sigma	Preferred Age (Ma)
174.32	36.46	36.36	806.43	1612.87	1434.01	174.32
179.86	5.69	5.69	387.52	190.34	179.72	179.86
180.29	4.79	4.79	277.07	201.36	189.59	180.29
181.23	17.57	17.55	338.10	341.24	308.62	181.23
181.92	5.56	5.55	227.81	308.31	281.62	181.92
182.74	4.27	4.27	257.17	191.71	181.03	182.74
183.97	4.78	4.78	252.00	222.50	208.24	183.97
185.31	7.78	7.78	285.85	198.48	187.03	185.31
185.67	3.84	3.84	243.02	131.67	126.55	185.67
185.75	5.17	5.17	250.46	209.91	197.18	185.75
186.99	4.88	4.88	267.80	214.55	201.25	186.99
186.99	6.12	6.12	206.16	147.09	140.74	186.99
187.04	4.57	4.57	242.17	168.65	160.33	187.04
187.13	4.96	4.96	247.04	192.88	182.08	187.13
187.32	8.45	8.44	112.60	225.21	235.14	187.32
187.34	8.44	8.44	301.62	206.26	193.91	187.34
187.80	7.18	7.18	252.33	195.94	184.80	187.80
187.84	5.00	5.00	263.90	155.91	148.76	187.84
188.51	9.81	9.80	231.33	140.26	134.47	188.51
188.74	8.02	8.02	324.82	215.48	202.02	188.74
189.06	6.64	6.64	257.44	178.19	168.92	189.06
189.25	4.70	4.70	204.82	135.21	129.83	189.25
189.44	7.92	7.92	162.12	185.98	175.97	189.44
189.71	5.73	5.73	292.89	277.61	255.70	189.71
189.83	4.43	4.43	229.05	144.19	138.08	189.83
190.11	7.67	7.67	231.32	218.03	204.33	190.11
191.40	12.13	12.12	280.23	203.38	191.37	191.40
198.09	5.17	5.17	193.24	98.32	95.44	198.09
0.00	0.00	0.00	0.00	0.00	0.00	198.85
419.87	12.72	12.71	644.31	295.04	269.90	419.87

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2 -sigma	2 +sigma	Age Type	Concordant Scans	Total Scans
36.46	36.36	206Pb/238U concordant scans	2	125
5.69	5.69	206Pb/238U concordant scans	86	121
4.79	4.79	206Pb/238U concordant scans	81	124
17.57	17.55	206Pb/238U concordant scans	97	125
5.56	5.55	206Pb/238U concordant scans	87	122
4.27	4.27	206Pb/238U concordant scans	94	125
4.78	4.78	206Pb/238U concordant scans	91	125
7.78	7.78	206Pb/238U concordant scans	99	125
3.84	3.84	206Pb/238U concordant scans	93	125
5.17	5.17	206Pb/238U concordant scans	67	125
4.88	4.88	206Pb/238U concordant scans	105	125
6.12	6.12	206Pb/238U concordant scans	110	125
4.57	4.57	206Pb/238U concordant scans	87	125
4.96	4.96	206Pb/238U concordant scans	92	125
8.45	8.44	206Pb/238U concordant scans	98	125
8.44	8.44	206Pb/238U concordant scans	119	125
7.18	7.18	206Pb/238U concordant scans	88	125
5.00	5.00	206Pb/238U concordant scans	99	125
9.81	9.80	206Pb/238U concordant scans	98	125
8.02	8.02	206Pb/238U concordant scans	71	125
6.64	6.64	206Pb/238U concordant scans	78	125
4.70	4.70	206Pb/238U concordant scans	96	124
7.92	7.92	206Pb/238U concordant scans	80	125
5.73	5.73	206Pb/238U concordant scans	107	125
4.43	4.43	206Pb/238U concordant scans	91	125
7.67	7.67	206Pb/238U concordant scans	99	125
12.13	12.12	206Pb/238U concordant scans	98	125
5.17	5.17	206Pb/238U concordant scans	91	125
73.00	92.27	Pbc-corrected isotopic sums	0	125
12.72	12.71	206Pb/238U concordant scans	101	125

7.2.2 Jurassic Conway Granite (Jcg) – Sample 504

Mineral	Zrn						
Sample Name	#504						
GSS Name	084-02						
	Uranium and Thorium			Concordant Scans: Isotopic Ratios			
Analysis Name	[U] (ppm)	[Th] (ppm)	U/Th	207Pb/235Uc Ratio	2 sigma	206Pb/238U Ratio	2 sigma
0842AZ1_3	2142	1127	1.90	0.00000	0.00000	0.00000	0.00000
0842AZ1_9	1746	989	1.77	0.19960	0.00894	0.02857	0.00070
0842AZ1_26	1034	650	1.59	0.20284	0.01460	0.02881	0.00132
0842AZ1_12	1875	1170	1.60	0.20445	0.01059	0.02884	0.00103
0842AZ1_30	2060	1687	1.22	0.20728	0.01029	0.02911	0.00094
0842AZ1_22	1777	1158	1.53	0.19901	0.01222	0.02914	0.00103
0842AZ1_6	1139	675	1.69	0.20561	0.01172	0.02914	0.00072
0842AZ1_24	1927	1206	1.60	0.20597	0.01264	0.02915	0.00147
0842AZ1_11	2230	962	2.32	0.20108	0.00932	0.02916	0.00070
0842AZ1_25	3195	1826	1.75	0.20240	0.01008	0.02917	0.00117
0842AZ1_17	1773	1294	1.37	0.20278	0.00881	0.02917	0.00065
0842AZ1_8	513	505	1.02	0.20578	0.01679	0.02919	0.00069
0842AZ1_13	1788	751	2.38	0.20885	0.01041	0.02947	0.00079
0842AZ1_4	2161	1546	1.40	0.20505	0.00873	0.02949	0.00082
0842AZ1_19	1877	1046	1.80	0.00000	0.00000	0.00000	0.00000
0842AZ1_10	2129	1292	1.65	0.20570	0.00882	0.02959	0.00072
0842AZ1_23	3082	1872	1.65	0.20586	0.01256	0.02963	0.00155
0842AZ1_28	193	169	1.14	0.21522	0.02677	0.02964	0.00140
0842AZ1_29	3267	1731	1.89	0.20601	0.00906	0.02988	0.00091
0842AZ1_20	2520	1610	1.57	0.20716	0.00917	0.02991	0.00090
0842AZ1_27	1872	820	2.28	0.21541	0.01326	0.02992	0.00154
0842AZ1_1	2506	1296	1.93	0.21188	0.01039	0.02995	0.00100
0842AZ1_5	4116	2749	1.50	0.20577	0.00699	0.02998	0.00076
0842AZ1_16	194	172	1.13	0.21098	0.02858	0.03004	0.00091
0842AZ1_14	1304	567	2.30	0.20950	0.01194	0.03009	0.00097
0842AZ1_2	4847	3537	1.37	0.20437	0.00738	0.03010	0.00083
0842AZ1_21	617	491	1.26	0.21931	0.01483	0.03022	0.00118
0842AZ1_7	2673	1580	1.69	0.22529	0.03580	0.03026	0.00273
0842AZ1_15	3044	1761	1.73	0.20975	0.00845	0.03041	0.00076
0842AZ1_18	2370	1303	1.82	0.21302	0.00875	0.03055	0.00069

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Concordant Scans: Ages					
207Pb/206Pb Ratio	2 sigma	Error Correlation	207Pb/235Uc Age (Ma)	2 -sigma	2 +sigma
0.00000	0.00000	0.00	0.00	0.00	0.00
0.05068	0.00222	0.30	184.79	7.58	7.55
0.05106	0.00382	0.25	187.52	12.37	12.29
0.05142	0.00241	0.47	188.88	8.94	8.90
0.05165	0.00244	0.39	191.26	8.67	8.64
0.04953	0.00283	0.40	184.29	10.37	10.32
0.05117	0.00293	0.19	189.86	9.89	9.85
0.05125	0.00304	0.44	190.17	10.67	10.61
0.05001	0.00222	0.33	186.04	7.89	7.86
0.05032	0.00241	0.44	187.16	8.53	8.50
0.05041	0.00209	0.32	187.48	7.45	7.42
0.05112	0.00418	0.12	190.01	14.19	14.09
0.05140	0.00243	0.35	192.59	8.76	8.72
0.05044	0.00209	0.35	189.39	7.37	7.34
0.00000	0.00000	0.00	0.00	0.00	0.00
0.05042	0.00205	0.36	189.94	7.44	7.42
0.05038	0.00293	0.47	190.07	10.60	10.55
0.05266	0.00678	0.09	197.93	22.50	22.25
0.05000	0.00202	0.45	190.20	7.64	7.62
0.05023	0.00214	0.38	191.16	7.72	7.69
0.05222	0.00316	0.43	198.08	11.11	11.05
0.05131	0.00245	0.37	195.13	8.72	8.68
0.04978	0.00160	0.43	189.99	5.90	5.88
0.05095	0.00701	0.03	194.38	24.11	23.83
0.05049	0.00277	0.34	193.14	10.05	10.00
0.04924	0.00170	0.42	188.81	6.23	6.21
0.05263	0.00374	0.18	201.33	12.38	12.31
0.05400	0.00811	0.38	206.30	29.89	29.46
0.05002	0.00187	0.41	193.34	7.10	7.08
0.05056	0.00200	0.33	196.08	7.33	7.31

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						Preferred Age
206Pb/238U Age (Ma)	2 -sigma	2 +sigma	207Pb/206Pb Age (Ma)	2 -sigma	2 +sigma	Preferred Age (Ma)
0.00	0.00	0.00	0.00	0.00	0.00	176.84
181.56	4.37	4.37	226.18	102.90	99.75	181.56
183.11	8.29	8.28	243.53	177.06	167.92	183.11
183.27	6.45	6.45	259.61	109.64	106.06	183.27
184.96	5.89	5.88	269.78	110.33	106.70	184.96
185.16	6.47	6.46	173.22	136.19	130.74	185.16
185.17	4.53	4.53	248.64	134.50	129.15	185.17
185.22	9.20	9.19	252.04	139.37	133.64	185.22
185.29	4.40	4.40	195.66	104.62	101.37	185.29
185.37	7.33	7.33	209.77	113.06	109.27	185.37
185.37	4.05	4.05	214.04	97.69	94.85	185.37
185.51	4.35	4.35	246.28	194.10	183.16	185.51
187.22	4.94	4.94	258.82	110.29	106.67	187.22
187.33	5.12	5.11	215.13	97.36	94.53	187.33
0.00	0.00	0.00	0.00	0.00	0.00	187.85
187.97	4.49	4.49	214.55	95.38	92.66	187.97
188.25	9.71	9.70	212.78	137.77	132.18	188.25
188.31	8.78	8.78	314.15	306.76	280.19	188.31
189.79	5.71	5.71	195.19	95.17	92.47	189.79
189.98	5.64	5.64	205.83	100.28	97.29	189.98
190.05	9.64	9.63	294.84	141.40	135.49	190.05
190.24	6.28	6.28	254.60	111.75	108.03	190.24
190.43	4.79	4.78	184.63	75.79	74.07	190.43
190.77	5.68	5.67	238.38	334.00	302.88	190.77
191.14	6.05	6.05	217.61	129.52	124.57	191.14
191.17	5.20	5.20	159.42	81.85	79.85	191.17
191.95	7.36	7.36	312.68	166.09	157.98	191.95
192.16	17.06	17.04	371.09	357.04	321.42	192.16
193.12	4.76	4.76	195.97	88.11	85.79	193.12
194.02	4.34	4.34	221.02	92.78	90.21	194.02

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2 -sigma	2 +sigma	Age Type	Concordant Scans	Total Scans
32.69	27.51	Pbc-corrected isotopic sums	0	125
4.37	4.37	206Pb/238U concordant scans	97	125
8.29	8.28	206Pb/238U concordant scans	112	125
6.45	6.45	206Pb/238U concordant scans	81	125
5.89	5.88	206Pb/238U concordant scans	116	125
6.47	6.46	206Pb/238U concordant scans	107	125
4.53	4.53	206Pb/238U concordant scans	93	124
9.20	9.19	206Pb/238U concordant scans	115	125
4.40	4.40	206Pb/238U concordant scans	101	125
7.33	7.33	206Pb/238U concordant scans	118	125
4.05	4.05	206Pb/238U concordant scans	106	124
4.35	4.35	206Pb/238U concordant scans	96	124
4.94	4.94	206Pb/238U concordant scans	100	125
5.12	5.11	206Pb/238U concordant scans	104	125
45.58	31.81	Pbc-corrected isotopic sums	0	125
4.49	4.49	206Pb/238U concordant scans	106	125
9.71	9.70	206Pb/238U concordant scans	124	125
8.78	8.78	206Pb/238U concordant scans	84	124
5.71	5.71	206Pb/238U concordant scans	105	124
5.64	5.64	206Pb/238U concordant scans	113	125
9.64	9.63	206Pb/238U concordant scans	113	125
6.28	6.28	206Pb/238U concordant scans	97	125
4.79	4.78	206Pb/238U concordant scans	103	125
5.68	5.67	206Pb/238U concordant scans	81	121
6.05	6.05	206Pb/238U concordant scans	105	125
5.20	5.20	206Pb/238U concordant scans	107	125
7.36	7.36	206Pb/238U concordant scans	104	125
17.06	17.04	206Pb/238U concordant scans	5	125
4.76	4.76	206Pb/238U concordant scans	104	125
4.34	4.34	206Pb/238U concordant scans	116	124

7.2.3 Jurassic Rhyolite (Jr) – Sample 286

Mineral	Zrn							
Sample Name	#286							
GSS Name	084-03							
	Uranium and Thorium			Concordant Scans: Isotopic Ratios				
Analysis Name	[U] (ppm)	[Th] (ppm)	U/Th	207Pb/235Uc Ratio	2 sigma	206Pb/238U Ratio	2 sigma	
0843AZ1_13	0	0	0.00	0.00000	0.00000	0.00000	0.00000	
0843AZ1_27	0	0	0.00	0.00000	0.00000	0.00000	0.00000	
0843AZ1_24	416	208	2.00	0.20290	0.01665	0.02866	0.00073	
0843AZ1_6	1474	997	1.48	0.19735	0.00949	0.02884	0.00063	
0843AZ1_17	1899	1193	1.59	0.20997	0.01076	0.02949	0.00083	
0843AZ1_14	2339	1288	1.82	0.21360	0.01294	0.02958	0.00103	
0843AZ1_22	1635	737	2.22	0.28253	0.19056	0.03385	0.01143	
0843AZ1_30	292	390	0.75	0.49925	0.03980	0.06593	0.00351	
0843AZ1_20	235	277	0.85	0.49157	0.03508	0.06691	0.00165	
0843AZ1_7	95	41	2.31	0.49639	0.06064	0.06701	0.00245	
0843AZ1_15	109	89	1.22	0.55229	0.06205	0.06805	0.00291	
0843AZ1_10	431	37	11.66	0.53083	0.02527	0.06826	0.00143	
0843AZ1_21	120	121	0.99	0.53950	0.05186	0.06833	0.00167	
0843AZ1_3	142	194	0.73	0.52739	0.04786	0.06841	0.00189	
0843AZ1_1	74	66	1.13	0.53482	0.07171	0.06882	0.00474	
0843AZ1_19	592	59	10.08	0.53117	0.02261	0.06888	0.00132	
0843AZ1_8	152	90	1.69	0.52220	0.04244	0.06892	0.00181	
0843AZ1_4	84	73	1.16	0.57874	0.06979	0.06923	0.00249	
0843AZ1_25	115	104	1.11	0.55586	0.05216	0.06926	0.00189	
0843AZ1_18	81	71	1.14	0.60573	0.07825	0.06933	0.00318	
0843AZ1_26	133	135	0.99	0.54056	0.04637	0.06982	0.00159	
0843AZ1_23	105	97	1.08	0.51356	0.05615	0.06993	0.00228	
0843AZ1_12	166	217	0.77	0.53055	0.04884	0.06994	0.00168	
0843AZ1_9	198	288	0.69	0.52912	0.03474	0.07005	0.00168	
0843AZ1_11	421	401	1.05	0.54870	0.02938	0.07017	0.00190	
0843AZ1_16	77	91	0.84	0.56409	0.07568	0.07019	0.00228	
0843AZ1_2	184	206	0.90	0.56735	0.04410	0.07104	0.00269	
0843AZ1_5	124	148	0.84	0.67698	0.16494	0.07209	0.00627	
0843AZ1_29	153	144	1.06	0.60457	0.09532	0.06958	0.01043	
0843AZ1_28	198	238	0.83	0.61812	0.12681	0.06848	0.01235

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Concordant Scans: Ages					
207Pb/206Pb F 2 sigma	Error	Correlation	207Pb/235Uc Age (Ma)	2 -sigma	2 +sigma
0.00000	0.00000	0.00	0.00	0.00	0.00
0.00000	0.00000	0.00	0.00	0.00	0.00
0.05135	0.00435	0.03	187.57	14.11	14.01
0.04964	0.00236	0.24	182.88	8.06	8.03
0.05164	0.00249	0.37	193.53	9.05	9.01
0.05238	0.00298	0.38	196.57	10.86	10.80
0.06054	0.03788	0.39	252.67	156.77	145.53
0.05492	0.00451	0.28	411.20	27.14	26.78
0.05329	0.00393	0.06	405.98	24.02	23.74
0.05373	0.00670	0.07	409.26	41.57	40.73
0.05886	0.00678	0.12	446.50	41.00	40.19
0.05640	0.00273	0.16	432.36	16.83	16.70
0.05727	0.00561	0.04	438.09	34.49	33.92
0.05591	0.00517	0.08	430.08	32.07	31.57
0.05637	0.00765	0.23	435.00	48.00	46.89
0.05593	0.00244	0.13	432.59	15.05	14.94
0.05495	0.00455	0.09	426.62	28.51	28.12
0.06063	0.00750	0.05	463.65	45.39	44.40
0.05821	0.00560	0.04	448.83	34.33	33.76
0.06337	0.00829	0.14	480.87	50.09	48.89
0.05615	0.00489	0.06	438.79	30.79	30.33
0.05327	0.00596	0.06	420.84	38.02	37.32
0.05502	0.00516	0.05	432.18	32.66	32.15
0.05479	0.00367	0.11	431.22	23.20	22.94
0.05671	0.00314	0.16	444.14	19.35	19.17
0.05829	0.00791	0.07	454.19	49.73	48.55
0.05792	0.00460	0.19	456.30	28.77	28.37
0.06811	0.01712	0.09	524.95	102.41	97.49
0.06302	0.01025	0.44	480.13	61.23	59.44
0.06546	0.01297	0.48	488.67	81.18	78.06

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206Pb/238U Age (Ma)	2 -sigma	2 +sigma	207Pb/206Pb Age (Ma)	2 -sigma	2 +sigma
0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00
182.15	4.57	4.57	256.41	200.90	189.20
183.26	3.95	3.95	177.98	112.61	108.85
187.34	5.22	5.22	269.68	112.70	108.92
187.91	6.42	6.42	301.89	132.49	127.28
214.57	71.49	71.09	623.07	1246.14	1122.23
411.60	21.22	21.18	408.96	189.18	178.66
417.48	9.96	9.95	341.04	171.34	162.70
418.10	14.79	14.78	359.67	294.18	269.59
424.42	17.55	17.53	561.89	261.24	241.43
425.65	8.64	8.64	468.27	108.80	105.22
426.06	10.08	10.08	501.81	223.19	208.62
426.58	11.41	11.40	448.88	212.22	199.05
429.01	28.63	28.57	466.85	315.58	287.27
429.40	7.97	7.97	449.57	98.57	95.63
429.67	10.94	10.93	410.19	190.86	180.16
431.53	15.00	14.98	626.04	278.50	256.01
431.71	11.39	11.38	537.53	217.72	203.80
432.11	19.20	19.17	720.58	290.72	266.17
435.07	9.57	9.57	458.37	199.35	187.67
435.71	13.72	13.71	340.12	263.92	243.98
435.80	10.10	10.09	412.92	216.62	202.94
436.43	10.11	10.10	403.49	153.42	146.44
437.19	11.47	11.46	480.29	124.80	120.12
437.31	13.77	13.75	540.53	311.28	283.58
442.42	16.19	16.17	526.83	178.85	169.36
448.72	37.76	37.65	871.90	569.11	481.31
433.63	63.00	62.70	708.78	366.28	328.16
427.00	74.75	74.32	789.28	446.04	390.52

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Preferred Age			Age Type	Concordant Scans	Total Scans
Preferred Age (Ma)	2 -sigma	2 +sigma			
0.00	0.00	0.00	failed	0	0
0.00	0.00	0.00	failed	0	0
182.15	4.57	4.57	206Pb/238U concordant scans	99	125
183.26	3.95	3.95	206Pb/238U concordant scans	106	125
187.34	5.22	5.22	206Pb/238U concordant scans	107	125
187.91	6.42	6.42	206Pb/238U concordant scans	35	121
214.57	71.49	71.09	206Pb/238U concordant scans	1	123
411.60	21.22	21.18	206Pb/238U concordant scans	109	125
417.48	9.96	9.95	206Pb/238U concordant scans	105	125
418.10	14.79	14.78	206Pb/238U concordant scans	78	125
424.42	17.55	17.53	206Pb/238U concordant scans	63	122
425.65	8.64	8.64	206Pb/238U concordant scans	103	125
426.06	10.08	10.08	206Pb/238U concordant scans	100	122
426.58	11.41	11.40	206Pb/238U concordant scans	92	125
429.01	28.63	28.57	206Pb/238U concordant scans	97	125
429.40	7.97	7.97	206Pb/238U concordant scans	104	120
429.67	10.94	10.93	206Pb/238U concordant scans	87	125
431.53	15.00	14.98	206Pb/238U concordant scans	83	125
431.71	11.39	11.38	206Pb/238U concordant scans	91	125
432.11	19.20	19.17	206Pb/238U concordant scans	84	125
435.07	9.57	9.57	206Pb/238U concordant scans	102	122
435.71	13.72	13.71	206Pb/238U concordant scans	87	118
435.80	10.10	10.09	206Pb/238U concordant scans	102	124
436.43	10.11	10.10	206Pb/238U concordant scans	109	125
437.19	11.47	11.46	206Pb/238U concordant scans	115	125
437.31	13.77	13.75	206Pb/238U concordant scans	99	125
442.42	16.19	16.17	206Pb/238U concordant scans	116	125
448.72	37.76	37.65	206Pb/238U concordant scans	12	125
480.13	61.23	59.44	207Pb/235Uc concordant scans	114	125
488.67	81.18	78.06	207Pb/235Uc concordant scans	121	125