A Geochemical Study of Cenozoic Magmatism Along an
East-West Transect from Central Great Basin, Nevada to
the Ancestral Cascade Arc, California – A Compositional
Journey Over Space and Time

by

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A thesis submitted to the Faculty of Graduate and Postdoctoral
Affairs in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Earth Sciences

Carleton University
Ottawa, Ontario

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Abstract

Processes linked to shallow subduction, slab rollback and extension are recorded in the whole-rock major, trace element and Sr, Nd, Pb and O isotopic compositions of magmatic rocks in both time and space. Over 250 Eocene to Mio-Pliocene volcanic rocks were sampled along a transect across Central Great Basin (GB) in Nevada to the Ancestral Cascade Arc (ACA) in northern Sierra Nevada, California (ca. 39 to 40 ° latitude), which are interpreted to represent the southwestward migration of magmatism that occurred as a result of the shallow subduction and eventual rollback of the Farallon plate. Volcanic rocks from the study area are chemically, spatially and chronologically zoned into four broad regions: central GB (5 to 35 Ma), western GB (5 to 14 Ma), eastern and western ACA (2.5 to 16 Ma). The volcanic products are dominantly calc-alkalic but transitional to alkalic in the eastern part of the study area. Intermediate lavas (andesites and dacites) are the dominant lava-type, which evolved from the mafic lavas by fractional crystallization and, in selected regions, variable degrees of assimilation of crustal melts. Central Great Basin lavas erupted far inland from the continental margin, which have shoshonitic affinities with higher K, P, Ti, La/Sm as well as lower $(\text{Sr/P})_{\text{pmn}}$ and Ba/Nb compared to ACA lavas. Western GB lavas are chemically uniform with low K, La/Sm and Rb/K. Compared to GB lavas, ACA lavas were largely modified by subduction processes with higher La/Sm, Ba/Nb, and Th/Rb values. Pb-Pb isotope plots for ACA mafic to intermediate lavas show linear trends to higher Pb-isotopic values, which combined with lower Ce/Ce* and high Th/Nb ratios are interpreted to come from slab sediment. Pb-isotope ratios for GB lavas increase with increasing silica, indicating assimilation of continental

crust. Mafic and intermediate lavas from GB and ACA have overlapping $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ values that are consistent with primary melts mixing with a subduction-modified lithospheric mantle source. A smaller subset of lavas from the westernmost ACA region of the study area has lower $^{87}\text{Sr}/^{86}\text{Sr}$ at a given $^{143}\text{Nd}/^{144}\text{Nd}$. $\delta^{18}\text{O}$ values for mafic lavas are derived at the source and increase with increasing age; whereas GB lavas have the overall highest $\delta^{18}\text{O}$ values (+7.09 to +8.54), eastern ACA lavas have an intermediate range (+7.21 to +8.01) and western ACA lavas include the lowest values and the widest range (+6.3 to +8.04). Percent melting of the mantle is enhanced by fluid flux from the dehydrating subducting slab, which is lowest for GB lavas due to low P-T conditions from a shallow slab dip, and highest for western ACA lavas, generated from higher slab dehydration and P-T conditions due to greater slab dip. Extensional processes were active in the Pyramid Lake region (eastern ACA) ca. 13-14 Ma, triggering low-degree melting, possibly due extension-related faulting, producing melts enriched in incompatible elements and chemically similar to central GB lavas. Western GB lavas were also affected by extension and lithospheric thinning at ca. 8-12 Ma.

Acknowledgements

Thank you first and foremost to Dr. Brian Cousens for his valuable supervision, mentorship and patience. Thank you for introducing me to the stunning Basin and Range province to the Sierra Nevada Mountains and to the passionate people who strive to unlock their geological secrets. I am very grateful for the immense amount of time in the field, training as well as support and advice provided over the years. I am also deeply grateful to Dr. Christopher Henry from the Nevada Bureau of Mines and Geology for his excellent council in the field and through personal communication. This project was financially supported by NSERC grants to Dr. Brian Cousens with additional funding by the Mineralogical Association of Canada.

I have benefited from the discussions and encouragement from the Cousens Community as a wonderfully encouraging group for scientific discussion and learning. In particular I would like to extend my appreciations to Dr. Richard Ernst, Christopher Rogers, Susan Kingdon, Alana MacKinder, Cole Kingsbury and Seamus Magnus.

Thank you to Keith Bell, Lizzy Ann Spencer, Mike Jackson, Beth Halfkenny, John Blenkinsop, Claire Samson, and Susan Carr for training, encouragement and overwhelming support. Thank you to Alan Donaldson, Ron Pickeral, Cliff Shaw and David Lentz for your valuable reviews, support and council.

Finally, this journey would not have been possible without the support of my family,

and friends. I am especially grateful to my parents Shashi and Janice Makhija, who supported me and my family through very busy times. To my children Jacqueline, Jasmine and Mikaela: thank you for your patience, for encouraging me in all of my pursuits and inspiring me to follow my dreams. Most of all, to Gerry, my husband, best friend and soul mate. Gerry: you are wonderfully helpful, incredibly patient and the kindest person I know. I always knew that you believed in me and wanted the best for me. Thank you.

Original Contribution

My thesis research fills a gap in geochemical understanding for the Central Basin and Range Province to the Ancestral Cascade Arc, southwestern United States during the tectonic transition from subduction to extension. This study involved major, trace element and isotopic analyses of volcanic rocks between ages of 40 and 2.5 Ma over an east-west transect representing the resultant magmatism from this tectonic transition. Work completed for this study involved acquiring new major, trace and radiogenic isotopic data as well as new $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology and oxygen isotope geochemistry.

For this project I completed two seasons of fieldwork focused on the collection of Cenozoic volcanic rocks guided by existing geologic and topographic maps (Morrison 1964; Page 1964; Jones 1997; Jones et al. 1997; Stewart & Carlson 1976; Green et al. 1991). Samples were specifically selected to fill the geochemical data gaps along the east-west transect of the study region. Sample stations were precisely located using a handheld global positioning system (GPS). I performed all stages of sample collecting, crushing, grinding, powdering, preparation for petrographic and isotopic analyses, and data interpretation under the supervision of Brian Cousens at Carleton University.

As part of the geochemical study I prepared samples for X-ray fluorescence analyses that were then analyzed by Ron Hartree and Tara Kell at the University of Ottawa. Inductively coupled plasma mass spectrometry (ICP-MS) for trace element analyses were acquired commercially at GeoLabs in Sudbury, ON. For the Sr, Nd and Pb isotopic study I performed thermal ionization mass spectrometry (TIMS) at Carleton

University's Isotope Geochemistry and Geochronology Research Centre (IGGRC) using the techniques presented in Cousens (1996). Samples were run on the ThermoFinnigan Triton TI thermal ionization mass spectrometer. I obtained the isotopic ratios for Sr, Nd and Pb for 150 samples from all regions and lava compositions across the study area.

My objective was to analyze the interplay of Cenozoic volcanism through a changing tectonic environment by generating volcanic space-time composition patterns from central Great Basin to central Sierra Nevada Mountains. I acquired additional major, trace element as well as Sr, Nd and Pb isotopic data from several published and online sources that allow us to construct a profile from east to west across the GB and northern Sierra Nevada representing 35 Ma. The geochemical data for lavas from the study region was sourced from the following: 1) GB: Tobin Range, Shoshone Range and Fish Creek Mountains from Stevens (2013), 2) GB, eastern and western ACA from Timmermans et al. (*in preparation*), and Cousens et al. (2008), 3) Post-ACA SN and TTVF from Cousens et al. (2011), 4) Big Pine VF from Omerod et al. (1991). In the third paper I have included major and trace element data from the modern Cascades for further comparative discussion (Grove et al. 1988, Donnely-Nolan et al. 1991, Baker et al. 1994 and USGS public archives). I have also included data from personal communication with Dr. Christopher Henry, Dr. James E. Faulds, Nicholas Hinz, Holly McLachlan (Nevada Bureau and Mines and Geology, Reno), and Dr. David John (United States Geological Survey).

I prepared eleven samples for incremental ^{40}Ar - ^{39}Ar age determinations at the Noble Gas Laboratory, Pacific Centre for Isotopic and Geochemical Research, University of British Columbia, Vancouver. I also selected and prepared five samples from the

Great Basin for whole rock oxygen isotope analyses at the Laboratory for Stable Isotope Science (L.S.I.S.), University of Western Ontario, Ontario, Canada.

My thesis contributes to the greater geochemical understanding and data repository from the southwestward magmatic migration over the past 40 Ma due to the tectonic transition from the flat slab subduction, slab rollback and formation of the Ancestral Cascade Arc, development of a slab window and extension. My trace element and isotopic analyses are the key to understand melt generation at the source, contributions from the convecting upper mantle, subducted slab and metasomatised lithospheric mantle, as well as the nature of the relationship of source melts to the subsequent evolution and assimilation with the surrounding rock over space and time. I also compared these new data generated from this study to tectonomagmatic provinces outside the study area, as well as with existing data from magmatic products from the Eocene to Pleistocene (e.g. the Fish Creek Mountains in central GB through to west of the Lake Tahoe region into the Sierra Nevada) and time (from arc volcanism (3 to 40 Ma) to post-arc volcanism (<3 Ma).

Table of Contents

Abstract.....	2
Acknowledgements	4
Original Contribution.....	6
Table of Contents	9
List of Tables	13
List of Figures.....	14
List of Appendices.....	18
1 Chapter: Introduction	19
1.1 Purpose of Study	19
1.2 Tectonic setting of southwestern United States.	20
1.3 Field Work.....	26
1.4 Local Geological Setting for the Central-West GB and ACA	32
1.4.1 <i>The Great Basin (GB)</i>	33
1.4.2 <i>The Eastern and Western Ancestral Cascades Arc (eastern ACA, western ACA)....</i>	35
1.5 Specific Questions Addressed in this Study.....	37
2 Chapter: (PAPER 1) Geochemical Study of Cenozoic Mafic Volcanism in West- Central Great Basin, Western Nevada and Ancestral Cascades Arc, California.....	57
2.1 Introduction	57
2.1.1 <i>Regional Geological Setting</i>	60
2.1.2 <i>Local Geological Setting</i>	63
2.1.2.1 The Great Basin (GB).....	63
2.1.2.2 Eastern and Western Ancestral Cascades Arc (eastern and western ACA)	65
2.2 Methodology	68

2.2.1	<i>Field Work and Data Mining</i>	68
2.2.2	<i>Petrography</i>	69
2.2.3	<i>Geochronology</i>	70
2.2.4	<i>Geochemistry</i>	70
2.3	Results	72
2.4	Discussion	78
2.4.1	<i>Evidence for Post-Magma Generation Crustal Contamination</i>	79
2.4.2	<i>High-K Magmatism and Degree of Partial Melting</i>	80
2.4.3	<i>More on Chemical Contributions from Source Components</i>	83
2.4.3.1	Variations over Space and Time.....	83
2.4.3.2	Source Components.....	85
2.4.4	Model for GB-ACA Mafic Magmatism	91
2.5	Summary	95

3 Chapter: (PAPER 2) Petrological Evolution During Cenozoic Arc Migration in West-Central Great Basin, Western Nevada and Ancestral Cascades Arc, California **120**

3.1	Introduction	120
3.1.1	<i>Geological Setting</i>	122
3.1.1.1	Great Basin (GB).....	124
3.1.1.2	East Ancestral Cascade Arc (eastern ACA)	126
3.1.2	<i>West Ancestral Cascade Arc (western ACA)</i>	128
3.2	Analytical Methods	129
3.2.1	<i>Geochronology</i>	129
3.2.2	<i>Oxygen Isotopes</i>	131
3.2.3	<i>Field and Analytical Techniques</i>	132
3.3	Results	132

3.3.1	<i>Great Basin</i>	133
3.3.2	<i>Ancestral Cascades Arc (ACA)</i>	136
3.3.3	<i>Oxygen Isotopes</i>	138
3.4	Discussion	138
3.4.1	<i>Variation over Space and Time</i>	139
3.4.2	<i>Origin of Melts</i>	143
3.4.2.1	<i>Mafic Melts (summary of Chapter 2)</i>	143
3.4.2.2	<i>Intermediate Melts</i>	145
3.4.3	<i>Assimilation vs. Fractional Crystallization</i>	147
3.4.4	<i>Compositional Gap</i>	152
3.5	Conclusions	154
4	Chapter: (PAPER 3) Arc to Post-Arc Related Cenozoic Volcanism in Central GB, Nevada to Sierra Nevada, California: A Comparative Geochemical Study....	179
4.1	Introduction	179
4.2	Geological Setting	182
4.2.1	<i>Regional Tectonic Setting</i>	182
4.2.2	<i>Local Geological Setting</i>	183
4.2.3	<i>Previous Work</i>	186
4.2.4	<i>Data Mining</i>	187
4.3	Geochemistry: Relationships Over Space and Time	188
4.4	Assimilation-Fractional Crystallization	193
4.5	Summary	197
5	Chapter: Conclusions	206
5.1	Introduction	206

5.2	Geochemical study of 25 to 2.5 Ma mafic lavas representing the southwestward magmatic sweep from the Central Great Basin to Ancestral Cascade Arc in Sierra Nevada, southwestern United States.....	206
5.3	Magmatic evolution of mafic and intermediate lavas	209
5.4	A magmatic model for the evolution of the Cenozoic southwestward magmatic sweep. 211	
5.5	Future Work	215
Appendices.....		217
	Appendix A MAJOR- AND TRACE-ELEMENT COMPOSITIONS FOR MAFIC ROCKS	217
	Appendix B MAJOR- AND TRACE-ELEMENT COMPOSITIONS FOR VOLCANIC ROCKS FROM THE STUDY AREA WITH IDENTIFIERS 04-LT AND 11-CN.	219
References.....		247

List of Tables

Table 1.1 Petrography of mafic lavas from the study area with identifiers 04-LT and 11-LT

Table 2.1 $^{40}\text{Ar}/^{39}\text{Ar}$ ages for selected Tertiary lavas from the Great Basin and Eastern ACA.

Table 2.2 Oxygen isotopic data from selected Tertiary lavas across the study area

Table 2.3 Maximum, minimum and average isotope and trace element ratios for Central GB, Western GB, Eastern ACA, Western ACA and Westernmost ACA.

List of Figures

Figure 1.1: Digital elevation map of the study area.

Figure 1.2: Paleographic maps of southwestern USA from 150 Ma to present day.

Figure 1.3: Diagrams from Bird (1984) and Humphreys (1995).

Figure 1.4: Series of animations showing the southwestern magmatic sweep.

Figure 1.5: Quadrangle and County maps of eastern California and central-west Nevada.

Figure 1.6: Photos from 2004 and 2011 field trips.

Figure 1.7a Series of digital elevation and simplified geologic maps that show the study area.

Figure 1.7b: A space-time diagram of volcanic events from 40 to 2.5 Ma in the Great Basin and Ancestral Cascade Arc.

Figure 2.1: Digital elevation map of eastern California and western Nevada showing the study area.

Figure 2.2: Photos from the field area: Stillwater Mountain Range (GB), Truckee Range and Andesite Ridge (western ACA).

Figure 2.3: Alkali-silica diagram for mafic lavas.

Figure 2.4: Thin section photos of various mafic lavas from the study area.

Figure 2.5: Major element Harker plots for the GB and ACA mafic lavas.

Figure 2.6: Trace element Harker plots for the GB and ACA mafic lavas.

Figure 2.7: Mafic lavas from the GB and ACA plotted along the various end members as defined in Pearce (2008).

Figure 2.8: Primitive mantle-normalized (Sun & McDonough 1989) REE plots for mafic lavas

Figure 2.9: Primitive mantle-normalized (Sun & McDonough 1989) incompatible element diagrams for mafic lavas

Figure 2.10: Plots comparing Sr, Nd and Pb radiogenic isotopic ratios for mafic lavas.

Figure 2.11: Crustal contamination plots: Nb/La and $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ versus SiO_2 wt%

Figure 2.12: Partial melting diagrams including A) TiO_2 vs. SiO_2 wt% and B) La/Sm vs. La.

Figure 2.13: Diagrams evaluating major, trace and isotopic data trends over distance (longitude) and time (age).

Figure 2.14: Isotopic and trace element ratio plots that compare the components that can influence source melts: the subducted slab-derived aqueous fluids (Ba, Sr), and elements from slab-derived sediment (Th) and/or in the CLM (initial $^{87}\text{Sr}/^{86}\text{Sr}$).

Figure 2.15: Sr-Nd and Pb isotopic plot of mafic lavas from the study area as well as the Gorda Ridge Mid-Ocean Ridge Basalts (MORB, Davis & Clague 1987), Mojave Desert and the Western Great Basin (GEOROC, 2007), the Sierran Granitic

rocks. The data on Gorda basin sediments are taken from Church (1976) and Church & Tilton (1973). Cascadia sediments are from Davis et al. 1998 and Prytulak et al. 2006).

Figure 2.16: Model summarizing the southwestward magmatic migration within the study area (37° latitude) from 40 to 3 Ma, based on the geochemical and petrological results on mafic magmas.

Figure 3.1: Digital elevation map of eastern California and western Nevada showing the study area.

Figure 3.2: Photos from the field: Stillwater Mountain Range, Truckee Range, Sparks and Ellis Peak.

Figure 3.3: Alkali-silica diagram for lavas from the GB and ACA.

Figure 3.4: Harker diagrams showing variations in major and trace elements with silica content for lavas from the GB (right column), eastern ACA (middle column) and western ACA (left column).

Figure 3.5: Chondrite normalized rare-earth element plots (Sun and McDonough 1989) for mafic and intermediate lavas.

Figure 3.6: Primitive mantle normalized incompatible element diagrams for mafic and intermediate rocks from the GB

Figure 3.7: Nd, Sr and Pb isotope plots for volcanic rocks from the study area.

Symbols for the Nd-Sr plot represent the 5 regions identified in the text. Symbols for Pb-Pb plots represent composition.

Figure 3.8: Plots of $\delta^{18}\text{O}$ compared to: A) initial $^{87}\text{Sr}/^{86}\text{Sr}$ B) SiO_2 , C) Ti/Zr , and D) $(\text{La}/\text{Sm})_{\text{pmn}}$, where pmn = primitive mantle normalized.

Figure 3.9: Graphs comparing major, trace element and isotopic ratios with longitude and age for the entire study area.

Figure 3.10: Plots of $\delta^{18}\text{O}$ as well as Ba/Nb versus La/Yb for ACA and GB lavas.

Figure 3.11: Plots of (A) $\delta^{18}\text{O}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ (*assimilation*) highlighting the five regions within the study area, (B) $\delta^{18}\text{O}$ versus $\text{CaO}/\text{Al}_2\text{O}_3$ (*assimilation and/or fractional crystallization*) and (C) Rb/K vs. Rb (ppm).

Figure 3.12: A model summarizing the various stages of magmatic evolution across the east-west transect.

Figure 4.1: (A) Total alkali versus silica diagram (Le Bas et al. 1986) for the GB, ACA and Post-ARC (including Big Pine) lavas. (B) Ternary diagram plotting MgO , FeO^t and $\text{Na}_2\text{O}+\text{K}_2\text{O}$ (wt%) values for GB, ACA and Post-ARC lavas (including Big Pine olivine basalts).

Figure 4.2: Total variation in SiO_2 values in weighted percent (wt%) of GB, ACA and Post-ARC lavas (including Big Pine) with respect to (A) K_2O , (B) Ba , (C) Zr and (D) Nb .

Figure 4.3: Back to mafics: variation of selected trace elements along with initial Sr-isotopic values for GB, ACA and Post-ARC mafic lavas (including Big Pine): (A) Ba/Zr vs. Nb/Zr, (B) $^{87}\text{Sr}/^{86}\text{Sr}$ vs. Ba/Zr, and (C) $^{87}\text{Sr}/^{86}\text{Sr}$ vs. Nb/Zr.

Figure 4.4: Series of LILE/HFSE (column A) and LREE/HREE (column B) vs. Sr-isotopic plots separated by space (rows 1 (ACA) and 2 (GB)) and time (row 3). See text for discussion.

Figure 4.5: Variation of selected A $^{143}\text{Nd}/^{144}\text{Nd}$ vs. La/Sm plot for GB (left) and Post-ARC (including Big Pine) (right) lavas. The AFC curves represent assimilation-fractional crystallization models.

Figure 4.6: A space-time diagram of volcanic events from 40 to <1 Ma in the Great Basin and the Sierra Nevada.

List of Appendices

Appendix A: Major, trace and isotopic for mafic lavas

Appendix B. Major, trace and isotopic data for mafic and intermediate lavas

Appendix C: Sr, Nd and Pb isotope standards

Appendix D: Trace element internal standard and duplicate (precision) data

Appendix E: Oxygen isotope internal standards and duplicate data

Appendix F: Ar-Ar analytical data from this study: data sheets, plateau age, normal isochron and inverse isochron.

1 Chapter: Introduction

1.1 Purpose of Study

The study area (Figure 1.1) is located to the southwest of the United States of America spanning the Great Basin (Basin and Range province) and Ancestral Cascade Arc representing an east-west transect that follows a southwestward migration of magmatism that commenced in north-eastern Nevada ca. 45 Ma. Specifically, the approximately 220 x 150 km study area spans the California-Nevada border extending from longitude 117° in the east (Desatoya Mountain Range) to longitude 121° in the west (Sierra Nevada mountains) by latitude 39° to the south (Lake Tahoe) and 40.5° to the north (Susanville, California). This study area is comprised of overlapping tectonomagmatic provinces: 1) the *Great Basin* (GB), a province defined by its hydrology and physiography, is largely bounded by the Cascade Range to the north, Colorado Plateau and the Rocky Mountains to the east, subdivisions of the Basin and Range province to the south, and the Sierra Nevada mountains to the west. The GB evolved along the western fringe of Precambrian Laurentia and is made up of Precambrian continental crust, Mesoproterozoic accreted terrain, and Neoproterozoic passive margin sedimentation. The GB is capped by magmatic material and then underwent deformation due to several episodes of rifting and orogenic events. Presently, the GB is viewed as a series of north-south trending, linear, fault-block mountain ranges separated by wide valleys formed by structural (extensional) processes. 2) The *Ancestral Cascade Arc* (ACA) represents magmatism that commenced ca. 20 Ma preceeding the present-day Cascade Arc. This magmatism was dominated by calc-

alkaline andesite, basaltic andesite to basalt, the compositions of which are defined by the increasing slab dip through time and the inception of extensional tectonics (e.g. Dickinson 2002).

The Cenozoic volcanic rocks of the study area are of interest because they were generated and extruded as part of the magmatic sweep across Nevada (ca. ca. 40 to ca.3 Ma). At each point of the magmatic sweep, these volcanic rocks capture the geochemical fingerprint at each phase during slab rollback, establishment of stable arc system and the transition from subduction to extensional tectonics. This study investigates the geochemistry of the basaltic, intermediate and felsic volcanic lavas in order to understand melt generation, interaction and influence of the subducted slab, lithospheric mantle, mantle wedge and overlying continental crust, timing and special relationship of the Eocene to Pliocene magmatism as well as the geochemical relationship of neighbouring tectonomagmatic provinces and Post-ACA magmatism.

1.2 Tectonic setting of southwestern United States.

The tectonic history of southwestern North America has been described by several authors including Dickinson (2002, 2006), DeCelles (2004), Henry & Ressel (2000), Sonder & Jones (1999), Lipman (1992) and Atwater & Stock (1998) along with references therein. At the present latitude of the Central GB and western ACA, the region developed into several distinct tectonomagmatic provinces. The GB is the widest segment of the vast Basin and Range taphrogen, the bulk of which lies within the state of Nevada. Pre-Cenozoic rocks comprise Precambrian to Mesozoic meta-volcanic and meta-sedimentary material (Bonham 1969, Sears & Price 2003), which accumulated and

were modified by the Antler, Sonoma, Sevier and Laramide Orogenies. The following paragraphs are a reconstruction of important tectonic events in southwestern United States, which was mainly achieved by: 1) palinspastic adjustments to reconstruct paleotectonic movements, 2) investigations of slab/sediment components of volcanic products, and 3) examination of various ages of subducting oceanic crust, arc magmatism, arc-related faults and extensional tectonism.

Precambrian

The Archean continental nucleus of western Laurentia is located in eastern Nevada and part of western Utah. The province was expanded by accretion of younger terranes during the formation and eventual breakup of the supercontinent Rodinia ca. 1000 Ma (Sears and Price 2003). Geological evidence of continental rifting and depositional events during the pre- and post-continental breakup of the supercontinent that may have caused mantle-derived magmas to surface are found in northern Utah as well as central and southern GB (Sears and Price 2003).

Paleozoic

During the early Paleozoic, the western USA was a passive continental margin that experienced extensive sedimentation and shelf-thickening. Sediments were deeply buried then later tectonically uplifted and exposed. By mid-Paleozoic, the Antler and later the Sonoman Orogenies were underway (John 2001, Dickinson 2004, 2006).

The Antler orogeny began in the Late Devonian and eventually formed the Roberts Mountains, Golconda allochthons and Antler Peak (near Battle Mountain). The renowned Carlin Unconformity (or Carlin Trend), famed for its enrichment in various

ores (see below), is situated along the collision zone formed by the Antler Orogeny (John 2001, Dickinson 2006).

Another period of mountain building, named the Sonoma Orogeny, began during the Permian (John 2001, Dickinson 2006). East-dipping subduction of the Mezcalera plate under the North American plate began, accompanied by accretionary events along the Cordilleran margin, which are now exposed in the eastern Klamath Mountains and Northern Sierra Nevada (Dickinson 2004, 2006). The Havallah sequence, another remnant of the Sonoma Orogeny, was thrust along the Golconda allochthon and can be found in the Sonoma and Tobin Ranges as well as in Battle Mountain (Ingersol, 2008, Brueckner and Snyder 1985).

Mesozoic

Accretion continued into the mid-Jurassic forming a southwest-northeast Cordilleran magmatic arc across the GB (Figure 1.2A). The young Farallon plate displaced the Mezcalera plate and began its subduction under the North American Plate (Mann et al. 2007, Dickinson 2006). Late Jurassic extension and normal faulting in northeastern Nevada may have been related to the gravitational collapse of overthickened crust resulting in the deep elongated basin named the Utah-Idaho trough (Bjerrum & Dorsey 1989).

Major deformation during the Sevier Orogeny formed the Sevier fold belt that was later suggested to be the most important thrust belts in the world because it was the source of economical and tectonic principles of thrust belt geology (Henry & Ressel 2000, John 2001, Dickinson 2006).

The Laramide orogeny (a continuation of the Sevier Orogeny and arguably the

largest mountain building episode to influence western United States) spanned the Late Cretaceous to Eocene (80 to 40 Ma) and gave rise to the Laramide block uplifts not only in the United States, but also the Rocky Mountain fold-and-thrust belt in Canada and the Sierra Madre Oriental fold-and-thrust belt in east-central Mexico (English & Johnston 2004). Whereas the Sevier deformation was primarily characterized by thrusting and folding, the Laramide orogeny was characterized by uplifts of Precambrian crystalline rocks thought to be due to the rapid, northeast-directed convergence between the Farallon and North American plates. A relatively high convergence rate meant that the North American plate overrode the buoyant Farallon plate faster than the Farallon plate was able to sink. As a result, the Farallon plate subducted beneath the North American plate at a very shallow angle that increased the distance between the trench and the volcanic front (Lipman 1992). The interior of western North America was tilted toward the Cordillera by the late Cretaceous (Mitrovica et al. 1989, Humphreys et al. 2003) as the younger and more buoyant lithosphere of the Farallon Plate continued to subduct at a shallow angle (Humphreys et al. 2003). Otherwise known as a “flat slab”, the shallow slab created traction on the base of the lithosphere, pulling it down causing the opening of the Cretaceous Seaway (Mitrovica et al. 1989), also called the Western Interior Seaway or North American Inland Sea (Figure 1.2B and C). The narrow seaway connected the Arctic Ocean to the north with the proto-Gulf of Mexico to the south, was separated from the Pacific by a mountain belt, and hosted plentiful Mesozoic marine life.

Cenozoic

As mentioned in the previous section, subduction of the Farallon plate under the North American plate began during the Jurassic (Mann et al. 2007, Dickinson 2006)

resulting in Andean-style arc volcanism and emplacement of the Sierra Nevada batholith and overlying volcanic rocks until ca. 74 Ma (Figure 1.2B). Subsequently, the arc front migrated several hundred kilometers inboard of the trench due to flat-slab subduction (Bird 1984, Lipman 1992), commonly referred to as the Laramide Migration (e.g. Dickinson 2006) because it accompanied the Laramide orogeny. By mid-Eocene, the Farallon slab detached (Schellart et al., 2010) from the overriding lithosphere (Figure 1.3), “buckled” (Humphreys 1995) or “rolled back” (Best & Christiansen 1991, Dickinson 2004 2006, Henry & Ressel 2000) along an east-northeast trending axis, followed by a southwestward magmatic “sweep” through Nevada before finally steepening to a “normal” subduction angle (Coney & Reynolds 1977, Dickinson & Snyder 1978, Bird 1984, Best & Christiansen 1991, Seedorf 1991, Hofstra et al. 1999, Cline et al. 2005, Ressel & Henry 2006, Henry & Ressel 2000). Humphreys (1995) proposed that simple westward foundering of the Farallon slab explains neither the Eocene-Miocene southward sweep of magmatic activity in the northern GB nor the coincident northwestward magmatic sweep through the southern GB. As presented in Figure 1.3b, Humphreys (1995) explains that the shallow-dipping slab detached from the overlying lithosphere along east-west trends near the U.S.-Canada and U.S.-Mexico borders and along a north-south trend near the trench. The detached slab then foundered along an east-west-trending axis through what is now the central Great Basin, giving it a U-shape, folded cross section, pulling the north edge of the slab southward and the south edge of the slab northward. Pressure-release melting of upwelling asthenosphere around the edges of the slab induced magmatism in the wake of the foundering slab. I support the considerations presented by workers such as Cousens et al. (2008) that although the

model proposed by Humphreys (1995) serves to explain the migration of volcanism in the GB, it does not explain the late reestablishment of the Ancestral Cascades arc south of Oregon-California border compared to the arc north of the border. Therefore I favour the model proposed by workers such as Bird (1984). Andesitic-rhyolitic arc volcanism began at 43 Ma as far east as the San Juan volcanic field in southwestern Colorado (Lipman et al. 1978) that migrated southwestward across the GB until ca. 3 Ma. During this magmatic sweep, andesitic flows and dacite to rhyolitic ash flows and dome complexes were emplaced (John 2001), as well as small volumes of basaltic, andesitic and dacitic lava. Figure 1.4 shows magmatism across the southwestern USA; note the direction of magmatism over time within the study area represented by the grey box.

By 34 Ma, a northwest trending belt of rhyolitic ash-flow calderas began to develop through central Nevada referred to as the “ignimbrite flare-up” (John et al. 2008, Best et al. 2009, Best & Christiansen 1991). These silicic ash-flow tuffs constituted the largest volume of volcanism in the Great Basin (Best & Christiansen 1991, Henry & John 2013).

Intermediate to rhyolitic activity reached westernmost Nevada, just east of the Sierra Nevada between 28 and about 18 Ma forming major volcanic centers including stratovolcanoes (Cousens et al. 2008). Between 17 and 14 Ma, subducted-related igneous activity in the GB was overlapped in time by rift or hotspot volcanism to the north in the Northern Nevada Rift, Oregon High Plains and Columbia River Flood Basalt province (Dickinson 2006). During this time, the GB was subject to various geodynamic processes that presented a complex progression of extension, volcanism and plate boundary tectonics (Henry and Perkins 2001, Sonder & Jones 1999). This latest chapter

of the geological history of the GB occurred when the a change in plate geometry and relative plate motions resulted in magmatism and an extensional orogeny (e.g. Elston 1984) that radically reshaped the landscape of the modern Basin and Range province (Figure 1.2D). At ca. 28 Ma the East Pacific Rise impacted the North American Plate, bringing the Pacific plate into contact with the North American plate. A triple junction marked the initial point of contact of the Pacific, North American and Farallon plates, the latter of which then split into smaller plates that include the Juan de Fuca to the north (Mendocino Triple Junction, MTJ) and Cocos plate to the south (Rivera Triple Junction, RTJ). The MTJ migrated northward and, by 20 Ma, was approximately at the latitude of San Diego (Atwater & Stock 1998). The southern edge of the volcanic (modern Cascade) arc associated with Cenozoic subduction beneath the North American plate has migrated northward since the Miocene. Today the MTJ coincides with the Mendocino fracture zone located offshore of northern California (Atwater & Stock 1998). The renowned San Andreas fault of California is a continental transform fault, which is the transform boundary between the Pacific and North American plates (Figure 1.2E) (Atwater 1970, Atwater & Stock 1998).

1.3 Field Work

Figure 1.5 presents maps with quadrangle and county information for eastern California and western Nevada. Figure 1.6 is a series of photos that represent the 2004 and 2011 field trips. I completed two field trips to the study area during the spring of 2004 and 2011. My mission was one of reconnaissance and recovery: seeking volcanic mafic to intermediate lavas between 40 and 3 Ma. The field day began with finalizing our

target areas on geologic and topographic maps. Using existing maps, geologists from the Nevada Bureau of Mines and Geology advised me on travel routes and details on specific sample sites (e.g. Dr. L. Garside and Dr. C. Henry, Figure 1.6, Photo A). Maps used included Stewart & Carlson (1978), Bell & Bonham Jr. (1987), Page (1965), Hudson et al. (2009), Saucedo (2005), Bell et al. (2010), Jones (1997), Castor et al. (2006), Henry et al. (2004), Henry (1996), and Stewart (1999). Most target areas were accessible by vehicle (we typically drove a Jeep Liberty, Figure 1.6, Photo B) with short hikes to the sample sites. Bedrock was well exposed throughout the study. Pleistocene glacial events over the Sierra Nevada in California and western GB removed material leaving only remnants of lava flows, debris flows and volcanic necks. Bedrock exposure in the GB is also good, though outcrops suffer from higher degrees of weathering.

The southern portion of the Desatoya Mountains is largely made up of Miocene welded ash-low tuffs, and lesser lavas flows and intrusive rocks of similar age. The Miocene volcanic rocks intrude into or overlie Oligocene and Miocene andesite lava flows. The rhyolitic welded tuffs, lava flows and intrusive rocks are the products of a Miocene volcano that collapsed to form a large 25 Ma caldera located in what is now the central part of the Desatoya Mountains (McKee & Conrad 1987). Within the southwest region of Desatoya, a trachyandesite flow near Buffalo Creek Road (south of Hwy 2) is a large, hillside exposure with tilted columnar joints. The fresh dark grey (almost black) groundmass weathers to brown or red, and phenocrysts make up to 30% of the rock (Figure 1.5, Photos C and D). Further east is a remnant of an andesitic volcanic neck, possibly the source of the material in the surrounding area. The outcrop is well exposed on top of the small hill (elevation 1993 meters). Texture within the volcanic neck is

phaneritic, therefore “diorite” would be an appropriate name for the rock. Within the neck are andesite inclusions (xenoliths) up to 30 cm in diameter. I collected a sample from the xenolith and host lava (photo E and F).

Hotsprings Mountains are located to the east of Truckee Mountain Range. The west side consists of 9.8 Ma basaltic trachyandesite flows interbedded with weathered limestone (Photo 5). The eastern part of the range shows more oxidation; however, persistent searching resulted in a fresh sample for analysis (Figure 1.6, Photos G and H).

Seventeen samples were collected from the Southern Stillwater Mountain range. The southeast side of Stillwater features old shorelines from the large endorheic lake named Lake Lahontan (Morrison 1964). As a result, the outcrops are commonly encrusted by tufa (carbonate deposits formed by precipitation from saline lake water due to significant departure from ambient temperature, Figure 1.5, Photos I, J, K), so samples were collected from above the shorelines. Further into the Stillwater Range, the entrance to La Plata Canyon is located on the southeast side. Along the canyon, sedimentary deposits are overlain by middle Miocene intermediate and mafic lava flows, flow breccias, and lahars. The oldest lavas are 15 Ma hornblende and pyroxene andesite and dacite that crop out east, west, and south of Mountain Well Canyon (the northwest end of the canyon). The andesitic lavas interfinger laterally southward, westward, and northward with basaltic lava flows whose age ranges between 13-14.5 Ma (Figure 1.5, Photo L) (John & Silberling 1994).

The Truckee Range is located to the southwest of Pyramid Lake, Nevada. The boarder of Washoe County and Churchill County runs along the ridge of the Truckee

Range. The principal peaks in the Truckee Range (in order from north to south) are Black Warrior Mountain (1,932 m), Juniper Peak (2,197 m) and Two Tips (2,156 m). Black Warrior Mountain consists of a steep-sided round-topped peak set on top of a low ridge, which makes it dominate the eastern skyline in the southern Pyramid Lake area. Five 12.09 Ma vesicular-capped basaltic trachyandesite flows (4 to 10 meters thick) make up the south side of Black Warrior Mountain which together scale to over 1000 meters high. Flows are jointed massive units separated by oxidized clay/ash-rich units (ca. 1 m) (Photos Q, R, S, T). Samples were collected from each flow unit.

Several samples were collected from the Carson City Quadrangle in Nevada. Cliffside outcrop at Table Mountain rises to over 30 meters, where multiple mafic flows are well exposed. The unit top is an 'a'-type blocky flow, which overlays two columnar-jointed mafic flows. Float blankets the slope down to the road. A sample was collected from two flows. The higher (younger) flow is a lower silica content unit, a basaltic andesite with an Ar-Ar age of 7.4 Ma (11-CN-03) compared to the lower unit (andesite, age 6.6 Ma) (Figure 1.6, Photo U).

The Lahontan Mountains, located east of Fallon, Nevada, collectively consists of Seho, Eetza, Salt Wells and Rainbow Mountains. All four mountains are capped with Tertiary basaltic flows. Sedimentary strata are exposed between Rainbow Mountain and Seho Mountain. Miocene basaltic trachyandesite and trachydacite flows cap Rainbow Mountains, and Pliocene olivine basaltic andesite lavas overlie the Rainbow Mountain volcanics on Seho, Salt Wells and Eetza Mountains. For Seho and Salt Wells Mountains, the Miocene and Pliocene lava flows are separated by Tertiary sediments, pumice deposits and other volcanic material. Trachydacites from Rainbow Mountain

(east side) contain round to irregular vesicular basalt xenoliths up to 10 cm in diameter (Figure 1.6, Photo M). Basaltic andesite lavas on Eetza Mountain were encased in tufa, so samples were collected only from Sehoo, Salt Wells and Rainbow Mountains. Specifically, these include a 13.5 Ma trachydacite porphyry from the east side of Rainbow Mountains (Figure 1.5, Photo M), a 9.06 Ma basaltic trachyandesite from the south side of Rainbow Mountains (Photo N; note that this exposed outcrop was highly weathered and fissile – I obtained a sample from one of the larger blocks), and a 4.23 Ma basaltic andesite from Salt Wells and Sehoo (Figure 1.6, Photos O and P).

The Lousetown Formation exposed at Long Valley, Churchill County, consists of a ~150-m-thick sequence of thin jointed olivine-pyroxene basaltic lava flows that are dated at 7.5 Ma (Schwartz and Faulds, 2001; Figure 1.6, Photo 9). Outcrop can show blocky to columnar joints and spheroidal weathering. Further down Long Valley, Lousetown basalt is underlain by ca. 12 Ma hornblende andesitic lava flow identified as Chalk Hills. Further down the valley, the andesite is underlain by flow-layered rhyolite with light grey to pink to vitric groundmass and phenocrysts of quartz, feldspar and biotite.

Virginia City and Flowery Peak, located south of Reno, hosts a series of intermediate to felsic rocks named the Virginia City or Flowery Peak magmatic suites. Virginia City intermediate rocks were collected from remnants of lava flows and dikes. Samples include medium-gray andesite flows, generally not vesicular, with common columnar and platy jointing, well exposed on relatively small hills. The 15 Ma lavas are occasionally distinguished by the presence of olivine that is partially to wholly replaced by glassy orange iddingsite.

Several samples were collected between Portola, Sierraville and Henness Pass, Plumas County. South of Hwy 70 is Beckwourth Peak, where the slopes are of Miocene-Pliocene andesite breccia, capped by Miocene flows. Along Cotton Wood Road, just south of Cotton Wood Creek, is a small roadside exposure consisting of platy andesite flow that underlies glacial till (Figure 1.5, Photo X). Further northeast is Beckwourth Peak, which includes a large cliffside exposure of a Miocene andesite porphyry with columnar joints (columns <0.5 m width) and large blocks of float at the base (Figure 1.6, Photo Y).

Mt. Lincoln (Figure 1.6, Photo AC), Boreal Ridge (Figure 1.6, Photo AB), Andesite Ridge (Figure 1.6, Photo AA) and Castle Peak (Figure 1.6, Photo Z) are located along a south to north line that crosses Interstate 80, northeast of Lake Tahoe. In this region, Tertiary rocks comprise ca. 13 to 8 Ma hornblende andesitic rocks occasionally overlain by ca. 7 Ma basaltic andesite and basaltic trachyandesite with rare olivine microphenocrysts, and pyroxene andesite. Photo AB shows andesitic volcaniclastic rocks and block and lapilli tuff breccia with scattered patches and intercalated flows of hornblende andesite from Andesite Ridge, probably representing the rocks emplaced to the north and west of Donner Lake. Roundness of the clasts indicate that these volcaniclastic rocks were emplaced by fluvial processes and include reworked volcaniclastic beds of sandstone and conglomerate (Sylvester et al. 2012). Mt. Lincoln hosts stubby, aphyric basalt flows, plugs, and dikes through to Andesite Ridge and on the west shoulder of Castle Peak. One of these flows is a vitric, non-vesicular basalt that caps the crest of Boreal Ridge (Photo AB). Remnant linear vents are arranged between the highest point on Boreal Ridge westward to Crater Lake, a small lake at the west end of

the ridge (Sylvester et al. 2012). About two kilometers north of Boreal Ridge is a prominent outcrop of basaltic scoria near the crest of Andesite Ridge. Because of its similar elevation, petrography, short distance from Boreal Ridge, and its similar relation to underlying porphyritic andesite, it correlates the Andesite Ridge rocks with the basalt on Boreal Ridge.

1.4 Local Geological Setting for the Central-West GB and ACA

Where section 1.3 presented observations recorded in the field, section 1.4 provides a broad overview of the regions across the field area.

Voluminous volcanic activity throughout the research area is recorded by numerous calderas (Henry & John 2013, and references therein), volcanic necks (Cousens et al. 2008), and partially eroded lava flow and volcanoclastic rock complexes. Samples collected from individual volcanic centres included in this study occurred over several field excursions from 1997 to 2011 between Latitudes 39° and 41°. Preliminary geochemical results and physiographic observations allows for longitudinal divisions into three broad regions: 1) **GB**, longitudes 117.00° to 119.52° (includes the Stillwater Mountain Range, Truckee Range, Hotspring Mountains and Churchill Group), 2) the **eastern ACA**, longitudes 119.52° to 120.00°, that covers the portion of the Ancestral Cascade lavas (as presented in Figure 18, Cousens et al. (2008)) *east* of the Sierra Nevada block and *west* of the Great Basin (includes Sparks, Silver City, Pyramid, I-80 Suite and Lousetown), and 3) **western ACA**, longitudes 120.00° to 121.00°, including the lavas located on the Sierra Nevada block (Stampede Reservoir, Ladybug, Portola, Mt. Lincoln,

Dog Valley, Stanford/Twin Peaks, Pond Terrace, Andesite Ridge, Devil's Peak, Boreal Ridge, Needle Peak, Squaw, Lowell Ridge, Sawtooth, Henness Pass, and Susanville). Justification for these divisions is as follows. Physiographically, the GB lavas are generally older (8 to 35 Ma), less voluminous and more evolved compared to the ACA lavas. Western ACA lavas erupted within the Sierra Nevada block, whereas the eastern ACA lavas erupted to the east of the Sierra Nevada block but, similar to western ACA lavas, are subalkaline with a strong calc-alkaline signature. Further chemical distinctions amongst the lavas from the three broad regions are discussed in chapters 2 and 3. Chapter 3 of this thesis also further divides the GB into two regions: **Central GB** and **Western GB**, which is based on geochemical differences that are discussed in section 3.4.1. Figure 1.7a is a shaded digital elevation map showing regional divisions used within chapters 2 and 3. Figure 1.7b presents space-time diagrams of volcanic events from 40 to 2.5 Ma in the GB and ACA.

1.4.1 The Great Basin (GB)

“...a pattern of mountains and valleys on a scale so large, so empty and undifferentiated by shape and form and color, that the visual and cognitive expectations of the human mind are confounded and impaired. (William J. Fox, “The Void, the Grid, and the Sign: Traversing the Great Basin”)

The GB is the northern part of the Basin and Range Province, a region characterized by its elongated parallel mountain ranges separated by down-faulted sediment-filled basins. Cenozoic volcanic rocks in the GB include the oldest in the dataset (up to 35 Ma) and typically are emplaced over Mesozoic metasedimentary,

plutonic and metavolcanic sequences. Identifying Cenozoic versus pre-Cenozoic lavas was primarily achieved by textural observation in the field and later confirmed by Ar-Ar geochronology. Two samples from Stillwater Mountain Range collected in 2011 were rejected from this study after it was determined that their ages were ca. 130 Ma (i.e. too old! See Table 3.1). Post-volcanic extension has resulted in closely spaced normal faults that cut entire sequences of Cenozoic volcanic and older rocks (Stewart 1971, Best & Christiansen 1991). Included in this study are Clan Alpine, Desatoya Mountains, Stillwater Mountains, Bell Canyon, Bell Mountain, Table Mountain & Churchill Butte (Carson City Quad), Lahontan Mountains, Truckee Range, Stud Horse, Churchill, and Virginia Hills.

The *Clan Alpine Mountains*, situated to the east of Stillwater Range, host several sequences of rhyolitic flows dated between 22 and 30 Ma (Riehle et al. 1972, Hardyman et al. 1988). Two sets of intermediate flows (basaltic trachyandesites and trachyandesites) were extruded both earlier (35 Ma) and later (<16 Ma) than the rhyolitic episodes. Relative evidence of neighbouring flows, however, shows that both flows are most likely younger than 16 Ma (Riehle et al. 1972). Ten samples were collected within the Clan Alpine Mountains representing the three separate magmatic episodes.

Desatoya Mountains are located southeast of the Clan Alpine Mountains and Antelope Valley. The area is a massive volcano-tectonic trough composed of primarily volcanoclastic material including rhyodacitic ash-flow tuffs, rhyolitic flows and dacitic intrusives (Benjamin 1986). Quaternary alluvium overlies much of the low-lying areas.

The *Stillwater Range* is a ridge approximately 110 km long that trends north-northeast along the east side of Carson Sink, northeast of Fallon. The Stillwater Range is

composed of pre-Triassic strata intruded by and intercalated with post-Triassic volcanic rocks (Page 1965, John 1995), all of which have been affected by structural folding and faulting. Mio-Pliocene basalt and basaltic andesite occur at various sites including near Mountain Well Road and La Plata Canyon. Lavas from the Stillwater Range show high levels of hydrothermal alteration as well as extreme saussuritization of plagioclase to primarily sericite, calcite and chlorite. ***Bell Canyon*** southeast of the Stillwater Range encompasses most of a range that includes Fairview Peak and the northern part of Slate Mountain (Henry 1996). Rock units include Jurassic to Triassic metamorphic rocks intruded by Cretaceous granodiorite, a wide range of Oligocene to Miocene volcanic and volcanoclastic rocks (most of which are related to a ca. 19 Ma caldera), and upper Cenozoic to Quaternary sedimentary deposits. The ***Hot Springs Mountains*** and ***Truckee Ranges*** lie in west-central Great Basin abutting against the Walker Lane (Bonham, 1969). They comprise a series of hills that form part of the northwestern boundary of the large Carson Sink depression. Exposed rocks in the region range from Triassic to Holocene (Wildden & Speed 1974). Cenozoic rocks are primarily volcanic and consist of alternating sequences of flows, tuffs, and shallow intrusive rocks.

1.4.2 The Eastern and Western Ancestral Cascades Arc (eastern ACA, western ACA)

"All Nature's wildness tells the same story: the shocks and outbursts of earthquakes, volcanoes, geysers, roaring, thundering waves and floods, the silent uprush of sap in plants, storms of every sort, each and all, are the orderly, beauty-making love-beats of Nature's heart." Quote by John Muir, a Scottish born American, environmentalist, naturalist, traveler, writer scientist, and lover of the Sierra Nevada Mountains

The division between the eastern and western ACA is placed ca. 120° Latitude, at the foot of the Sierra Nevada block. The pre-Cenozoic rocks of the eastern ACA are mainly Mesozoic granitoids with minor Paleozoic metasedimentary and metavolcanic rocks (Ashley et al. 1979). A series of intermediate magmatic events occurred between 17 and 12 Ma that resulted in several formations including the Kate Peak Formation (highly porphyritic, pyroxene- or hornblende-plagioclase andesites to dacites, from numerous stratovolcano complexes, Prytulak et al. 2001) and Alta and Truckee formations (Ashley et al. 1979) over basement rocks of the Mesozoic Sierra Nevada Batholith. Magmatism that began again at ca. 10 Ma (Cousens et al 2008) included more mafic compositions ranging from pyroxene andesite to olivine-pyroxene basalt.

Sparks is located on the north side to the town of Sparks, just east of Reno. Mafic lavas from Sparks are basaltic andesites that contain phenocrysts of clinopyroxene, plagioclase and iddingsitized olivine. The extensive *Lousetown* Formation (southwest of Reno), covers about 40 km² in the Virginia City Quadrangle, and extends into the Mount Rose, Wadsworth and Churchill Butte quadrangles (Ashley et al. 1979). The *I-80 Suite* refers to lavas with similar ages (<10 Ma), and chemical and physical characteristics that are located along the Interstate-80 corridor between Lake Tahoe and Reno (Henry & Perkins 2001, Cousens et al. 2008). *Ladybug Peak*, at the north end of Verdi Range, represents an explosive and effusive episode of mafic volcanism (Cousens et al. 2008) that may be related to the region's 12-10 Ma widespread extensional event (Henry & Perkins 2001).

The *Pyramid Sequence* (ca. 13-14 Ma), located to the southeast of Pyramid Lake, consists primarily of complexly interbedded basalt to basaltic andesite, sparse andesitic

lavas and rare rhyolitic lava, coarse to fine grained clastic rocks, and a dacitic ash-flow tuff (Henry et al. 2004). The northern end of the Carson Range, just south of Reno, is composed primarily of tilted, porphyritic lavas capped by gently- dipping to flat-lying, poorly phyric lava flows (Thompson & White 1964, Latham 1985). Here I collected comparatively younger (ca. 3 Ma) and less phyric, olivine-clinopyroxene basaltic andesites and basaltic trachyandesites.

Samples from the western ACA named *Pond Terrace, Andesite Peak, Devil's Peak, Mount Lincoln, Twin Peaks, Stanford Peak, Squaw Peak, Sawtooth and Henness Pass* are highly eroded volcanic complexes emplaced 6 - 8 Ma and 5 - 3 Ma that cap high Sierra Nevada granitoid intrusions from the west side of Lake Tahoe north to Donner Pass (Cousens et al. 2008, Harwood 1981, Saucedo & Wagner 1992). The volcanic rocks of this area include lava flows, agglomerates, tuffs and plug intrusions of lava and breccia (Hudson 1951), as well as volumetrically minor amounts of olivine-clinopyroxene basalt and basaltic andesite lava flows (Cousens et al. 2008). At Squaw Peak and Mount Lincoln, dome-collapse deposits are composed of irregular fragments of plagioclase-phyric lavas in a mineralogically similar volcanic matrix. Subordinate lava flows are commonly >10 m thick, massive, and highly plagioclase porphyritic.

1.5 Specific Questions Addressed in this Study

The results of this study are presented in the form of a paper-based thesis, for which the next three chapters represent publishable papers, each addressing unique objectives and outputs contributing to the overall project.

The first paper is presented in Chapter 2 of this study, which addresses the lingering issue of whether the Eocene to Mio-Pliocene “sweep” of magmatism across the GB was the result of either *subduction* of the Laramide (Farallon) Plate underneath the North America plate or *extensional tectonism* that formed the Basin and Range province (Fitton et al. 1988, Ormerod et al. 1991, Asmerom et al. 1994, Yogodzinski et al. 1996). This is done by analyzing the petrology (Appendix B) and geochemistry (Appendix C) of the most “primitive” lavas erupted in an east-west transect across the GB to help understand the forces behind magma generation and tectonic evolution during the 35 to 3 Ma magmatic sweep. As primitive lavas ($Mg\# > 0.7$, where $Mg\# = Mg/(Mg+Fe^{2+})$) are rare in the study area, I have filtered our data to include only lavas with $SiO_2 < 57$ wt.% and $Mg\# > 0.55$, which limits the eastern reach of this study area to the Stillwater Mountain Range. I have compiled new data along with data from existing databases (Henry & Sloan 2003, duBray et al. 2007) for a total of 98 basalts, basaltic andesites and basaltic trachyandesites from the GB and ACA. Samples were analyzed for petrography, detailed major and trace element contents as well as Sr, Nd, Pb and O isotopic ratios to evaluate (a) mantle sources, (b) potential lithospheric and continental crustal contamination, (c) variation in magmatic processes over time and space in the GB.

Chapter 3 of this study is the second paper of the series, which addresses the petrogenesis of all volcanic rocks of each region in order to discuss their evolution across the GB and ACA during the magmatic southwestward migration. This aspect of the study includes mafic, intermediate and felsic lavas for comprehensive petrographic as well as trace element data and Sr-Nd-Pb and O isotopic characteristics to examine the importance of crust-mantle interaction as a function of distance and geological time

induced by flat-slab subduction and slab rollback. The dataset were used to (1) better geochemically subdivide the GB and ACA, (2) to further understand the assimilation-fractional crystallization processes on the magmas from each region (2) examine these regional and geochemical subdivisions and how they relate to tectonic evolution over space and time, (3) discuss the significance of a Daly Gap that occurs between most intermediate and felsic lavas, and (4) present new age and O-isotopic information for mafic and intermediate lavas from the GB and ACA.

Chapter 4 is the third paper in this three-paper series where data from this study are compared to regions adjacent to the study area. I also compare the data to magmas that erupted <3 Ma in the Sierra Nevada Mountains and western Nevada, after the opening of a slabless window beneath the continental margin and the cessation of the Farallon arc system in the study area. Specifically, this chapter examines crust-mantle interaction as a function of distance and geological time induced by flat-slab subduction, slab rollback and the opening of a slab window associated with formation of the San Andreas transform fault system (Atwater & Menard 1970, Cousens et al. 2008, 2011). Included are existing data for mafic to intermediate lavas from central GB as far northeast as the Fish Creek Mountains as well as post-ACA data (<3 Ma) that geochemically reflect a slab-window setting (Cousens et al. 2011).

Chapter 5 is a project summary. It also discusses the tectonic evolution of the southwestern United States from 40 to 1 Ma with reference to tectonic models of the area.

Figure 1.1: Simple digital elevation map of the study area. The western edge of the Precambrian continental basement lies just outside of the study area, as is indicated by the 0.706 isopleth (modified from Kistler & Peterman 1978, Wooden et al. 1999).

A

Western USA 150 Ma

B

Western USA 70 Ma

C

Western USA 50 Ma

D

Western USA 5 Ma

E

Figure 1.2: Series of paleogeographic and paleotectonic maps of southwestern USA at A) 150 Ma – Andean-style magmatism during subduction of Farallon plate underneath North American plate, B) 70 Ma – cessation of subduction related magmatism due to increase of subduction rate causing flatslab subduction, C) 50 Ma – Laramide Orogeny is underway, and the slab migrates far into North American Plate (into Colorado); rate of subduction is decreasing and slab rollback is imminent D) 5 Ma – magmatism migrated southwestward across Nevada and into California, Basin and Range extension has modified the terrain since ca. 25 Ma, E) Southwestern USA as it is today highlighting the current tectonomagmatic provinces. Yellow rectangle shows the area of interest. Maps A to D modified from © Ron Blakey, <https://www2.nau.edu/rcb7/RCB.html>. Map E modified image from Google Earth.

A

B

(Humphreys 1995)

Figure 1.3: Farallon plate flat slab versus buckling theories as proposed by A) Bird (1984) and B) Humphreys (1995) respectively. The rollback theory is favoured in the literature (e.g. Cousens et al. 2008) and within this thesis. However, it is valuable to present Humphreys' explanation for the buckling theory: "Buckling option for post-Laramide removal of the Farallon slab. Accretion of Siletzia [a large fragment of ocean lithosphere that accreted to the North American continent towards the end of the Laramide orogeny] (stippled pattern) caused tear in the Farallon slab, which subducts steeply beneath northern USA. This tear has enabled the flat-slab portion to buckle, with its northern edge propagating to the south and exposing the hydrated lithosphere to asthenosphere. ... In the figure, a tear developed near the strength contrast at the Mendocino fracture zone (MFZ). By using the propagation of magmatism during the ignimbrite flareup, downwelling occurred along an axis extending WNE from southern Nevada. Plate motion in the 20 m.y. since the ignimbrite flareup ended leaves this buckled slab where high velocity mantle is imaged."

Figure 1.4: Maps of the southwestern United States at various points in time over the past 50 Ma. The dots represent active volcanism as the Farallon Plate (east of the red line) subducts underneath the North American plate, and the Pacific Plate (west of red line) meets the edge of the continent. Red dots = mafic lavas, orange = intermediate, yellow = felsic and purple = unknown composition. The blue box encompasses the area of interest for this doctoral thesis and west into the western Great Basin. Note the changes in composition and location of the magmatism as it “sweeps” across the blue box at circa a) 50 Ma, b) 40 Ma, c) 30 Ma, d) 20 Ma, e) 10 Ma and f) 5 Ma). (Maps modified from a quick time animation provided by NAVDAT; www.navdat.org)

California and Nevada County Maps with Quadrangles

Figure 1.5: Maps of central-east California and central-western Nevada with names for Counties and Quadrangle that covers the study area. Source: USGS

Desatoya Mountains, Churchill County

Jointed Andesite lava Flow

Hot Springs Mountains, Churchill County

Stillwater Mountain Range (Southern end), Churchill County

Truckee Mountain Range, Churchill County

Carson City Quadrangle

Jointed: blocky
(‘a’a-type flow?)

Jointed: columnar
(~1 meter width)

Jointed: columnar
(< 1 meter width)

Float

Long Valley, Storey County, Nevada

Hennes Pass and surrounding area, Portola Quadrangle, Plumas County

Figure 1.6: Photos of various sample locations across the field area: A: Consulting maps with colleagues from the Nevada Bureau of Mines and Geology (from left: B. Cousens, L. Garside, C. Henry); B: transportation primarily by jeep; C, D, E, F: Intermediate lavas from Desatoya Mountains; G, H: Trachyandesite from Hot Spring Mountains; I, J, K: Southeast side of Stillwater Mountains; L: La Plata Canyon, Stillwater Mountains; M, N, O, P: Segment of Geologic Map from Lahonton Mountains Quadrangle. Portion of legend showing Tertiary Volcanic rocks is also shown. Photos show basaltic trachyandesite from Rainbow Mountain and basaltic andesite from Seho Mountain; Q, R, S, T: Series of basaltic trachyandesite flows from Truckee Mountain Range; U: Table Mountain, Carson City Quadrangle; V, W: Lousetown and Chalk Hills from the Long Valley region; X, Y: Henness Pass and surrounding area, Plumas County, Z, AA, AB, AC: I-80 region, including Mt. Lincoln, Boreal Ridge, Andesite Ridge and Castle Peak. Rock hammers are 40 cm in length, orange backpack is about 50 cm in length. See text for further discussion.

Figure 1.7a: Series of maps showing the study area. Map A: Digital elevation map of California and Nevada. The Sierra Nevada block is shaded in blue, the eastern ACA is shaded in green and the GB is shaded in purple. The map insert to the top right shows the location of the Walker Lane, which spans across parts of eastern ACA and western GB. The study area is shown as the black box. Map B: the study area zoomed in, showing the three broad divisions used in Chapter 2. Symbols represent sample locations and composition (see legend). Maps C and D are similar to A and B; however, the GB is further divided into two: Western GB and Central GB. These divisions are used in Chapter 3. Map E: Simplified geology map showing the study area. Open blue squares represent the western ACA lavas, the open stars represent the Westernmost ACA Lavas. Modified from Geologic Map of California, 1966 (1:250 000), compiled by U.S. Geological Survey and California Division of Mines and Geology. Map F: Generalized Geology Map of Nevada. Symbols represent sample locations: green triangles = eastern ACA, filled purple crosses = Western GB, open purple crosses = central GB. Map modified from Nevada Bureau of Mines and Geology, Map 57 Million Scale. Geology Map of Nevada by John H. Stewart and John E. Carson 1977 and fault map by Craig M dePolo 1998.

Figure 1.7b A space-time diagram of volcanic events from 40 to 2.5 Ma in the Great Basin and Ancestral Cascade Arc. The Laramide Migration represents the Late Cretaceous to Paleogene inland migration of Laramide magmatism from the Sierra Nevada on the west toward the Rocky Mountain continental interior due to the increased convergence rate between the North American and Farallon plate (between 80 and 40 Ma). For clarity only representative Cenozoic volcanic centres are included in the diagram. The examples are follows: **CENTRAL GREAT BASIN:** FCM = Fish Creek Mountains, TR = Tobin Range, SR = Shoshone Mountain Range; **WEST GREAT BASIN:** BM = Bell Mountains, BC = Bell Canyon, SR = Sillwater Mountain Range, CA = Clan Alpine Mountains, DM = Desatoya Mountains; **WESTERNMOST GREAT BASIN:** TM = Table Mountain, Carson City Quadrangle, CH = Churchill, C12 = Churchill for lavas 12 Ma, HM = Hotspring Mountains, TR = Truckee Range, SL = Soda Lake; **EASTERN ACA:** KP = Kate Peak, L = Lousetown, VC = Virginia City, RM = Rattlesnake Mountains, ELT = East Lake Tahoe, P = Pyramid, FP = Flowery Peak, CR = Carson Range, R = Reno, SWVC = Southwest Virginia City; **WESTERN ACA:** BR = Boreal Ridge, CP = Castle Peak, DV = Dog Valley, EP = Ellis Peak, HP = Heness Pass, ML = Mount Lincoln, VL = Verdi Lookout, S = Squaw, Stanford/Twin peaks.

2 Chapter: (PAPER 1) Geochemical Study of Cenozoic Mafic Volcanism in West-Central Great Basin, Western Nevada and Ancestral Cascades Arc, California

2.1 Introduction

The relationship between magmas derived at destructive plate margins and those at within-plate settings has long been explored (e.g. Hofmann et al. 1984, Ellam & Hawkesworth 1988, Omerod et al. 1991, Pearce & Peate 1995, Pearce & Stern 2006). The Pacific margin of North America has an extensive tectonomagmatic history of orogenic events, passive and Andean-style convergent margins, hotspot magmatism and extension (Dickinson 2006 and references therein). Between ca. 45 Ma and ca. 3 Ma, regions in both the Great Basin (GB) and Ancestral Cascades Arc (ACA) were covered by extensive magmatic events that migrated southwestward from western Utah to eastern California, commonly referred to as a “magmatic sweep” (Coney 1978, Christiansen & Yeats 1992, Humphreys 1995, Dickinson 2006). Calderas related to ash-flow magmatism began as early as 49 Ma with southwest migrating eruptions in the GB and Sierra Madre Occidental of Mexico, commonly referred to as the “ignimbrite flare-up” (Henry et al 2010 and references therein). The ignimbrite flare-up was both preceeded and followed by mafic to felsic volcanic events, consisting predominantly of subalkaline and marginally alkaline basalts and basaltic andesites (Figure 2.1). Cenozoic magmatism in the GB is thought to be due to the rollback of the shallow-dipping Farallon slab, inducing the southwestward magmatic sweep as the slab continued to roll back across the GB and

transitioned into the Ancestral Cascade Arc (Cousens et al. 2008, John et al. 2012). These volcanic rocks began erupting far from the continental margin (as far east as the San Juan Volcanic Field in Colorado, USA), are chemically complex, and to date have received little attention in studies relevant to the origin and evolution of this migrating sweep of volcanism.

Geochemical studies of neighbouring regions outside the thesis study area are well represented in the literature, including the modern Cascade arc (e.g. Baker et al. 1994, Bacon et al. 1997, Green & Harry 1999, Borg et al. 2002, Strong & Wolff 2003, Leeman et al. 2004, Green & Sinha 2005), Yellowstone and the Snake River Plain (e.g., Camp 1995, Christiansen et al. 2002, Jordan et al. 2004), the Western Great Basin (WGB; Ormerod et al., 1988), the Mojave Desert and Basin and Range (e.g. Glazner et al. 1991, Perry et al. 1993, Farmer et al. 1995, Yogodzinski et al. 1996), and the San Andreas fault and offshore California (e.g. Cole & Basu 1995, Davis et al. 1995, Dickinson 1997). The Ancestral Cascades Arc (ACA), known as the Miocene-Pliocene Cascade Arc (to the south of the modern Cascades), is also well established in the literature (Priest 1990, Du Bray et al. 2006, Christiansen & Yeats 1992, Lipman 1992, John 2001, Dickinson 1997, 2002, 2004, Cousens et al. 2008), with particular emphasis on the ACA within the Sierra Nevada (e.g. Putirka et al. 2012 and references therein). Late Cenozoic uplift of the southern Sierra Nevada is linked to on-going delamination of the underlying lithospheric mantle, based on geophysical (Wernicke et al. 1996, Boyd et al. 2004, Zandt et al. 2004), geological and petrological work (Ducea & Saleeby 1996, 1998, Manley et al. 2000, Ducea 2001, Lee et al. 2001, Lee 2005, Farmer et al. 2002, Putirka & Busby 2007, Putirka et al. 2012).

A lingering issue that plagues this region is whether the Eocene to Mio-Pliocene “sweep” of magmatism across the GB was the sole result of *subduction and rollback* of the Laramide (Farallon) Plate underneath the North America plate and/or does *extensional tectonism* that formed the Basin and Range province contribute to the melt generation during slab rollback (Fitton et al. 1988, Ormerod et al. 1991, Asmerom et al. 1994, Yogodzinski et al. 1996). Studies from surrounding tectonomagmatic provinces outside the study area have determined specific geochemical signatures that represent subduction- versus extension-related processes. For example, Eruptions from the southern Cascades are calc-alkaline, dominantly intermediate in composition with enrichment in large ion lithophile (LIL) and light rare earth (LRE) elements, and depletion in high field strength (HRE) elements (e.g. Borg et al., 1997). Eruptions due to extension are bimodal (basalt and rhyolite), high-K (typically) alkaline lavas, with higher radiogenic Sr and lower radiogenic Nd due to higher degrees of melting from the modified lithospheric mantle (e.g. Ormerod et al. 1991). This study offers a comprehensive geochemical investigation of the most “primitive” lavas erupted in an east-west transect across the GB to help understand the forces behind magma generation and tectonic evolution following the 35 Ma to 3 Ma magmatic surge (Figure 2.1). For this study, a total of 98 basalts, basaltic andesites and basaltic trachyandesites from the GB and ACA were analyzed for petrography, detailed major and trace element contents as well as Sr, Nd, Pb and O isotopic ratios to evaluate (a) mantle sources, (b) potential lithospheric and/or continental crustal contamination, (c) variation in magmatic processes over time and space in the GB. Note that “lithosphere” is defined as used in Kempton et al. (1991), who in turn used the definition from McKenzie (1989) as “the mechanical

boundary layer beneath the continental crust which remains physically isolated for geologically long periods from the convecting mantle beneath because it is relatively cold (so that heat passes through it entirely by conduction) and buoyant (due to chemical differentiation by melt extraction)". Thus the "asthenosphere" is the hot convecting upper mantle and is for the most part chemically separate from the lithosphere.

The study area covers latitudes 39° and 40°, and divided longitudinally into three broad regions (Figure 1.4a): 1) **GB** at longitudes 117.00° to 119.52°, 2) the **eastern ACA** at longitudes 119.52° to 120.00°, and **western ACA** at longitudes 120.00° to 121.00°. As primitive lavas ($Mg\# > 0.7$, where $Mg\# = Mg/(Mg+Fe^{2+})$) are rare in parts of the study area, I have filtered our data to lavas with $SiO_2 < 57$ wt.% and $Mg\# > 0.55$, which limits the eastern reach of the east-west transect to the Stillwater Mountain Range within the central GB. A more complete dataset that includes the intermediate and felsic rocks is presented in Chapter 3.

2.1.1 Regional Geological Setting

The tectonic history of southwestern North America has been described by several authors including Dickinson (2002, 2006), DeCelles (2004), Henry & Ressel (2000), Sonder & Jones (1999), Lipman (1992) and Atwater & Stock (1998) along with references therein. Pre-Cenozoic rocks range in age from Precambrian to Mesozoic and almost all are meta-volcanic and meta-sedimentary (Bonham 1969, Sears & Price 2003); all were subjected to the Antler (Late Devonian into the Mississippian), Sonoma (during the Permian/Triassic transistion), Sevier (Jurassic to Eocene) and Laramide (Late Cretaceous to Eocene) Orogenies. Subduction of the Farallon plate under the North American plate began during the Jurassic (Mann et al. 2007, Dickinson 2006), and the

North American coast underwent Andean-style arc volcanism centred in the Sierra Nevada arc and batholith until ca. 74 Ma. Subsequently, the arc front migrated several hundred kilometers inboard of the trench (Lipman 1992). This event is commonly referred to as the Laramide Migration (ca. 70 to ca. 40 Ma) (e.g. Dickinson 2006) because it accompanied the Laramide orogeny. The Sevier deformation (ca. 140 to 50 Ma) was primarily characterized by thrusting and folding, whereas the Laramide orogeny (ca. 80 to 35 Ma) was characterized by uplift of Precambrian crystalline basement thought to be due to the rapid, northeast-directed convergence between the Farallon and North American plates. This relatively high convergence rate meant that the North American plate overrode the buoyant Farallon plate faster than the Farallon plate was able to sink. As a result, the Farallon plate was subducted beneath the North American plate at a very shallow angle, increasing the distance between the trench and the volcanic front (Lipman 1992). By the late Cretaceous, the thickened and uplifted interior of western North America was tilted toward what is now referred to as the Sierra Nevada (Mitrovica et al. 1989, Humphreys et al. 2003) while the slab of younger and more buoyant lithosphere of the Farallon Plate continued to subduct (Humphreys et al. 2003). This descending “flat slab” created traction on the base of the lithosphere, pulling it down, which caused the opening of the Cretaceous Seaway (Mitrovica et al. 1989), also called the Western Interior Seaway or North American Inland Sea. By mid-Eocene, the Farallon slab detached (Schellart et al., 2010) from the overriding lithosphere, and “rolled back” (Best & Christiansen 1991, Dickinson 2004, 2006, Henry & Ressel 2000) along an east-northeast trending axis, followed by a southwestward magmatic “sweep” through Nevada before finally steepening to a “normal” subduction angle (Coney &

Reynolds 1977, Dickinson & Snyder 1978, Best & Christiansen 1991, Seedorf 1991, Hofstra et al. 1999, Cline et al. 2005, Ressel & Henry 2006, Henry & Ressel 2000). The magmatic sweep involved the emplacement of andesitic and dacite to rhyolitic ash flows and dome complexes (John 2001), as well as small volumes of basaltic, andesitic and dacitic lava as far east as the San Juan volcanic field in southwestern Colorado (Lipman et al. 1978). A northwest trending belt of rhyolitic ash-flow calderas that developed through central Nevada have been referred to as the “ignimbrite flare-up” (John et al. 2008, Best et al. 2009, Best & Christiansen 1991). Magmatic activity reached westernmost Nevada forming major volcanic centers. Between 17 and 14 Ma, subduction-related igneous activity in the Sierra Nevada and western Nevada was overlapped by rift or hotspot volcanism in the Northern Nevada Rift, Oregon High Plains and Columbia River Flood Basalt (Dickinson 2006).

The latest geological chapter of the GB and ACA is occasionally referred to as an *extensional orogeny* (e.g. Elston 1984). At ca. 28 Ma the East Pacific Rise impacted the North American Plate, bringing the Pacific plate into contact with the North American plate. A triple junction marked the initial point of contact of the Pacific, North American and Farallon plates. The Farallon plate later split into smaller plates that include the Juan de Fuca to the north (Mendocino Triple Junction, MTJ) and Cocos plate to the south (Rivera Triple Junction, RTJ). The MTJ migrated northward and, by 20 Ma, was approximately at the latitude of San Diego (Atwater and Stock 1998). The southern end of the volcanic (Cascade) arc associated with Cenozoic subduction beneath the North American plate has migrated northward since the Miocene.

2.1.2 *Local Geological Setting*

Samples of mafic rocks for this study were collected over several field excursions from 1997 to 2011 between Latitudes 39° and 40°, and divided longitudinally into three broad regions: 1) **GB**, longitudes 117.00° to 119.52° (includes Stillwater Mountain Range, Truckee Range, Hotspring Mountains and Churchill Group), 2) the **eastern ACA**, longitudes 119.52° to 120.00° (includes Sparks, Silver City, Pyramid, I-80 Suite and Lousetown), and **western ACA**, longitudes 120.00° to 121.00° (includes Stampede Reservoir, Ladybug, Portola, Mt. Lincoln, Dog Valley, Stanford/Twin Peaks, Pond Terrace, Andesite Ridge, Devil's Peak, Boreal Ridge, Needle Peak, Squaw, Lowell Ridge, Sawtooth, Henness Pass, and Susanville) (Figure 2.2). I have attained additional geochemical and isotopic data for all three regions from Sloan et al. (2003) and du Bray et al. (2009). Petrography for samples with the identifiers *04-LT* and *11-CN* are summarized in Table 2.1.

2.1.2.1 **The Great Basin (GB)**

The ***Stillwater Range*** is a ridge approximately 110 km long that trends north-northeast along the east side of Carson Sink, northeast of Fallon (Figure 2.1). The Stillwater Range is composed of pre-Triassic strata intruded by and intercalated with post-Triassic volcanic rocks (Figure 2.2A and B) (Page 1965, John 1995), all of which have been affected by structural folding and faulting. Mio-Pliocene basalt and basaltic andesite occur at various sites including near Mountain Well Road and La Plata Canyon. Lavas from the Stillwater Range show high levels of hydrothermal alteration causing

extreme saussuritization of plagioclase to primarily sericite, calcite and chlorite. Basalt from La Plata Canyon is aphyric and plagioclase-rich. *Bell Canyon* southeast of the Stillwater Range encompasses most of a range that includes Fairview Peak and the northern part of Slate Mountain (Henry 1996). Rock units include Jurassic to Triassic metamorphic rocks intruded by Cretaceous granodiorite, a wide range of Oligocene to Miocene volcanic and volcanoclastic rocks (most of which are related to a ca. 19 Ma caldera), and upper Neogene to Quaternary sedimentary deposits. Vitrophyric basaltic andesitic lava flows and dykes (25% phenocrysts of plagioclase and clinopyroxene) have a hyalocrystalline groundmass (Figure 2.4A). The basaltic unit (04-LT-51) has basal scoria breccia that develops into a massive but highly vesicular lava with 20% phenocrysts including plagioclase, clinopyroxene and iddingsitized olivine (Henry 1996). A sample from Bell Canyon (04-LT-48) has a holohyaline groundmass.

The *Hot Springs Mountains* and *Truckee Ranges* lie in west-central GB abutting against the Walker Lane (Bonham 1969). They comprise a series of hills that form part of the northwestern boundary of the large Carson Sink depression. Exposed rocks in the region range from Triassic to Holocene (Willden & Speed 1974). Cenozoic rocks are primarily volcanic and consist of alternating sequences of flows, tuffs, and shallow intrusive rocks. Lavas are basaltic andesites that commonly contain abundant plagioclase and minor olivine and/or augite phenocrysts (Figure 2.4C). Olivine is generally euhedral and mildly to completely altered to iddingsite. Subhedral augite commonly shows subophitic texture with plagioclase, and most include plagioclase phenocrysts with sieve texture and oscillatory or normal zonation (Figure 2.4B).

2.1.2.2 Eastern and Western Ancestral Cascades Arc (eastern and western ACA)

The pre-Cenozoic rocks are mainly Mesozoic granitoids with minor Paleozoic metasedimentary and metavolcanic rocks (Ashley et al. 1979). A series of intermediate magmatic events occurred between 17 and 12 Ma resulted in several formations including Kate Peak, Alta and Truckee formations (Ashley et al. 1979). Magmatism that began again at ca. 10 Ma (Cousens et al 2008) included more mafic compositions ranging from pyroxene andesite to olivine-pyroxene basalt. Basalts from the eastern and western ACA are primarily porphyritic with olivine and/or augite phenocrysts. Basaltic andesites are mineralogically similar to the basalts, although plagioclase dominates over olivine and sparse microphenocrysts of orthopyroxene and/or clinopyroxene. Seriate texture is present in sample 04-LT 41, whereas other lava flows show at least two stages of feldspar growth. Plagioclase phenocrysts (as much as 15% by volume) typically occur as glomerocrysts that are either zoned with resorbed interiors or, more commonly, are zoned and subhedral. Smaller feldspar grains are; skeletal to euhedral and generally lack zoning.

Sparks is located on the north side to the town of Sparks, just east of Reno. Mafic lavas from Sparks are basaltic andesites that contain phenocrysts of clinopyroxene, plagioclase and iddingsitized olivine. The extensive *Lousetown* Formation, southwest of Reno, covers about 40 km² in the Virginia City Quadrangle, and extends into the Mount Rose, Wadsworth and Churchill Butte quadrangles (Ashley et al. 1979). The *I-80 Suite* refers to lavas with similar ages (<10 Ma), and chemical and physical characteristics that are located along the Interstate-80 corridor between Lake Tahoe and Reno (Henry & Perkins 2001, Cousens et al. 2008). *Ladybug Peak*, at the north end of Verdi Range, represents an explosive and effusive episode of mafic volcanism (Cousens et al. 2008)

that may be related to the region's 12-10 Ma extensional event (Henry & Perkins 2001). Basalts and basaltic andesites contain as much as 15% olivine grains up to 4 mm in size, 10% augite up to 2 mm in size and minor plagioclase set in a fine-grained matrix of feldspar and pyroxene (Cousens et al. 2008).

The *Pyramid Sequence* (ca. 13 Ma), located to the southeast of Pyramid Lake, consists primarily of complexly interbedded basalt to basaltic andesite, sparse andesitic lavas and rare rhyolitic lava, coarse to fine grained clastic rocks, and a dacitic ash-flow tuff (Henry et al. 2004). The mafic lavas considered in this study range from aphyric to coarsely porphyritic. The coarsely porphyritic rocks are characterized by prominent, tabular plagioclase phenocrysts up to 20 mm long and 2 to 4 mm wide (Henry et al. 2004).

Younger (ca. 3 Ma) and mildly phyric, olivine-clinopyroxene basaltic andesites and basaltic trachyandesites were extruded atop the northern *Carson Range*, just south of Reno. The northern end of the Carson Range is composed primarily of tilted, porphyritic lavas capped by gently- dipping to flat-lying, poorly phyric lava flows (Thompson & White 1964, Latham 1985). Samples 01-LT-10, 11 (basaltic andesites) and 12 (basaltic trachyandesite) are from a set of flows near Fuller Lake. Locations for samples 01-LT-46 to 53 are included in Cousens et al. (2011). These samples commonly include minor olivine phenocrysts, with or without minor plagioclase and pyroxene phenocrysts, in a trachytic matrix. Samples 01-LT-10 and 11 contain altered olivine and rare plagioclase phenocrysts, whereas sample 12 is much fresher with minor olivine and pyroxene phenocrysts. The basaltic and basaltic andesitic lava flows of *Dog Valley* (3-4 Ma) are located just west of the Carson Range.

Samples from *Pond Terrace, Andesite Peak, Devil's Peak, Mount Lincoln, Twin Peaks, Stanford Peak, Squaw Peak, Sawtooth and Henness Pass* are highly eroded volcanic complexes emplaced 6 - 8 Ma and 5 - 3 Ma that cap high Sierra Nevada granitoid intrusions from the west side of Lake Tahoe north to Donner Pass (Cousens et al. 2008, Harwood 1981, Saucedo & Wagner 1992). The volcanic rocks of this area include lava flows, agglomerates, tuffs and plug intrusions of lava and breccia (Hudson 1951), as well as volumetrically minor amounts of olivine-clinopyroxene basalt and basaltic andesite lava flows (Cousens et al. 2008). At Squaw Peak and Mount Lincoln, debris lava flows and dome-collapse deposits are composed of fragments of plagioclase-phyric volcanic rock set in a mineralogically similar volcanic matrix. Subordinate lava flows are commonly >10 m thick, massive, and highly plagioclase porphyritic. Some basaltic andesites, particularly those in Squaw-Twin Peaks area, include abundant anhedral sieve-textured plagioclase grains that may be xenocrystic. Trachytic texture in the groundmass is less common in the basaltic andesites compared to the basalts. Farther north into the Sierra Nevada along Hwy 70, basalts and basaltic andesites from *Portola* contain phenocrysts of embayed olivine and rare augite in a hypocrySTALLINE matrix of plagioclase and olivine.

In general, the basaltic lavas from the study area with $Mg\# > 0.55$ closely follow the idealized olivine-clinopyroxene fractionation trend (Harker 1909). Many of the lavas contain phenocrystic olivine and clinopyroxene along with plagioclase implying that the initial magma evolution was at relatively high pressure in hydrous and/or non-hydrous conditions (>8 kbar, Green & Hibberson 1970 2010).

2.2 Methodology

2.2.1 *Field Work and Data Mining*

See section 1.3 for photos and discussion on field work. Data were compiled from our own fieldwork guided by existing geologic and topographic maps, and from public databases (Morrison 1964, Page 1964, Jones et al. 1997, Henry 1996, Stewart & Carlson 1976, Green et al. 1991). Figure 2.1 shows the sample locations; identifiers for analyzed sample materials are presented without modification.

Sample stations were located using a handheld global positioning system (GPS) and GPS coordinates are presented in Appendix A. Samples with identifiers 04-LT and 11-CN were collected by the author during two field trips in 2004 and 2011 for the purpose of filling data gaps along the east-west transect of the study region. Sampling in the field was occasionally obstructed by middle to late Pleistocene lacustrine and interlacustrine deposits, the result of several glacial episodes that also eroded the Sierra Nevada Mountain landscape (Morrison 1964). Outcrops surrounding the Carson Sink (e.g. Lahontan Mountains, Stillwater Mountain Range) are commonly encrusted by tufa (carbonate deposits formed by precipitation from saline lake water due to significant departure from ambient temperature), precipitated from a large endorheic lake named Lake Lahontan (Morrison 1964). Samples from these regions were collected from outcrops above the ancient shorelines.

Existing published data from the study area were included in the database. Samples with identifiers *LT* and *Towle* were collected between 1997 and 2008 by workers Julie Prytulak and Russell Towle. Hand samples, thin sections, and geochemistry

data from these samples were all processed and analyzed at Carleton University (see section 2.3). Sample data with all other identifiers were obtained from du Bray et al. (2009) and Sloan et al. (2003) geochemical databases, for which only the geochemical data were adopted. Petrographic data for these samples were obtained through individual publications (Appendix A).

2.2.2 *Petrography*

The mineralogy and textures of rocks were examined in thin-section from rocks collected during this study. These observations were used to characterize rock types, record textures, note signs of alteration and weathering, as well as and lay the foundations for subsequent chemical analyses and geochronologic investigations.

2.2.3 *Geochronology*

Ages for the mafic samples used in this study are based on 1) radiometric ages, and 2) estimated geologic ages. *Radiometric ages* were primarily derived from $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology from the Nevada Bureau of Mines and Geology (NBMG) using methodology as described by Henry et al. (1996) and Henry et al. (1997). References for ages used in this study are found in Appendix D.

Geological ages were determined through geologic inference, correlations and other data sources (du Bray et al. 2009). Ages are rounded to the nearest million years (du Bray et al. 2009).

2.2.4 *Geochemistry*

Geochemical data are listed in Appendix A. Collected samples from the GB and ACA were prepared at Carleton University, Ottawa. Rock samples were slabbed, crushed in a Bico Chipmunk jaw crusher and ground to a fine powder in an agate ring mill. Between samples, the jaw crusher and the chrome-steel ring mill were cleaned thoroughly using water, compressed air, and ethyl alcohol. The fine powder was mixed, and aliquots were separated for analysis. Replicate analyses for 11-CN-1 and 11-CN-11 through the chrome-steel ring mill at various time intervals and crushed by hand have been compared, indicating only minor Cr contamination (personal discussion with Cousens 2011). Whole rock major and trace element contents were determined by fused-disc X-ray fluorescence spectrometry (XRF; University of Ottawa) and solution mode inductively coupled plasma mass spectrometry (ICP-MS; Ontario Geological Survey, Sudbury). The precisions of the data, based on replicate analyses of samples and blind

standards are listed with the data presented in Appendix A, B and D. Detection limits indicate the minimum concentration that can be distinguished from a blank specimen; values were calculated by personnel at the Ontario Geological Survey Geoscience Laboratories.

All Pb, Sr, and Nd isotopic ratio analyses and sample preparations, including weighing, acid washing, dissolution, column chromatography, filament loading, and mass spectrometry, were performed at the Isotope Geochemistry and Geochronology Research Centre (IGGRC) at Carleton University, Ottawa, Canada using techniques presented in Cousens (1996). Between 100 and 200 mg of rock powder were dissolved in three steps, including 50% Hf-12 N HNO₃, then 8 N HNO₃ and finally 6 N HCl. The residue was taken up in 1 N HBr. Pb was separated in Bio-Rad 10 mL polyethylene Econo-columns with AGI-8X anion resin, using 1 N Hbr and 6 N HCl. The captured HBr solution was dried, the residue taken up in 2.5 N HCl and Sr was then separated in a borosilicate glass column using AG50-X8 cation resin and 2.5 N HCl, followed by the rare earth elements using 6 N HCl. The REE-bearing solution was dried and the residue dissolved in 0.26 N HCl then loaded into a column containing a 2-cm high bed of Teflon powder coated with HDEHP (di(2-ethylhexyl) orthophosphoric acid). Nd was eluted using 0.26 N HCl. For samples processed before 2002, samples were run on a Finnigan-MAT 261 thermal ionization mass spectrometer run in static mode. Strontium was loaded onto a single Ta filament with H₂PO₄. Isotope ratios were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.11940$. Two standards were run: NIST SRM987 ($^{87}\text{Sr}/^{86}\text{Sr} = 0.710257 \pm 0.000022$), and the Eimer and Amend (E&A) SrCO₃ ($^{87}\text{Sr}/^{86}\text{Sr} = 0.708350 \pm 0.000010$). Standards were loaded and run with each carriage. Neodymium was loaded with HCl on one side of a Re double filament

assembly. Isotope ratios are normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.72190$. Analyses of the La Jolla standard average $^{143}\text{Nd}/^{144}\text{Nd} = 0.511874 \pm 0.000019$. Lead was loaded onto single Re filaments with H_3PO_4 and silica gel. All mass spectrometer runs were corrected for fractionation by monitoring NIST SRM981. The average ratios for SRM981 are $^{206}\text{Pb}/^{204}\text{Pb} = 16.890 \pm 0.012$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.429 \pm 0.014$, and $^{208}\text{Pb}/^{204}\text{Pb} = 36.502 \pm 0.048$. Lead concentrations are precise to $\pm 0.5\%$. Analysis of USGS standard BCR-1 yields $\text{Pb} = 13.56 \text{ ppm}$, $^{206}\text{Pb}/^{204}\text{Pb} = 18.818$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.633$, and $^{208}\text{Pb}/^{204}\text{Pb} = 38.633$. Information on isotope standards is presented in Appendix C.

For samples processed after 2002, samples were run on the ThermoFinnigan Triton TI thermal ionization mass spectrometer. Strontium isotope ratios were normalized to $^{87}\text{Sr}/^{88}\text{Sr} = 0.11940$ and the lab average for NBS987 was $^{87}\text{Sr}/^{86}\text{Sr} = 0.710248 \pm 0.000026$. Neodymium isotope ratios are normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.72190$ and runs of the La Jolla standard averaged $^{143}\text{Nd}/^{144}\text{Nd} = 0.511877 \pm 0.000018$. All Pb ratio mass spectrometer runs are corrected for fractionation relative to the following accepted values for NIST NBS981: $^{206}\text{Pb}/^{204}\text{Pb} = 16.937 \pm 0.009$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.492 \pm 0.008$, and $^{208}\text{Pb}/^{204}\text{Pb} = 36.722 \pm 0.019$ (Todt et al. 1996). Standards were loaded on each carriage (for each run), and correspond closely with each run and with those obtained by other laboratories. All quoted uncertainties are 2 standard deviations of the mean.

2.3 Results

Low LOI values ($<3 \text{ wt}\%$) and petrological observations indicate that secondary processes have not significantly affected the collected samples. Secondary minerals such as sericite and chlorite are rarely seen during petrological examination with the exception of isolated samples from the Stillwater Mountain Range. No correlation between La/Sm

and LOI values for the ACA and GB lavas is apparent (not shown) as LOI is a good proxy to discriminate between fresh and weathered samples (Chauvel et al. 2005, Labanieh et al. 2012). The lack of correlation implies that weathering did not have a significant effect on the rare earth elements in the studied samples as more intense weathering produces abundant kaolinite group minerals that have preferentially retained LREE, which consequently display high LREE/HREE fractionation (Yusoff et al. 2013).

Mafic lavas that erupted within an east-west transect across the study area exhibit a wide range of compositions, and exhibit significant variations among and within the eruptive centers. Subalkaline lavas are found throughout the study area (Figure 2.3; Le Bas et al. 1986). The $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$ ratios, represented as the Mg#, range from 0.75 to 0.55, indicating that although some of the mostly subalkaline mafic lavas are near-primary melts [that is, if mantle olivine is Fo_{86-90} , primary magmas must be $\text{Mg\#} = 0.68-0.75$ (e.g. mafic samples from western ACA, $\text{Mg\#} > 0.65$; Le Bas et al. 1986)] most lavas have undergone some post-generation modification. In general, basalts, basaltic andesites and basaltic trachyandesites from the GB have an overall lower Mg# (0.55 to 0.65) than those from the eastern ACA and western ACA (up to 0.75 in the case of western ACA). Basalts with $\text{Mg\#} > 0.7$ also have $\text{Cr} > 600$ ppm, $\text{Ni} > 180$ ppm, and $\text{Sc} > 32$ ppm. The AFM diagram (not shown, Irvine & Baragar 1971) shows that most mafic lavas plot primarily in the mafic field along the calc-alkaline trend. The GB lavas have the highest $\text{Fe}_2\text{O}_3^{\text{t}}/\text{MgO}$ values compared to the ACA lavas. The concentrations of Ni, Cr and Sc all decrease with decreasing Mg#, along with $\text{CaO}/\text{Al}_2\text{O}_3$, reflecting that olivine, Cr-spinel and clinopyroxene in ACA lavas were dominant crystallizing mineral phases (Figures 2.5E and 2.6B). Al_2O_3 contents range from 13 wt% to as high as 20 wt%, with the eastern

ACA containing the highest Al_2O_3 and the least scatter. K_2O values range from 0.5 wt% to as high as 2.5 wt% (sample 01-LT-12 from the Carson Range trends to shoshonitic affinities). The TiO_2 , P_2O_5 , K_2O , REEs, Zr and Y contents all increase with decreasing Mg#, and are notably higher in lavas from the GB. The decrease in transition metal (Cr, V, Ni, Co, Cu) abundances during fractional crystallization is principally a function of the precipitation of olivine, Fe-Ti oxides (crystallization of Fe-Ti oxides is largely governed by the melt redox state), and immiscible sulfides. Vanadium generally decreases only slightly with decreasing Mg# (Figure 2.5) confirming together with increasing TiO_2 that for mafic melts, Fe-Ti oxides are not a dominant fractionating phase, which correlates with experimental studies for primitive lavas at oxygen fugacities typical for arcs (e.g. Lee et al. 2005). Large ion lithophile (LIL) element abundances for different localities in the study area generally do not co-vary with Mg#. Isolated flows of basalt and basaltic trachyandesite from the GB (in the Bell Mountains and the Stillwater Range) are characterized by similar SiO_2 and K_2O but lower Mg#, higher P_2O_5 , TiO_2 and Zr relative to the more abundant subalkaline basalts. These slightly alkaline lavas generally have higher abundances of and rare earth (RE) trace elements compared to the subalkaline basalts. The basaltic trachyandesites are very uniform in composition compared to the subalkaline basalt and basaltic andesite groups, and are generally enriched in TiO_2 , K_2O , P_2O_5 , Rb, Ni, Zr, Nb, Pb, Zr/Y and the REEs.

Figure 2.7 compares Th/Yb, Zr/Yb with Nb/Yb. Mafic melts generally possess only a small range of Yb contents, whereas the Nb contents can reflect variations from the source (Pearce 2006). All samples plot above the MORB–OIB array indicating that they derived from mantle contaminated by either a slab or continental crust (higher

Th/Yb) or a continental lithospheric mantle (CLM) component (higher Zr/Yb). The ACA lavas trend parallel to the MORB-OIB array, indicating the importance of melt extraction during subduction in an arc system (Pearce & Peate 1995). The GB lavas, however, do not parallel the array, which may indicate that the higher Th/Yb values (Figure 2.7B) are derived from another source. Comparing Zr/Yb with Nb/Yb (Figure 2.7A), most lavas from the eastern ACA and western ACA have Zr/Yb values that also lie within and slightly above the MORB array, whereas GB lavas trend towards the EMORB or OIB mantle array (Pearce & Peate 1995, Pearce 2008). Basaltic trachyandesites from the Carson Range lie outside the eastern ACA and western ACA fields (basalts and basaltic andesites) with comparatively higher La/Yb, Th/Yb, Zr/Yb and Nb/Yb values than other lavas from the study area.

Rare earth and trace element variation diagrams (Figures 2.8 and 2.9) have been normalized to chondrites and primitive mantle abundances of Sun & McDonough (1989) respectively. The three regions within the study area are represented separately by symbols representing composition (see legend in Figure 2.8). All lavas have primitive mantle normalized La/Sm between 2 and 3.7. Eastern and western ACA lavas have a range of 2 to 3.7, and the GB lavas have a more restricted range of 2.4 to 3.6. All GB lavas show higher abundance in all REEs with no fractionation of the LREEs/HREEs. GB lavas also have negative Eu-anomalies that increase with increasing REE abundance to a maximum of $\text{Eu}/\text{Eu}^* = 0.77$ (Eu anomalies are denoted Eu/Eu^* , and calculated as $(\text{Eu}/\text{Eu}^*)_{\text{pmn}} = \text{Eu}_{\text{pmn}} / ((\text{Sm}_{\text{pmn}} + \text{Gd}_{\text{pmn}}) / 2)$). The REE patterns in Figure 2.8 show that all GB lavas share the same REE patterns but vary in overall abundance. For eastern ACA lavas, normalized values are variable from La to Sm, but then the REE patterns converge

towards HREEs. Western ACA lavas also show a lower range of La to Sm ratios compared to eastern ACA lavas, variations in overall abundance and relatively flat HREE patterns. Lavas with higher silica and alkali content generally have higher REE abundances and higher La/Sm ratios compared to lavas with lower silica and alkali contents. All samples show a slight negative anomaly ($\text{Eu}/\text{Eu}^* = 0.997$ to 0.768 , average 0.911) with lavas from the GB containing the lowest Eu anomalies (averaging 0.834). Basaltic trachyandesites from the Hotsprings Mountain Range (GB) have the overall largest Eu anomaly of 0.768 . A basalt from Portola and a basaltic andesite from Stanford/Twin Peaks, both from western ACA, have an atypical negative Ce-anomaly ($\text{Ce}/\text{Ce}^* = 0.849$ and 0.713 respectively), where Ce/Ce* anomalies are calculated $\text{Ce}/\text{Ce}^* = \text{Ce}_{\text{pmn}}/((\text{La}_{\text{pmn}} + \text{Pr}_{\text{pmn}})/2)$. All other samples have Ce-anomalies that hover just under 1 (average 0.954).

Most trace element patterns show large enrichments in LIL (e.g. Ba, Rb, K and Pb) and lesser enrichments in light rare earth (LRE, e.g. La, Ce, Nd, and Sm) elements relative to high field strength (HFS, e.g. Nb, Ti and Ta) and heavy rare earth (HRE, e.g. Tb, Tm and Yb) elements, characteristic of arc magmas (Figure 2.9, Gill 1981, Pearce 1983, Rollinson 1993, Briquet et al. 1984, Weaver et al. 1987). The subduction signature seen in Figure 2.9 (i.e. depleted Nb and Ta anomalies, enrichment in LILEs when compared to the primitive mantle) is strongest in the eastern ACA (i.e. larger variation from PM), and weakest in the GB and western ACA (i.e. less variation from PM). Eastern and western ACA mafic rocks show a larger Sr enrichment compared to the GB. Mafic rocks from the GB generally have higher overall REE abundances.

Isotopic compositions of Sr, Nd and Pb have been measured for select samples

from the GB, eastern and western ACA, the results of which are listed in Table 2.2.

Isotopically, the groups are highly heterogeneous with the western ACA containing the widest range: $^{87}\text{Sr}/^{86}\text{Sr} = 0.70381 - 0.70612$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.51242 - 0.51283$. The eastern ACA and GB have more restricted ranges: $^{87}\text{Sr}/^{86}\text{Sr} = 0.70411 - 0.70552$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.51261 - 0.51272$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.70453 - 0.70531$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.51262 - 0.51283$ respectively (Figure 2.10A). The isotopic ratios overlap for GB, part of I-80 Suite, Sparks, Carson Range, Lousetown, Heness Pass and Susanville. Note that five samples from the westernmost part of the ACA (Sierra Crest) plot to the left of the main array of mafic lavas: i.e. at low $^{87}\text{Sr}/^{86}\text{Sr}$ given their $^{143}\text{Nd}/^{144}\text{Nd}$. These lavas include Mt. Lincoln (basalt), Squaw Peak, Pond Terrace, Devil's Peak and Lowell Ridge—these subsequently will be referred to as the westernmost part of the ACA (circled in Figure 2.10A). However, other lavas from the Sierra Crest plot within the main data array.

Lead isotope compositions for mafic lavas are also heterogeneous, shown in Figures 2.10B and C relative to the Northern Hemisphere Reference Line (NHRL) for oceanic basalts [most $^{207}\text{Pb}/^{204}\text{Pb}$ data (especially from the N hemisphere) plot above a linear mixing line between DM and HIMU endmembers, a line called the Northern Hemisphere Reference Line (NHRL) - Data from the southern hemisphere (particularly Indian Ocean) departs from this line, and appears to include a larger EM component (probably EMII)] (Hart 1984). The GB and ACA lavas range in $^{206}\text{Pb}/^{204}\text{Pb}$ between 18.85 and 19.15, $^{207}\text{Pb}/^{204}\text{Pb}$ between 15.52 and 15.69, and $^{208}\text{Pb}/^{204}\text{Pb}$ between 38.33 and 38.97. For $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ (Figure 2.10B), all lavas plot above the NHRL towards an enriched end member, whereas for $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$, the values parallel the NHRL trending towards a mantle component with high μ ($^{238}\text{U}/^{204}\text{Pb}$) and high Th/Pb (Figure

2.10C). GB mafic lavas commonly have lower $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ values than the ACA mafic lavas.

Figures 2.10D and E show that $^{206}\text{Pb}/^{204}\text{Pb}$ correlate with Sr and Nd isotope ratios. Comparing $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ (Figure 2.10D), the westernmost part of the ACA and GB lavas plot in a tight cluster, and all lavas trend towards an enriched component, exemplified by the Sawtooth Ridge basalt. Lavas in the westernmost part of the ACA have lower $^{87}\text{Sr}/^{86}\text{Sr}$ given their $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ values, as well as lower $^{206}\text{Pb}/^{204}\text{Pb}$ values for their given $^{207}\text{Pb}/^{204}\text{Pb}$ values compared to ACA lavas. Sample Towle#1 (Sawtooth) has the highest $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ values of 19.12 and 15.69 respectively. Looking to $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{208}\text{Pb}/^{204}\text{Pb}$ (Figure 2.10E), GB lavas show poor correlation of $^{208}\text{Pb}/^{204}\text{Pb}$ with $^{143}\text{Nd}/^{144}\text{Nd}$ values compared to ACA lavas.

2.4 Discussion

A geochemical model of the Cenozoic magmatic sweep of western North America should explain the following: 1) the decrease in age from east (>25 Ma) to west (ca. 3 Ma), 2) the sparse mafic magmatism within the east-end of the study area, and comparatively higher volumes of mafic magmatism within the western ACA, and 3) the variation in trace elements and isotopic ratios over space and time.

The trace element and isotopic magmatic signatures within mafic lavas indicate variation of source and influences on the source melts. The source components in primary continental arc lavas may include: 1) fluids derived from the subducting basalt, 2) fluids derived from the subducting sediment, 3) partial melts of subducting basalt, 4) partial melts of subducting sediment, 5) fertile mantle peridotite, 6) depleted upper mantle

peridotite, 7) enriched mantle similar to the source of ocean island basalt, 8) melt from the sub-continental lithospheric mantle, and 9) melt from the continental crust. Before examining the possible source components, I must address possible crustal contamination of the lavas after they left the source region.

2.4.1 *Evidence for Post-Magma Generation Crustal Contamination*

Within the confines of the study area, various authors (e.g. Farmer & DePaolo 1983, 1984) have recognized a range of different granitoids and eugeoclinal material, many of which are the direct or indirect product of subduction processes. Addition of these crustal components would increase the SiO_2 content and $^{87}\text{Sr}/^{86}\text{Sr}$ while lowering the $\text{Mg\#}$, Nb/La and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios (Brown et al. 2014). Most Sierra Nevada granitoids have high $^{87}\text{Sr}/^{86}\text{Sr}$, low $^{143}\text{Nd}/^{144}\text{Nd}$ and high $^{207}\text{Pb}/^{204}\text{Pb}$ (Cousens et al. 2008); however, the Ba/La and $(\text{Sr/P})_{\text{pmn}}$ values are lower in the Sierran granitoids compared to the mafic lavas in the study region. The volcanic rocks from the GB have a lower range in $\text{Mg\#}$ and higher range in SiO_2 values compared to the ACA lavas. Note that during the Oligocene, what is now the Great Basin was a high plateau resulting from Mesozoic compressive forces and crustal thickening (Henry 2009). At the time of their eruptions, GB mafic lavas may have travelled through as much as 100 km of compositionally heterogeneous continental crust compared to lesser thickened crust within the younger western ACA lavas (Figure 1.1).

Figure 2.11 tests the possibility of crustal contamination in the mafic melts by investigating correlations of Nb/La (Figure 2.11A) and $^{143}\text{Nd}/^{144}\text{Nd}$ (Figure 11B) with SiO_2 values. Nb/La values are low (<1) for all three regions and both Figures 2.11A and

B demonstrate no variation with increasing SiO_2 values. The lack of correlation of Sr- (insert) and Nd-isotopic composition with SiO_2 , combined with the absence of inherited crustal quartz or zircons into the melts (determined petrographically), suggests that the isotopic and trace element compositions of the ACA and GB mafic volcanic rocks are not strongly effected by upper crustal contamination.

2.4.2 *High-K Magmatism and Degree of Partial Melting*

Moving from east to west across the study area, mafic melts generally decrease in their K_2O , P_2O_5 , TiO_2 contents and Nb/Yb (examples shown in Figures 2.5A, D and 2.12A). Mafic magmas with K_2O contents between 1-3% are most common in the central GB. Mafic lavas from Pyramid Lake and (basaltic trachyandesites) from Carson Range (eastern ACA) also show higher ranges in K_2O , P_2O_5 , and TiO_2 , similar to the GB mafic lavas. Ranges in Na_2O contents do not change much for GB and eastern ACA mafic lavas (2.6 to 4.5 wt%), slightly lower in western ACA mafic lavas (2.5 to 3.8 wt%) and lowest for the westernmost ACA lavas (2.1 to 2.6 wt%). The positive correlation between K_2O and U (not shown) suggests both behave as incompatible mobile elements, and so U paired with immobile Nb shows highest Nb/U values for GB lavas (along with 3 Ma basaltic trachyandesites from Carson Range and Clark Mountain, western ACA). High-K mafic lavas from the ACA do not increase in Nb/U values with increasing K_2O . Additionally, the $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio increases with increasing K_2O from 0.2 in the low-K melts to 1.2 in high-K melts (highest are basaltic trachyandesites from the Stillwater Mountains Range).

Major and trace element chemistry shown in Figures 2.5 (K_2O , TiO_2 , P_2O_5 vs. Mg#) and 2.12 (TiO_2 vs. SiO_2 , La/Sm vs. La) confirms that the proportion of high-K (and

shoshonitic) rocks changes from east to west across the study area. Low degrees of partial melting can produce melts with enriched K, Ti, and P, as well as LREE enriched patterns because the low atomic weight REEs (La-Eu) are enriched over the heavier REEs. I can plot the ratio of highly incompatible elements like La and Ce to a less incompatible element, like Sm and Yb, versus the concentration of the highly incompatible element. Crystal fractionation will not have a great affect on the La/Sm ratio. During low-percent melting, however, fractionation between La and Sm will increase with increasing La abundance. That is, fractional crystallization does not affect the ratios of incompatible elements and therefore produce a trend with less steep slope, providing a method for distinguishing between partial melting and crystal fractionation

Fractional crystallization can be responsible for the slightly higher range in SiO_2 and lower range in Mg# for GB mafic lavas compared to ACA lavas; however, it cannot be the only mechanism responsible for the results I see in Figure 2.12. The chondrite-normalized REE patterns for the GB mafic lavas (Figure 2.8) exhibit parallel patterns of increasing abundance with slight enrichment in LREEs relative to HREEs. The parallel REE patterns of the GB rocks implies that the mafic melts were derived from a similar mantle source region and underwent similar degrees of partial melting. The parallel REE patterns also confirm that the GB mafic melts underwent fractional crystallization before erupting at the surface. Additionally, the high LREE and incompatible trace element contents (Figure 2.9) suggest that the mantle source must have been previously metasomatically enriched. Trace element data indicates that melting occurred at a depth within the spinel peridotite field, between 70 and 35 km (Rollinson 1998), which dismisses the possibility of partial melts generated from garnet peridotites and/or garnet-

bearing (eclogitic) subducted slab or lower crust (i.e. $(\text{Dy/Yb})_{\text{pmn}} < 1.6$).

We can consider low degrees of partial melting (low F , where F is melt fraction) due to 1) low non-synchronous tensile stresses or faulting (Putirka & Busby 2007, Busby & Putirka 2009) and 2) a function of temperature and water (volatile) content released into the mantle source by the subducted slab. High K_2O volcanism is represented within the GB (age > 14 Ma) and selected eastern ACA (age < 14 Ma) (Pyramid Lake and Carson Range) irrespective of age. These high- K_2O lavas are also enriched in TiO_2 , Na_2O , and P_2O_5 at $\text{Mg\#}$ between 0.45 to 0.65 for GB mafic lavas, and 0.58 to 0.72 for Pyramid mafic lavas (Figure 2.12). This observation may signify differences in the petrogenesis of these two regions. Namely, the high-K mafic lavas from the GB erupted during the initial stages of slab rollback after > 30 million years of flat slab subduction. The low angle between the slab and overlying CLM would result in low temperatures and therefore lower volatile release from the slab compared to the “normal” arc system (e.g. Pearce & Parkinson 1993).

I suggest the high- K_2O , TiO_2 , Na_2O , and P_2O_5 lavas are due to either *source-region enrichments* or to *low degrees of partial melting*. The 13-14 Ma mafic lavas from Pyramid Lake erupted near the north-south trending Pyramid Lake Fault (PLF), which formed during development of the Walker Lane (see Figure 3B from Faulds et al. 2005). The exact age of the PLF is debated, however, it has been determined that the PLF has accommodated ca. 10 km of dextral offset since ca. 3 to 9 Ma (Faulds et al. 2005), indicating a region under considerable tensile stress since before 9 Ma. Generation and composition of the Pyramid mafic lavas are consistent with the idea that tensile stresses (in the Walker Lane) favored eruption of low- F magmas (Takada 1994, Putirka & Busby

2007). The 15 to 25 Ma GB lavas, however, were erupted in regions that were not heavily faulted. GB mafic lavas have lower Ba/Nb and Pb isotope ratio compared to Pyramid Lake mafic lavas, and so it is suggested that the GB mafic lavas were generated under less hydrous, lower P-T conditions during the early phases of the slab rollback.

Basaltic trachyandesites from the Stillwater Mountains do not show the same partial melting trend as the other central GB mafic lavas. These GB basaltic trachyandesites show a lower-F melting percentage (Figure 2.12C) as well as similar chemical behaviours as post-ACA lavas proposed to be generated from the lithospheric mantle: higher $^{87}\text{Sr}/^{86}\text{Sr}$ (>0.705) and $\text{K}_2\text{O}+\text{Na}_2\text{O}$ (>5 wt%). Workers such as Ormerod et al. (1988) and Cousens et al. (2011) suggested that the chemical signatures signify melting (possibly exclusively) within the CLM. I therefore suggest that basaltic trachyandesites from the central GB melted with greater component from the CLM.

2.4.3 *More on Chemical Contributions from Source Components*

2.4.3.1 Variations over Space and Time

It has been suggested that flat slab subduction of the Farallon Plate hydrated the North American CLM, perhaps as far east as the Rocky Mountains (Lee 2005, Smith et al. 1999, Humphreys et al. 2003, Smith et al. 2004). Unlike chemical contributions from a dehydrating slab (LILEs such as Rb, Ba, Sr), the CLM contributes a proportion of its content to the melt (Ce, Sm, P, Ta, Nb, Zr, Hf, Ti, Y and Yb). Lee et al. (2001) and Kempton et al. (1991) suggested that the CLM is enriched in Mg and Ni compared to the continental crust, and also is enriched in LREEs compared to the primitive mantle. Also,

melts from the CLM have low $^{143}\text{Nd}/^{144}\text{Nd}$ and variable $^{87}\text{Sr}/^{86}\text{Sr}$ compositions compared to the asthenosphere (e.g., Cousens et al 2008). Figure 2.13 presents major, trace and isotopic data trends along the east-west transect (left column) as a function of age (right column). Note that the data symbols in the left column represent composition whereas symbols in the right column represent location (see legend). Figure 2.13 explores assimilation within the lower crust (Figure 2.13A, K_2O) and fractional crystallization (Figure 2.13B, $\text{CaO}/\text{Al}_2\text{O}_3$), both of which are higher in the basaltic trachyandesites of the GB and some eastern ACA lavas (Carson Range) compared to other lavas from the study area. Mafic lavas show a slight increase in $\text{Mg}\#$ (Figure 2.13C) from east to west, and all three rock types overlap. $(\text{La}/\text{Sm})_{\text{pmn}}$ values vary between 2.0 and 3.5 with distance and time, showing abrupt peaks at longitude 120° and at ages 12 Ma and 3 Ma (Carson Range) (Figure 2.13D). This pattern is mirrored by La/Yb and Cs/Rb (not shown), with the highest values in scoria for Ladybug Peak and Carson Range basaltic trachyandesites ($(\text{La}/\text{Sm})_{\text{pmn}} > 4$ for samples 01-LT-46 to 48). The sum of REEs (not shown) and the depth of negative Eu/Eu^* anomalies steadily decrease from east to west, whereas $(\text{Sr}/\text{Nd})_{\text{pmn}}$ and $(\text{Sr}/\text{P})_{\text{pmn}}$ values increase from east to west as well as from oldest to youngest (Figures 2.13 E, F and G). LILE/HFSE values also increases to the west and with younger age. Figure 2.13 H, I and J show proxies for sediment melts, represented by Th/Nb , Pb/Ce and Ce/Ce^* ratios. These ratios are considerably higher in sediments (e.g. $\text{Pb}/\text{Ce} > 0.3$) compared to more uniform values for sediments in a MORB-like mantle (e.g. $\text{Pb}/\text{Ce} < 0.04$, White 2013). Under low P-T conditions, both Th and Nb are not particularly soluble in slab aqueous fluids; however, under higher P-T conditions subducted sediment will melt releasing Th into the mantle wedge while Nb remains

within the slab (Pearce & Peate 1995). Therefore fractionation between Th and Nb results from the assimilation of sediment melts in an arc system (White 2013, Johnson & Plank 1999). The Th/Nb and Ce/Ce * data show the sediment signature in the mafic lavas increases from east to west. An example of radiogenic isotopic variation is shown in Figure 2.13K and L: initial Sr and Nd (not shown) isotopic ratios have a more restricted range in values towards the east end of the study area compared to the larger variation in values to the west. Pb isotopic ratios show the highest variation in central GB mafic lavas as well as towards the western ACA lavas, compared to very little variation in westernmost GB lavas.

The least evolved subalkaline lavas are from the westernmost part of the ACA (e.g. Portola, Sawtooth, Devil's Peak, Mt. Lincoln) with $Mg\# > 0.65$, $CaO/Al_2O_3 > 0.6$, $Sc > 30$ ppm, $Ni > 200$ ppm and $Cr > 350$ ppm. The large range in Ni content is consistent with olivine fractionation (Hart & Davis 1978), where Ni/Co decreases as $Mg\#$ decreases during the fractionation of olivine and then pyroxene from primary magmas. Positive correlation between CaO/Al_2O_3 and $Mg\#$ can be best explained by fractionation of clinopyroxene. As with most other mafic melts from the study area, the absence of Eu-anomalies supports a plagioclase-free fractionating assemblage.

2.4.3.2 Source Components

Depth of Melting: Since heavy REEs and yttrium are compatible in garnet, heavy REE and yttrium concentrations in partial melts of a garnet-bearing source (i.e. garnet-peridotite or eclogite) should be depleted and light to middle REE ratios should be enriched relative to melts of spinel peridotite. With the exception of one sample from Carson Range ($(Dy/Yb)_{pmn}=1.6$), the $(Dy/Yb)_{pmn}$ ratios for the mafic lavas from all

regions within the study area are <1.5 , supporting a garnet-free source (George et al. 2003). Also considering geochemical evidence of a plagioclase source (absence of Eu-anomaly, high Al_2O_3 and Sr values), I can conclude that the mafic melt originated at a depth of between 35 and 70 km (Kinzler 1997).

Contributions from the slab: Aqueous fluid-mobile elements, such as Cs, Sr, Rb, Ba, Pb and U, would be released from the dehydrating slab (basalt and sediments) into the overlying mantle, increasing their abundance in the mantle compared to the HFSE and REE. Therefore aqueous fluid transport should result in large fractionations of Ba from Th, Pb from Ce and Sr from Nd. In contrast, enrichments in “fluid immobile” Th relative to a less mobile element (HFSEs, e.g. Th/Nb) can be attributed to a partial melt of subducted sediment (e.g. Elliott 2003, Elliott et al. 1997, Hawkesworth et al. 1997, Johnson & Plank 1999, Plank 2003; Plank & Langmuir, 1988 1993 1998) along with negative Ce/Ce* anomalies and isotopic characteristics of $^{87}\text{Sr}/^{86}\text{Sr}$ (up to 0.7060) and $^{143}\text{Nd}/^{144}\text{Nd}$ (as low as 0.51270). Figures 2.14A and B (as well as Figures 2.13 H and J) show less influence from slab fluid values and the sediment component to be absent in the east and in older rocks (GB mafic lavas), whereas higher influence from slab fluid and a minor sediment signature is present for ACA lavas. The sediment signature occurs at 120° longitude at ca.10 to 12 Ma, which may indicate either P-T conditions more favourable for sediment melting ($>800^\circ\text{C}$ at 3 GPa, Nicholas et al. 1994, Johnson & Plank 1999) or variation in sediment abundance on the slab surface.

Involvement of sediment in subduction-related melts may also have had an influence on the $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios. Components from subducted oceanic sediments can emerge in arc volcanics in the form of chemical tracers (e.g Johnson &

Plank 1999, Kessel et al. 2005). The question is whether subducted sediments melted underneath the ACA and/or GB volcanoes?

Ocean sediment is chemically variable from a composition that includes volcanoclastic deposits, chert, silt, biogenic deposits, clay, continental discharge and interstitial seawater (Church 1976, Lackschewitz et al. 2000, Kessel et al. 2005, Prytulak et al. 2006). In continental subduction zones, sea-floor sediments are either scraped off the subducting plate at the ocean trench and accreted along the continental plate margin, or subducted along with the oceanic plate; as a result, they contribute to arc magmatism and/or are recycled in the convecting mantle (Plank & Langmuir 1993). Melts from subducted sediments should leave a chemical signature in the erupted arc lavas; however, the bulk chemical composition of the original sediments needs to be determined. The terrigenous sediments that have been scraped off along the Coast Range in California and accreted as metasediments are >100 Ma (Wakabayashi 1992), and therefore are too old to be associated with the Cenozoic magmatism from this study. I therefore compare our geochemical data to the bulk compositions of sediments from modern subduction environments, namely drill core acquired from the Gorda Plate, which is located off the Coast of northern California. Sediments recovered from the Escanaba Trough, the southernmost point of the Gorda Plate, are olive green to grey hemipelagic silty clay. Bulk chemical analyses, including trace elements (Th, Ce and Nb, Lackschewitz et al. 2000) as well as radiogenic isotopic compositions (Prytulak et al. 2006), are plotted in the graphs presented in this section.

Trace element and isotopic tracers for sediment melts in arc volcanics include Th and Pb (Hawkesworth et al. 1997, Plank & Langmuir 1992 1993), which can be

presented as high Th/Nb and radiogenic Pb isotope ratios as Pb, Th and Nb are not mobile in aqueous fluids, and Pb and Th only become mobilized within sediment melts (Plank & Langmuir 1992, Hawkesworth et al. 1997).

Figures 2.10B and C show that all samples have elevated Pb ratios compared to MORB, and plot above (Figure 2.10B) or along (Figure 2.10C) the Northern Hemisphere Reference Line (NHRL, Hart 1984). The GB mafic lavas have slightly less radiogenic Pb and plot closer to the NHRL than the western ACA lavas, perhaps due to lower influence from the slab and less recycled crustal Pb in the mantle farther away from the plate margin. Figures 2.10D and E compares $^{206}\text{Pb}/^{204}\text{Pb}$ to $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ respectively. Combined with the Ce/Ce* data, ACA mafic lavas that trend to higher $^{206}\text{Pb}/^{204}\text{Pb}$ at equal $^{143}\text{Nd}/^{144}\text{Nd}$ values are consistent with more sediment in the ACA mantle source.

All mafic lavas have variable Sr and Nd isotope compositions (Figure 2.10). The degree of variation increases from east to west, with the greatest variation occurring in mafic lavas from the eastern and western ACA. Figure 2.15 compares the Sr, Nd and Pb isotopic data from this study with data from several neighbouring physiographic regions summarized in Cousens et al. (2008). All lavas shift away from the MORB field and trend towards an isotopically enriched source. In Figure 2.15A, most mafic lavas from all locations plot along a mixing line between the modern south Cascade arc mantle wedge and the enriched CLM that is a typical source for alkali basalts in the Western Great Basin (Ormerod et al. 1991, Menzies et al. 1983). Mafic lavas from the westernmost part of the ACA, however, plot to the left of the array, with lower Sr-isotopic ratios compared to other lavas with at a given $^{143}\text{Nd}/^{144}\text{Nd}$ from the study area. Radiogenic sources of Sr

include seawater, subducted sediments, upper continental crust and metasomatised CLM. If radiogenic Sr within the other ACA and GB lavas is derived from mixing with the metasomatised CLM (Figure 2.15A), the lower $^{87}\text{Sr}/^{86}\text{Sr}$ values in westernmost ACA lavas could be attributed 1) absence of the metasomatised CLM, 2) melt generation deeper in the mantle wedge or 3) mixing with crustal terrain distinct from the CLM. The westernmost ACA mafic lavas also show lower La/Sm, Pb/Ce and Sr values, which support melting of a CLM of a different composition to the rest of the study area. The north-south trending CLM under the westernmost ACA is possibly older and less enriched in LIL and LRE elements, including Sr.

Earlier I noted that high abundances of LILE and LREE and low abundances of HFSE in lavas erupted in an arc system can be attributed to involvement of fluids transported into the mantle wedge from the subducted slab (Bacon 1990, Leeman et al. 1990, Hughes 1990, Baker et al. 1994, Borg et al. 1997). Similarly, by confirming correlation between $((\text{Sr}/\text{P})_{\text{pmn}})$ and $(\text{Sr}/\text{LREE})_{\text{pmn}}$ previous workers have used higher $(\text{Sr}/\text{P})_{\text{pmn}}$ values as a proxy for slab-derived components in the mantle wedge (Borg et al. 1997). I can compare the results from GB and ACA lavas to neighbouring provinces presented in Borg et al. (1997) and Cousens et al. (2008). Figure 2.15C shows the variation in Sr relative to P (used to reflect variation in Sr-rich slab-derived fluids added to the mantle wedge) at a given $^{87}\text{Sr}/^{86}\text{Sr}$ for mafic rocks within the study region and compared to other regions in the western United States. Increases in $(\text{Sr}/\text{P})_{\text{pmn}}$ for mafic lavas from western ACA, from Lousetown and sample 01-LT-53 from the Carson Range, are consistent with higher slab fluid content of mantle sources overlying the subducted slab. The $(\text{Sr}/\text{P})_{\text{pmn}}$ values from the eastern ACA samples show a negative correlation

with $^{87}\text{Sr}/^{86}\text{Sr}$. Mafic lavas from the GB have very low $(\text{Sr}/\text{P})_{\text{pmn}}$ values compared to other regions but have $^{87}\text{Sr}/^{86}\text{Sr}$ that are elevated compared to all other nearby magmatic suites with the exception of the WGB. To the west, $(\text{Sr}/\text{P})_{\text{pmn}}$ values increase indicating an increasing contribution from slab fluids to the mantle source. This is consistent with trace element patterns shown in Figures 2.9 and 2.13, such as Ba/Nb, which suggests that although all lavas from the study area show influence from the subducted Farallon slab, this subduction signature increases from east (older) to west (younger). The similarities in phenocryst compositions, REE and isotopic signatures amongst GB mafic compositions further support the derivation of their primary magmas from similar source regions, with variations in chemistry due to a wide range of contributions from the CLM and variable degrees of partial melting (F). I can conclude that the mafic lavas that erupted within the GB were generated within dry, low P-T conditions compared to the mafic ACA lavas. Western ACA mafic lavas were generated within highest P-T conditions with highest slab fluid content compared to other melts from the study area. The P-T conditions and volatile content relates to the degree of slab dip: that is, shallow dip would result in lower P-T and less dehydration of the slab. A larger subduction angle would result in higher P-T and greater dehydration, releasing more fluids (Ba, Rb, Sr, La). Then, as the slab continues to descend, sediment melts (Th, Pb) and contributes to the mantle wedge. Pressure-Temperatures conditions were not high enough to melt the basaltic slab itself, therefore retaining the HSFE (Nb, Ta).

The 0.706 Line: The $^{87}\text{Sr}/^{86}\text{Sr} = 0.706$ isopleth (where $^{87}\text{Sr}/^{86}\text{Sr}$ is the initial Sr isotope ratio of plutonic rocks) defined by Kistler & Peterman (1973 1978), commonly known as the 0.706 Line, has been interpreted to mark the transition from continentally

derived rocks on the east to volcanic-arc-derived rocks on the west (Kistler & Peterman, 1973 1978, Farmer & DePaolo 1983, Elison et al. 1990). Kistler & Peterman (1973) interpreted the 0.706 line as the western edge of the Precambrian crystalline basement (Figure 2.1).

The 0.706 line is recognized in Mesozoic and younger igneous rocks, which includes Mesozoic granitoids from western North America (Kistler 1990). Chemical characteristics in Cenozoic basalts from the southwestern United States have also been correlated with their proximity to the 0.706 line (Reid & Davis 1996), implying that they are at least partially derived from the CLM (Reid & Ramos 1996, Kempton et al. 1991). Figure 2.1 includes the 0.706 line (heavy dashed line) taken from Kistler 1990, which confirms that the study region mostly lies to the west of the 0.706 Line. I nevertheless can show that Cenozoic volcanic rocks reflect the 0.706 Line similar to that defined by Mesozoic granitoids. A basalt from Sawtooth Ridge (Sample Towle #1, 3.82 Ma, $\text{SiO}_2 = 48.93 \text{ wt\%}$, $\text{Mg\#} = 0.74$) has an $^{87}\text{Sr}/^{86}\text{Sr}$ value of >0.706 , $^{143}\text{Nd}/^{144}\text{Nd}$ value <0.5125 and a $\delta^{18}\text{O}$ value of 6.3‰ , which collectively is unique to all samples from the study area. Based on these results, I therefore suggest that the 0.706 Line can be bounded to include the region around the vent that extruded the basalt sample Towle#1.

2.4.4 Model for GB-ACA Mafic Magmatism

At 40 Ma, a high rate of convergence of the Farallon plate (10 to 15 cm/yr, English & Johnston 2004) resulted in flat-slab subduction (Liu et al. 2008, DeCelles 2004) underneath the North American plate that thickened the lithosphere and amplified the relief in the Sierra Nevada and in what is now the Great Basin, (Figure 2.16A) (Henry

2009, DeCelles 2004). The East Pacific Rise was ca. 200 km from the edge of the North American plate and the thermal structure of the Farallon plate was influenced by its young age, shear heating from the flat slab subduction (Peacock et al. 1994, Peacock 1996) and fast subduction rate, allowing incompatible elements to be released from the slab (i.e. dehydration) and chemically enrich the overlying CLM.

Flat slab subduction, which currently occurs in 10% of modern convergent margins (Gutscher et al. 2000), can be caused by 1) a high rate of convergence of the overlying plate, and/or 2) the buoyancy of thickened oceanic crust of moderate to young age (Gutscher et al. 2000). In the flat-slab scenario for the Farallon Plate, it has been argued that there is no asthenospheric gap between the lithospheric mantle and the Farallon plate (Liu et al. 2008, DeCelles 2004). This caused a delay in the basalt to eclogite transition by up to 8 to 10 Ma (Gutscher et al. 2000) due to the cool thermal structure of two overlapping plates (Gutscher et al. 2000, Arcay et al. 2007). Dehydration therefore took place from serpentinized metabasaltic oceanic crust directly enriching the CLM; however, no melting took place because of lack of heat. High intraplate coupling may have scraped much of the sediments at the wedge, possibly explaining the absence of a sediment-sourced chemical signature in the GB lavas. As subduction progressed, the serpentinized metabasaltic oceanic crust and oceanic lithospheric mantle underwent metamorphic transformation far into the North American plate, which would have increased the density of the subducted slab. As the hydrous minerals continued to break down they would have released substantial amounts of H₂O and other fluid-mobile elements into the CLM, thereby altering the rheological properties of the boundary between the slab and CLM, which would have reduced the intraplate coupling above a

flat slab segment (Gutsher et al. 2000). Density of the slab probably increased by up to 10% once the metabasalt was transformed to eclogite, causing the lithospheric plate to collapse and the slab to sink down, at which point slab detachment from the base of the North American plate was possible (Spencer et al. 1995).

As the convergence rate between the Farallon and North American Plates decreased, the density of the metamorphosed (eclogitic) slab increased, the slab hinge point started to roll back (Figure 2.16A). As the slab hinge point rolled back, hot asthenosphere likely moved in between the North American and subducted Farallon plates, initiating dehydration of the slab triggering low- F partial melting of the overlying mantle wedge at the CLM boundary. Low- F mafic melts of the GB were generated within the spinel-field of the upper mantle where they were enriched in incompatible elements including the REEs, K, P, Ti and HFSEs. Magmatism moved southwestward as the Farallon slab hinge point continued to roll back (Figure 2.16C), and high-K magmatism of Bell Canyon, Stillwater, Truckee Range and Hotsprings Mountains erupted in the GB at ca. 25 to 15 Ma (Figure 2.16C). The similarities in phenocryst compositions, REE and isotopic signatures amongst GB mafic compositions further support the derivation of their primary magmas from similar source regions, with variations in chemistry due to a wide range of contributions from the CLM and variable degrees of partial melting (F). Alkaline melts (basaltic trachyandesites) within the GB represents melting primarily in the CLM.

To the south west, the Pacific plate margin collided with the North American Plate at ca. 34° latitude at ca. 25 Ma, initiating a right-lateral strike-slip fault near the present site of Los Angeles (Schellart et al. 2010), creating the Mendicino Triple Junction

(MTJ) that began migrating northward relative to stable North America at about 33 mm/yr (Atwater & Stock 1998). Intermediate volcanism migrated southwestward across Nevada as the Farallon Plate hinge point rolled back and dipped more steeply into the mantle, increasing P, T and resultant dehydration (aqueous fluid) from the slab. Extensional tensile stress affected the chemistry of the melts starting ca. 14 Ma within the region of what is now identified as the Walker Lane. By 10-12 Ma, the rate of subduction slowed as well as the rate of east-west migration, and higher volumes of mafic magmatism erupted in the eastern ACA (Figure 2.16D). As the angle of subduction increased, heating of the slab resulted in larger contributions from the slab-derived fluids into the widening mantle wedge. Concurrently the slab window was expanding to the south of the study area (latitude ca. 31°) as the Mendicino Triple Junction continued to migrate northward (Schellart et al. 2010, Atwater & Stock 1998) at a rate of about 52 mm/yr (Atwater & Stock 1998). Extension continued to fracture and thin the lithosphere in northern and southern B&R (Schellart et al. 2010, Henry 2009, Dickinson 2002) as well as increasing lithospheric tensile stress between eastern ACA and western GB (from Sparks, around Pyramid Lake, Lousetown, Coal Valley and Carson Range). The angle of subduction increased and, west of longitude 120°, and P-T conditions are high enough to produce sediment melt components from the Farallon slab to infiltrate the mantle wedge. By 5 Ma, the rate of subduction slowed to 8 cm/yr (English & Johnston 2004) and the slab angle equilibrated in the mantle (Figure 2.16E). Slab components continued to infiltrate the mantle wedge ($(\text{Sr/P})_{\text{pmn}} = 2-5$) and melting resulted in mafic extrusives in the western ACA (Stampede Reservoir, Ladybug region, Portola and Mt. Lincoln). A distinct, less enriched lithospheric mantle component contributed to magmas in the

westernmost part of the ACA (Sierra Nevada) including lavas of Squaw Peak, Pond Terrace, Devil's Peak and Lowell Ridge, resulting in lower overall $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios (Putirka et al. 2012). The mafic melt generated at Sawtooth (3.82 Ma) mixed with a component possessing an exceptionally high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (0.7061) which suggests that the vent may be over the Precambrian CLM, represented by the 0.706 Line (Kistler 1990, Beard & Glazner 1995).

2.5 Summary

Using the geochemical data from this study, the question of subduction versus extension for mafic lavas can be addressed. Also, geochemical data for mafic lavas can explain the decrease in age from east (>25 Ma) to west (ca. 3 Ma), the sparse mafic magmatism within the east-end of the study area, and comparatively higher volumes of mafic magmatism within the western ACA, as well as the variation in trace elements and isotopic ratios over space and time.

Specifically, I can make the following conclusions:

1. The study area is geochemically divided into three broad regions: central GB (age range 5 to 35 Ma), eastern and western ACA (age range 2.5 to 16 Ma).
2. Basalt and basaltic andesite lavas from the study area follow olivine-clinopyroxene + plagioclase fractionating phases, with clinopyroxene noted as the dominant phase. The effects of plagioclase fractionation are minimal for all mafic lavas, though greater in the GB mafic lavas compared to ACA lavas.
3. Most mafic melts are dominated by a lithospheric mantle component that is revealed in normalized incompatible element patterns and in Sr and Nd isotopic

compositions. The westernmost ACA lavas, located within the western ACA region of the study area, are recognized by their lower $^{87}\text{Sr}/^{86}\text{Sr}$ values for equal $^{144}\text{Nd}/^{143}\text{Nd}$ values, probably because the lavas erupted over less enriched lithospheric mantle compared to the CLM underneath the rest of the study area.

4. Trace element models show that compositions of all mafic melts possess subduction zone signature. This subduction signature, which includes negative Ta, Nb and Ti anomalies and LREE + LILE enrichment, is weakest in GB (older) mafic lavas when dip angle and dehydration from the slab was the lowest. The subduction signature is strongest in western ACA (younger) mafic lavas, when the dip angle and slab dehydration into the mantle wedge was greater.
5. Item #4 indicates that although all lavas have a subduction signature, not all lavas have direct influence from slab fluids. GB mafic lavas have likely obtained a subduction signature from the metasomatised lithospheric mantle (re: the CLM was modified from exchange of incompatible elements from the slab during flat slab subduction). Although the Farallon slab rolled back across the GB, the shallow dip did not allow for large degrees of fluid release. Slab dip was sufficient for fluid release, however, for ACA lavas. Increased fluids in the mantle wedge also causes higher volumes of melt, which explains the larger volumes of melt in the ACA compared to the GB.
6. Contribution from sediment melts (higher Th/Nb, Pb/Ce and Ce/Ce*) is present for melts west of Longitude 120° (western and westernmost ACA lavas).
7. $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ values for western ACA values are higher compared to GB lavas for equal $^{143}\text{Nd}/^{144}\text{Nd}$ values. It is therefore likely that the more

radiogenic Pb was sourced from melted sediment as opposed to recycled crustal Pb.

8. Mafic lavas from GB and selected eastern ACA lavas have higher K₂O, TiO₂, P₂O₅, HREE and Nb contents for equal silica and lower Mg# values compared to ACA lavas. These results are consistent with low degrees of partial melting due to 1) lower temperatures and water (volatile) abundances generated from the shallow slab for GB mafic lavas, and 2) faulting due to extension. Basaltic trachyandesites are more alkaline with higher ⁸⁷Sr/⁸⁶Sr, suggesting these melts resulted from lower degrees of melting of the CLM.
9. The extensional orogeny affected the chemistry of the melts beginning ca. 14 Ma. Tensile forces during the early formation of the Walker Lane within the northern GB, Pyramid Lake region (14 Ma mafic lavas) triggered low-*F* melting which resulted in enrichment in incompatible elements within these melts. Other regions in the study area affected by extension-related forces are discussed in the next two chapters.
10. Item #9 supports the conclusion that extension contributes to melting of the CLM, and resultant eruptions in the study area. It should be noted, however, that extension, began in isolated areas within the GB and eastern ACA at ca. 15 to 8 Ma.

Figure 2.1 Digital elevation map of eastern California and western Nevada showing the study area. The region is divided into three parts: Great Basin (GB), eastern Ancestral Cascades Arc (eastern ACA) and western Ancestral Cascades Arc (western ACA). The symbols represent the various mafic compositions of the volcanic samples included in the study (see legend). The western edge of the Precambrian continental basement lies just outside of the study area, as is indicated by the 0.706 isopleth (modified from Kistler & Peterman 1978, Wooden et al. 1999). Southern edge of Juan de Fuca (Farallon) plate obtained from Atwater & Stock (1998); edge of Ancestral Cascade Arc obtained from Cousens et al. 2008, and edge of Nevada Caldera Belt obtains from Henry & John (2013).

Figure 2.2 Photos from the field area: A) basaltic boulders encapsulated in tufa from the southwest side of the Stillwater Mountain Range (GB), B) Basalt from same location as (A) at higher elevation (free of tufa), C) basaltic trachyandesite from the Truckee Range (GB), D) basaltic andesite from Andesite Ridge (western ACA). Rock hammer is about 35 cm in length, and the GPS is about 15 cm in length.

Figure 2.3 Alkali-silica diagram (Le Bas et al. 1986) for mafic lavas from the GB (open plus sign), eARC (solid triangles) and wARC (open squares).

Figure 2.4 Thin section photos of various mafic lavas from the study area. Each thin section has been divided: the left side shows the rock in plane polarized light (PPL), and the right side shows crossed polarized light (XPL). A) Sample 04-LT-51 is a basalt from Bell Canyon in the GB. B) Sample 04-LT-08 is a basaltic trachyandesite from the Truckee Range in the GB. C) Sample 04-LT-21 is a basaltic andesite from the Andesite Ridge in the western ARC. D) Sample 04-LT-24 is a basaltic andesite from Lousetown in the eastern ARC. On the photos, v = vesicle, ol = olivine, pl = plagioclase, cpx = clinopyroxene, gm = groundmass.

Figure 2.5 Major element Harker plots for the GB (open cross), eastern ACA (open square) and western ACA (filled square) regions from the study area (see legend) (Harker 1909). See text for discussion.

Figure 2.6 Trace element Harker plots for the GB (open cross), eastern ACA (open square) and western ACA (filled square) regions from the study area (see legend) (Harker 1909). See text for discussion..

Figure 2.7 Mafic lavas from the GB and ACA plotted along the various end members as defined in Pearce (2008). See text for further discussion.

Figure 2.8: Chondrite (Sun & McDonough 1989) REE plots for mafic lavas, split by region: western ACA (left), eastern ACA (middle) and GB (right). Symbols represent composition (see legend).

Figure 2.9 Primitive mantle-normalized (Sun & McDonough 1989) incompatible element diagrams for mafic lavas, split by region: western ACA (left), eastern ACA (middle) and GB (right). Symbols represent composition (see legend in Figure 2.8).

Figure 2.10 Plots comparing Sr, Nd and Pb radiogenic isotopic ratios for mafic lavas. Symbols for plots A, B and C are as follows: Great Basin (GB, open plus sign), eastern ACA (open squares), and western ACA (closed squares). A) $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ graph shows a mixing line between MORB and lithosphere end members (see Cousens et al. 2008 and references therein) for GB and most ACA lavas. Lavas with lower $^{87}\text{Sr}/^{86}\text{Sr}$ values for their given $^{143}\text{Nd}/^{144}\text{Nd}$ value (circled) will be referred to as westernmost ACA lavas. B) $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ plot shows a trend away from the NHRL towards the average continental crust. C) $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ plot shows lavas hovering along the NHRL towards HIMU. D) $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ plot includes the symbols closed star as the westernmost ACA lavas (also in grey) and the open star as Sawtooth (Towle #1). GB lavas are also shown in shaded grey. E) $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ plot showing the various end members. GB lavas show lower $^{206}\text{Pb}/^{204}\text{Pb}$ values for their given $^{143}\text{Nd}/^{144}\text{Nd}$ values, perhaps due to less influence from slab derived components.

Figure 2.11 Crustal contamination plots: Nb/La and ¹⁴³Nd/¹⁴⁴Nd and ⁸⁷Sr/⁸⁶Sr versus SiO₂ wt%. See text for discussion.

Figure 2.12 Partial melting diagrams including A) TiO_2 vs. SiO_2 wt% and B) La/Sm vs. La . Pyramid Lake mafic lavas are circled (trace element data for Pyramid Lake volcanic suite in diagram B acquired by personal communication (C. Henry, NBMG)). GB mafic lavas are shaded and westernmost ACA mafic lavas are circled. Mafic lava from Sawtooth (sample Towle #1) is recognized by a star. See text for further discussion.

Figure 2.13 Diagrams evaluating major, trace and isotopic data trends over distance (longitude) and time (age). Note that the data symbols presented in the left column represent composition, whereas the symbols presented in the right column represent location (see legend). See text for discussion.

Figure 2.14 Isotopic and trace element ratio plots that compare the components that can influence the source melts: from the subducted slab that can influence the source melts; fluid mobile elements from slab-derived aqueous fluids (Ba, Sr), fluid “immobile” elements from slab-derived sediment (Th) and/or in the CLM ($^{87}\text{Sr}/^{86}\text{Sr}_i$). A) $^{87}\text{Sr}/^{86}\text{Sr}$ vs. Ba/La , B) Ba/La vs. Th/Nb . Arrow indicates values for Ladybug scoria trend to $\text{Th}/\text{Nb} = 4.7$. Please refer to the text for further discussion.

Figure 2.15: Sr-Nd and Pb isotopic plot of mafic lavas from the study area as well as the Gorda Ridge Mid-Ocean Ridge Basalts (MORB, Davis & Clague 1987), Mojave Desert and the Western Great Basin (GEOROC, 2007), the Sierran Granitic rocks. The data on Gorda basin sediments are taken from Church (1976) and Church & Tilton (1973). The Sr-Nd isotopic values for Pacific Sediments are outside the graph with whole-rock values averaging $^{87}\text{Sr}/^{86}\text{Sr} = 0.7091$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.5124$ (Goldstein & O'Nions 1981). Mixing curve is for melts of lithosphere (Sr = 1200 ppm, Nd = 38 ppm, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7070$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.5123$) and melts of mantle wedge (Sr = 550 ppm, Nd = 15 ppm, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7038$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.5129$) with tick marks showing percentage of lithospheric melt in the mix (modified from Cousens et al. 2008 and Yogodzinski et al. 1996: The Northern Hemisphere Reference Line (NHRL) is from Hart (1984) and based on Pb isotopic values from MORB and OIB. The data on Gorda basin sediments are taken from Church (1976) and Church & Tilton (1973). Cascadia sediments are from Davis et al. 1998 and Prytulak et al. 2006). GB lavas represented by open crosses, eastern ACA lavas represented by open squares, western ACA lavas represented by filled squares.

Figure 2.16 Model summarizing the southwestward magmatic migration within the study area (37° latitude) from 40 to 3 Ma, based on the geochemical and petrological results on mafic magmas. Circle 1 represents the meta-basaltic subducting oceanic plate, circle 2 represents slab sediment, circle 3 represents the upper and lower the continental crust, circle 4 represents the continental lithospheric mantle, and circle 5 represents the convecting mantle (asthenosphere). 40Ma: thickened crust at the western North American margin resulting from flat-slab subduction towards the end of the Laramide Orogeny. The CLM is enriched in components derived from the slab (e.g. REEs, Sr and Pb). Panel (A) From 35 to 25 Ma the Farallon slab begins to roll back increasing heat into the system from the asthenosphere. Possible basaltic underplating and AFC processes resulted in violent volcanic eruptions, signifying the “ignimbrite flare-up” as presented in Henry & John 2013 (and references therein), B) By 20 to 15 Ma high-K intermediate and mafic magmatism in central GB migrated southwestward as the Farallon plate continued to roll back, C) Ca. 10 to 12 Ma extension related faulting in the western GB and selected eastern ACA regions (e.g. Pyramid Lake) altered the chemistry of the resultant melts. Intermediate to mafic magmatism continued in the eastern and western ACA. D) By 5 Ma and Farallon slab has equilibrated in the western ACA, and arc magmatism is established in the Sierra Nevada (western ACA). Please refer to the text for a more detailed discussion.

Table 1.1 Petrography of mafic lavas from the study area with identifiers 04-LT and 11-LT.

SAMPLE	Rock Type	PHENOCR			Fe-oxide	MATRIX	TEXTURE	Alteration
		ol	px	pl				
	Lavas							
GB								
04-LT-51	Basalt	<5			<5	pl, px, ol, gl	trachytic, vesicular, skeletal pl, vesicular, skeletal ol	c.i. of ol
04-LT-48	Basaltic Trachyandesite		5	10-15	<5	holohyaline	sieved pl	none
11-CN-26b	Basaltic Trachyandesite			10	<5	pl, ol, gl	textures and zonation inhibited by the extreme seritization	s. of pl (extreme)
11-CN-09	Basalt	5	5-10	20-25	<5	pl, ol, px, gl	subophitic, minor (<5%) zoned pl, minor (<5%) sieved pl	none
04-LT-41	Basaltic Andesite	<5	5	10-15	<5	pl, px, ol, gl	seriate or three stages of pl growth, largest pl sieved and zoned	c.i. of ol
04-LT-42	Basalt	<5		10	trace	pl, ,px ,ol, gl	zoned pl, sieved pl, groundmass is trachytic, subophitic	p.i. of ol
04-LT-06	Basaltic Trachyandesite	<5	<5		<5	pl, ol, px, mt, gl	phenocrysts very small (microcrysts), vesicular, trachytic	p.i. of ol
04-LT-02	Basaltic Trachyandesite	<5			<5	pl, ol, px, mt, gl	trachytic	p.i. of ol
04-LT-05	Basaltic Trachyandesite	<5	5-10		5	pl, ol, px, mt, gl	zoned pl	p.i. of ol
04-LT-08	Basaltic Trachyandesite	<5		5		pl, ol, px, mt, gl	gomeroporphyritic	p.i. of ol
04-LT-09	Basaltic Trachyandesite	5-10		10-15	trace	gl, pl, ol, px	trachytic	c.i. of ol
04-LT-10	Basaltic Trachyandesite	<5		<5	<5	pl, ol, px, gl	trachytic	c.i. of ol
Eastern ACA								
04-LT-32	Basaltic andesite	5-10			5	pl, ol, mt, gl	embayed ol, trachytic	rimmed ol
04-LT-31	Basaltic andesite	<5			5	pl, px, ol, mt	embayed ol, trachytic	p.i. of ol
04-LT-25	Basaltic andesite			5	5	pl, ol, px, mt	seriate pl,	p.i. of ol, sericite
04-LT-24	Basaltic andesite	5-10	5	15-20	5	pl, ol, px, mt	zoned pl, sieved pl	p.i. of ol
Western ACA								
04-LT-01	Basaltic Andesite	15	10	<5		pl, px, mt, gl		
04-LT-87	Basaltic Andesite	10			<5	pl, ol, mt, gl	embayed ol	
04-LT-83	Basalt	10	10	<5		pl, ol, px, mt, gl		p.i. of ol
04-LT-21	Basaltic Andesite	<5	5-10	<5	trace	pl, px, gl	zoned pl, sieved pl, embayed sometimes rimmed ol, trachytic	
04-LT-17	Basaltic Trachyandesite				5	pl, mt, ol, gl	aphyric, hypocrySTALLINE	c.i. of ol
04-LT-68a	Basalt							
04-LT-98	Basaltic Andesite							

Minerals: ol = olivine; cpx = clinopyroxene; opx = orthopyroxene pl = plagioclase; amph = amphibole; mt = magnetite, gl = glass.
Alteration: p.i., partial iddingsitization; c.i., complete iddingsitization; s., saussuritization op, opacite.

3 Chapter: (PAPER 2) Petrological Evolution During Cenozoic Arc Migration in West-Central Great Basin, Western Nevada and Ancestral Cascades Arc, California

3.1 Introduction

Despite the growing consensus that several mantle, crustal and subducted reservoirs contribute to arc magmas along continental margins, there is still discussion concerning the relative proportions of the various contributions and mechanisms involved. The Cenozoic magmatic event that swept southwestward across southwest United States provides the opportunity to compare and contrast the composition of arc magmatism within the interior of North American during a period of changing and overlapping tectonic environments. Eocene through Pliocene volcanic rocks from the Great Basin (GB) and Ancestral Cascades Arc (ACA) are variable in their major, trace element and isotopic compositions reflecting the addition of components from several possible geochemical sources. Previous work suggests that the Cenozoic lavas consist of mixtures of material derived from the mantle wedge, the subducted oceanic slab, a metasomatized continental lithospheric mantle (CLM; e.g. Kempton et al. 1991, Cousens et al. 2008) and assimilated continental crust. A comprehensive study of mafic lavas (Chapter 2) examined the chemical contributions of the subducted Farallon Plate, the enriched CLM, the mantle wedge and the lower crust on source melts across the central GB into the ACA within eastern high Sierra Nevada Mountains. In this chapter trace element data and Sr-Nd-Pb and O isotopic characteristics from mafic to intermediate lavas is combined to examine crust-mantle interaction as a function of distance and geological time induced by

flat-slab subduction and slab rollback. The dataset was used to (1) better geochemically subdivide the GB and ACA, and (2) examine the subdivisions for tectonic evolution over space and time.

Assimilation of the continental crust as well as fractional crystallization (AFC) can affect the chemistry of subduction and rift-related magmatism across the study region. The degree of either and both of these processes may vary as the southwestward magmatic sweep progressed across the study region. Examining the geochemistry of mafic lavas from the GB and ACA (Chapter 2), I proposed that as slab rollback reached the study region, hot asthenosphere infiltrated the wedge between the over-riding North American and the subducting Farallon plates, triggering partial melting in the mantle wedge at the CLM boundary at depths in which spinel is stable in peridotites. During the initial stages of the rollback underneath the GB, the low dip angle resulted in lower P-T conditions and minimal dehydration from the slab causing low- F melting. As a result, mafic melts of the GB were enriched in REEs, K, Ti, P and HFSEs as high-K magmatism erupted in the GB at ca. 25 to 15 Ma. To the south, the Pacific plate margin collided with the North American Plate at ca. 34° latitude initiating a right-lateral strike-slip fault near the present site of Los Angeles (Schellart et al. 2010), creating the Mendicino Triple Junction (MTJ; Atwater & Stock 1998). Established conduits from previous eruptions and possible preliminary extensional faulting and thinned lithosphere facilitated mafic eruptions in the western part of the GB (Dickinson 2002, Henry 2009, Schellart et al. 2010). By 10-12 Ma, the rate of subduction slowed as well as the rate of east-west migration, the slab dip angle and P-T conditions of slab dehydration increased, and higher volumes of mafic magmatism erupted in the eastern ACA. As the angle of

subduction increased, heating of the slab resulted in larger contributions from the slab-derived fluids into the widening mantle wedge. Extension fractured and thinned the lithosphere in northern and southern GB (Schellart et al. 2010, Henry 2009, Dickinson 2002). Mafic magmatism erupted in the eastern ACA as slab fluids continued to metasomatise the mantle wedge ($(\text{Sr/P})_{\text{pmn}} = 2\text{--}5$). The angle of subduction increased and sediment melt components from the Farallon slab infiltrated the mantle wedge, evidenced by higher Th/Nb, Pb/Ce and Ce/Ce* ratios. A thinner (accretionary) lithospheric mantle component mixed with the westernmost part of the ACA (Sierra Nevada) mafic lavas of the westernmost part of the western ACA.

It is becoming increasingly clear that a number of mantle, crustal and subducted reservoirs all play roles in the genesis of the magmas generated during the southwestward migration. Nevertheless, there is no consensus as to the relative contributions of these various components over the GB and ACA due to its unusual tectonic setting and diverse volcanic products. This study provides an excellent opportunity to examine the role of shallow subduction and resultant rollback in the arc magma genesis and subsequent evolution of the melts. The purpose of this paper is to: (1) present new age and O-isotopic information for mafic and intermediate lavas from the GB and ACA, (2) introduce trace element and Sr-Nd-Pb isotopic tracers to constrain petrogenetic processes on the intermediate composition lavas, and (3) discuss tectonic implications during the Cenozoic southwestward magmatic sweep

3.1.1 Geological Setting

The Cenozoic tectonic and magmatic history of the Great Basin of southwestern

North America is complicated by overlapping tectonic settings that involved episodes of Andean-style subduction and orogenic events, accretion of exotic terranes, long periods of passive margin deposition, and Basin and Range extension that extends into the Sierra Nevada mountains (Armstrong 1968, Coney & Harms 1984, Christiansen & Yeats 1992, Wernicke 1992, Henry & Perkins 2001, DeCelles 2004, Dickinson 2006) and even possible influence from hotspot magmatism related to the Yellowstone-Columbia River Basalt region (Wagner et al. 2000, Garrison 2004, Coe et al. 2005, Garrison et al. 2008).

Beginning at about 40 Ma, shortly before North America had evolved from a convergent to a transform margin, the southwestern United States was blanketed by widespread volcanic activity. Mid-Cenozoic (Late Eocene to Miocene) volcanism began to the northwest of the study area (Coney 1978, Best & Christiansen 1991, Best & Christiansen 2009) continuing as a southward-migrating calc-alkaline magmatic sweep through, which followed the northeast to southwest rollback of the subducting Farallon plate from beneath what is now the GB (Colgan et al. 2008, Dickinson 2006, Du Bray et al. 2009, Farmer & DePaolo 1983, Farmer et al. 1989, Feuerbach et al. 1993, Henry et al. 1998, Humphreys et al. 2003, Humphreys 1995, Livaccari & Perry 1993, Ryskamp et al., 2008; Valentine et al. 2006, Wooden et al. 1998). Steepening of the once ‘flat’ subducting slab brought hotter asthenosphere into contact with the overlying continental lithosphere (CLM) prompting voluminous magma generation. By ca. 13 Ma, east-west lithospheric extension was prevalent within the Central Great Basin (Stewart 1988, Best et al. 1989, Christiansen & Yeats 1992). In some places extension is thought to have begun as early as 24 Ma, such as in the Stillwater Range (Hudson et al. 2000) and was widespread after about 18 Ma (McQuarrie & Wernicke 2005; Colgan & Henry 2009).

Farther west a younger period of extension in the previously unextended Pine Nut Mountains, the Carson Range, and the Tahoe-Truckee depression occurred between 10 Ma and 3 Ma (Surpless et al. 2002). From 13 to 3 Ma, coincident with the northward migration of the Mendocino triple junction, arc volcanism retreated northwestward as Basin and Range normal faulting advanced westward (Dilles & Gans, 1995, Henry and Perkins 2001, Surpless et al. 2002), and strike-slip faulting began in the northern Walker Lane (Faulds et al. 2005).

The study area was selected to represent the changing geologic and tectonic history that extends from longitude 117° in the east (Desatoya Mountain Range) to longitude 121° in the west (Sierra Nevada mountains) by latitude 39° to the south (Lake Tahoe) and 40.5° to the north (Susanville). Figure 3.1 shows sample locations within the study area, which can be divided into three broad regions: Great Basin (GB), eastern Ancestral Cascade Arc (eastern ACA) and western Ancestral Cascade Arc (western ACA). Figure 3.2 presents photographs from each of these regions.

3.1.1.1 Great Basin (GB)

The GB is the northern part of the Basin and Range Province, a region characterized by its elongated parallel mountain ranges separated by down-faulted sediment-filled basins. Cenozoic volcanic rocks include the oldest in the dataset (up to 35 Ma) and typically are emplaced over Mesozoic metasedimentary, plutonic and metavolcanic sequences. Post-volcanic extension has resulted in closely spaced normal faults that cut entire sequences of Cenozoic volcanic and older rocks (Stewart 1971, Best & Christiansen 1991). Included in this study are Clan Alpine, Desatoya, Stillwater (Figure 3.2A), Bell Canyon, Bell Mountain, Table Mountain & Churchill Butte (Carson

City Quad), Lahontan Mountains, Truckee Range (Figure 3.2B), Stud Horse, Churchill, and Virginia Hills.

The *Clan Alpine Mountains*, situated to the east of Stillwater Range, host several sequences of rhyolitic flows dated between 22 and 30 Ma (Riehle et al. 1972, Hardyman et al. 1988). Two sets of intermediate flows (basaltic trachyandesites and trachyandesites) extruded both earlier (35 Ma) and later (<16 Ma) than the rhyolitic episodes. Ten samples were collected within the Clan Alpine Mountains representing the three separate magmatic episodes.

The *Desatoya Mountains* are located southeast of the Clan Alpine Mountains and Antelope Valley. The area is a massive volcano-tectonic trough composed of volcanoclastic material including rhyodacitic ash-flow tuffs, rhyolitic flows and dacitic intrusives (Benjamin 1986). Quaternary alluvium overlies much of the low-lying areas. Samples collected include dacite, andesite and rhyolitic ash flows.

The *Stillwater Mountain Range* is approximately 110 km long that trends north-northeast along the east side of Carson Sink, northeast of Fallon (Figure 3.1). Mio-Pliocene basalt and basaltic andesite occur at various sites including near Mountain Well Road and La Plata Canyon. Lavas from the Stillwater Range show high levels of hydrothermal alteration as well as hydrothermal-related saussuritization of plagioclase to primarily sericite, calcite and chlorite, affecting rocks from mountain ranges around the Carson Sink (Stillwater, Truckee and Hot Springs). Basalt from La Plata Canyon is aphyric and plagioclase-rich.

Bell Canyon southeast of the Stillwater Range encompasses most of a range that includes Fairview Peak and the northern part of Slate Mountain (Henry 1996). Rock units

include Jurassic to Triassic metamorphic rocks intruded by Cretaceous granodiorite, a wide range of Oligocene to Miocene volcanic and volcanoclastic rocks (most of which are related to a ca. 19 Ma caldera), and late Cenozoic to Quaternary sedimentary deposits.

The *Hot Springs Mountains* and *Truckee Ranges* lie in west-central Great Basin abutting against the Walker Lane (Bonham, 1969). They comprise a series of hills that form part of the northwestern boundary of the large Carson Sink depression. Exposed rocks in the region range from Triassic to Holocene (Wildden & Speed 1974). Cenozoic rocks are primarily volcanic and consist of alternating sequences of flows, tuffs, and shallow intrusive rocks. The 5.1 Ma **Soda Lake** andesites, located beneath the Carson Sink, were obtained by vertical drill holes at a depth of 1213.2 feet (369.8 meters), amidst older (9-11 Ma) and younger (< 3 Ma) mafic and intermediate flows. The 5.1 Ma andesite rocks are unaltered and suitable for chemical analysis (McLachlan 2013).

3.1.1.2 East Ancestral Cascade Arc (eastern ACA)

The eastern ACA is located on the west edge of the Great Basin and east of the Sierra Nevada mountains and consists of faulted terrain of sedimentary filled basins and ranges. Interestingly, the oldest volcanic rocks within the eastern ACA region are the andesites from southwest of Virginia City (27.8 Ma), much older than the average age of ca. 12 Ma. Another set of older rocks dated at ca. 20 Ma are an andesite and basaltic andesite (GC-213 and GC-124), sampled just south of Pyramid Lake. Other samples were collected from the Carson Range, Reno East, Lousetown, Kate Peak, Sparks (Figure 3.2C), Rattlesnake Mountains, Virginia City, Flowery Peak, Pyramid and Coal Valley.

Sparks is located on the north side of the town of Sparks, just east of Reno. Mafic lavas from Sparks are basaltic andesites that contain phenocrysts of clinopyroxene, plagioclase and iddingsitized olivine. The extensive *Lousetown* Formation, southwest of Reno, covers about 40 km² in the Virginia City Quadrangle, and extends into the Mount Rose, Wadsworth and Churchill Butte quadrangles (Ashley et al. 1979). The *I-80 Suite* refers to lavas with similar ages (<10 Ma), and chemical and physical characteristics that are located along the Interstate-80 corridor between Lake Tahoe and Reno (Henry & Perkins 2001, Cousens et al. 2008). *Ladybug Peak*, at the north end of Verdi Range, includes patchy episodes of mafic volcanism (Cousens et al. 2008) that may be related to the region's 12-10 Ma extensional event (Henry & Perkins 2001).

The *Pyramid Sequence* (ca. 13 Ma), located to the southeast of Pyramid Lake, consists primarily of complexly interbedded basalt to basaltic andesite, sparse andesitic lavas and rare rhyolitic lava, coarse to fine grained clastic rocks, and a dacitic ash-flow tuff (Henry et al. 2004).

Comparatively younger (ca. 3 Ma) and less phyric, olivine-clinopyroxene basaltic andesites and basaltic trachyandesites were extruded atop the northern *Carson Range*, just south of Reno. The northern end of the Carson Range is composed primarily of tilted, porphyritic lavas capped by gently- dipping to flat-lying, poorly phyric lava flows (Thompson & White 1964, Latham 1985). Samples 01-LT-10, 11 (basaltic andesites) and 12 (basaltic trachyandesite) are from a set of flows near Fuller Lake. Locations for samples 01-LT-46 to 53 are included in Cousens et al. (2011). The basaltic, basaltic andesitic lava flows of *Dog Valley* (3-4 Ma) are located just west of the Carson Range.

3.1.2 *West Ancestral Cascade Arc (western ACA)*

The western ACA lies mainly within the Sierra Nevada geomorphic province, which is comprised of Neogene volcanic rocks that were emplaced on Paleozoic and Mesozoic metavolcanic and metasedimentary rocks that were intruded by the Jurassic and Cretaceous granitic rocks of the Sierra Nevada batholith. Volcanism was widespread during the Cenozoic, the most abundant of which were Mio-Pliocene volcanic rocks of basalt to andesite compositions with lesser dacitic to rhyolitic compositions (Saucedo 2005, Cousens et al. 2008). Basin and Range-type faulting impacted the western ACA area between 10 and 3 Ma, creating a series of west-tilted blocks bounded by east-dipping faults that produce, for example, the north-south trending basin now occupied by Lake Tahoe (Saucedo 2005). The magnitude of extension and amount of westward tilting of individual extensional fault blocks increases from west to east, into the Basin and Range Province (Surpless et al. 2002).

Samples named *Pond Terrace*, *Andesite Peak*, *Devil's Peak*, *Mount Lincoln*, *Twin Peaks*, *Stanford Peak*, *Squaw Peak*, *Sawtooth* and *Hennes Pass* are highly eroded volcanic complexes from 6 - 8 Ma and 5 - 3 Ma that cap high Sierra Nevada granitoid intrusions from the west side of Lake Tahoe north to Donner Pass (Harwood 1981, Saucedo & Wagner 1992, Cousens et al. 2008). The volcanic rocks of this area include lava flows, agglomerates, tuffs and plug intrusions of lava and breccia (Hudson 1951), as well as volumetrically minor amounts of olivine-clinopyroxene basalt and basaltic andesite lava flows (Cousens et al. 2008). At Squaw Peak and Mount Lincoln,

debris lava flows and dome-collapse deposits are phyric volcanic fragments in a mineralogically similar volcanic matrix.

3.2 Analytical Methods

See Section 2.2 for methodology and analytical techniques. Data can be found in Appendix B. Geochemical data used in this study were obtained through our own fieldwork, public databases, open-file reports and from unpublished analyses. Samples were carefully selected to include only those from the southwesterly magmatic sweep between 35 and 3 Ma. The final dataset consists of 88 samples from 15 locations in the GB, 107 samples from 14 locations in the eastern ACA, and 57 samples from 22 locations in the western ACA. The database contains partial to complete major, trace and isotopic data as well as age data. The complete reference list is available in Appendix A

3.2.1 Geochronology

Ages for the samples used in this study are based on 1) radiometric ages, and 2) estimated geologic ages. *Radiometric ages* were primarily derived from K-Ar or $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology from the Nevada Bureau of Mines and Geology and the United States Geologic Survey as well as new $^{40}\text{Ar}/^{39}\text{Ar}$ ages from Pacific Centre for Isotopic and Geochemical Research, University of British Columbia. Whole-rock dating was used for aphanitic samples, whereas the matrix or minerals such as biotite, muscovite, plutonic/high grade hornblende or volcanic feldspar may have been analyzed for some porphyritic rocks. *Geological ages* were determined through geologic inference, correlations and other data sources (du Bray et al. 2009). Ages are rounded to the nearest million years (du Bray et al. 2009). Sixty-seven of the 87 samples from GB include radiometric and/or geologic ages. Samples that do not include ages are the rhyolites from Bell Mountain (04-LT-46a & b). Nine of the 106 samples from eastern ACA have not been dated,

which include two trachyandesites from Carson Range (01-LT-50 & 52), an andesite from east Lake Tahoe (08-LT-17) and the samples from Sparks (04-LT-29 to 33). For western ACA volcanic samples, 14 of the 56 samples were not dated, including andesites from Sierraville-Portola (04-LT-80 to 82), a rhyolite from Serene Lakes (04-LT-38), an andesite from Castle Peak Trail (04-LT-22), andesites from Henness Pass (04-LT-65 & 85), samples from Portola/Blairsden (04-LT-90 & 91) and samples from Susanville (04-LT-92, 94, 95 & 97).

Eleven samples from our fieldwork were selected for incremental ^{40}Ar - ^{39}Ar age determinations at the Noble Gas Laboratory, Pacific Centre for Isotopic and Geochemical Research, University of British Columbia, Vancouver (Table 3.1 and Appendix F). Mineral separates were step-heated at incrementally higher powers in the defocused beam of a 10W CO_2 laser (New Wave Research MIR10) until fused. The gas evolved from each step was analyzed by a VG5400 mass spectrometer equipped with an ion-counting electron multiplier. All measurements were corrected for total system blank, mass spectrometer sensitivity, mass discrimination, radioactive decay during and subsequent to irradiation, as well as interfering Ar from atmospheric contamination and the irradiation of Ca, Cl and K (Isotope production ratios: $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}} = 0.0302 \pm 0.00006$, $(^{37}\text{Ar}/^{39}\text{Ar})_{\text{Ca}} = 1416.4 \pm 0.5$, $(^{36}\text{Ar}/^{39}\text{Ar})_{\text{Ca}} = 0.3952 \pm 0.0004$, $\text{Ca/K} = 1.83 \pm 0.01(^{37}\text{Ar}_{\text{Ca}}/^{39}\text{Ar}_{\text{K}})$). Initial data entry and calculations were carried out using the software ArArCalc (Koppers 2002). The plateau and correlation ages were calculated using Isoplot ver.3.09 (Ludwig 2003). Errors are quoted at the 2-sigma (95% confidence) level and are propagated from all sources except mass spectrometer sensitivity and age of the flux monitor.

The majority of the samples yielded $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages, with the exception of 11-CN-26A and 26B from the east side of Stillwater Range for which the inverse isochron ages were the best results. These andesites were too old (>40 Ma) to be included in this study (11-CN-

26A= 142.1 ± 5.2 Ma and 11-CN-26B = 154.0 ± 4.9 Ma). Strontium, Nd and Pb analyses were also completed for 26A and 26B, the results of which presented in Appendix B.

An andesite from the southern Clan Alpine Mountains (11-CN-11) produced a plateau age of 24.02 ± 0.49 Ma, similar to a Desatoya Mountains rhyolite (11-CN-18) with a plateau age of 26.09 ± 0.32 Ma. Andesite from Lake Tahoe East (08-LT-17) and a basaltic trachyandesite from the Rainbow Mountains (Lahontan Mountains, 11-CN-15) have good plateau ages of 9.37 ± 0.16 Ma and 9.06 ± 0.52 Ma respectively. Within the Carson City Quadrangle, the basaltic andesite from Virginia Range (11-CN-02) yielded a plateau age of 11.8 ± 0.44 Ma, whereas an andesite and basaltic andesite from the east side of the Carson City Quadrangle (11-CN-04 and 5a) produced ages of 6.6 ± 0.2 Ma and 8.21 ± 0.52 Ma respectively. Lastly, the basaltic andesite from sample 11-CN-06 (Desert Mountain, Carson City Quadrangle) revealed a plateau age of 13.2 ± 1.0 Ma.

3.2.2 *Oxygen Isotopes*

Twenty-one samples, including basalts, basaltic andesites, basaltic trachyandesites and one trachyandesite from the study area underwent whole rock oxygen isotope analyses: 8 from the GB, 4 from the eastern ACA and 9 from the western ACA (Table 3.2, Appendix E). All but five of the oxygen isotope data values were obtained from Cousens et al. 2008. The other five were completed for this study at the Laboratory for Stable Isotope Science (L.S.I.S.), University of Western Ontario, Ontario, Canada. The methodology is outlined in Potter et al. (2008). Oxygen isotope results for whole-rock and mineral samples were obtained using the method of Clayton and Mayeda (1963), as modified by Borthwick and Harmon (1982) for use with ClF_3 . Whole-rock powders and mineral standards (ca.10 mg each) were weighed out and dried overnight at 200 °C while

being evacuated. The dried samples and standards were then loaded into Ni-reaction vessels under dry nitrogen gas, and heated at 300 °C for 2 h while being evacuated. Appropriate quantities of ClF₃ were then added to each vessel, the vessels were sealed, and the samples were reacted at 550 °C overnight to release O₂. The oxygen gas was then converted to CO₂ over red-hot graphite, and CO₂ yields were checked to ensure complete conversion and/or absence of contamination. The oxygen-isotope composition of the CO₂ gas was analyzed using an Optima dual inlet-mass spectrometer. Internal laboratory standard quartz, laboratory standard kaolinite (KGa-1) and laboratory standard CO₂ II had averages values of +11.54, +21.46, and +10.35 respectively, which compare well with their accepted values of +11.5, +21.5, and +10.3‰, respectively. Reproducibility of the δ¹⁸O values for samples was generally better than ± 0.2‰, where $\delta^{18}\text{O} = ((\delta^{18}\text{O} / \delta^{16}\text{O})_{\text{sample}} / (\delta^{18}\text{O} / \delta^{16}\text{O})_{\text{VSMOW}} - 1) \times 1000$ and $(\delta^{18}\text{O} / \delta^{16}\text{O})_{\text{VSMOW}} = 0.0020052$ (VSMOW being Vienna Standard Mean Ocean Water, Faure 1986, Eiler et al. 1998, Hoefs 2004).

3.2.3 *Field and Analytical Techniques*

See Section 2.2 , Appendices A, B, C And D.

3.3 **Results**

We have determined that the effect of weathering on the collected samples did not appreciably alter their geochemistry with the exception of the basaltic trachyandesite from Ranbow Mountains (11-CN-15). Low LOI values (<3 wt%) and petrological observations indicate that secondary processes have not significantly affected our samples. Secondary minerals such as sericite and chlorite are seen during petrological examination with. No correlation between La/Sm and LOI values for the ACA and GB

lavas is seen (not shown), as LOI is a proxy to discriminate between fresh and weathered samples (Chauvel et al. 2005, Labanieh et al. 2012).

The chemical data reveal compositional distinctions between lavas from eastern ACA and western ACA lavas, as well as between central GB (i.e. the easternmost part of the study area) and western GB.

3.3.1 Great Basin

Eighty-eight samples were analyzed from the GB, including basalts, trachybasalts, basaltic andesites, basaltic trachyandesites, andesites, trachyandesites, dacites, trachytes, and rhyolites (Le Bas et al. 1986, Le Maitre et al. 1989, 2002, Figure 3.3). Three trachytic and rhyolitic ash flow tuffs (ca.20 Ma) from the Desatoya Range are included in the dataset. Most lavas are subalkaline; however, mafic lavas from Stillwater, Truckee, Bell Mountain and Rainbow Mountain (Lahontan) ranges are transitional to alkaline. Magnesium numbers ($Mg\# = Mg / (Mg + Fe^{2+})$, where $Fe^{2+} = 0.9 Fe_{total}$) range from 0.09 to 0.64, and SiO_2 values range from ca.48 to 82 wt%. Lavas with high MgO (>6 wt%) are rare in the GB, found only in the southern Stillwater Range with Ni >50 ppm and Cr >100 ppm. All of the lavas are LREE enriched ($(La/Sm)_{pnn} = 2.1$ to 6.5, pnn = primitive mantle normalized) and have low HFSE abundances (e.g. Ba/Ta > 800) except for the Lone Rock (Stillwater Range) basaltic andesite (GD-03-10, Ba/Ta: 539).

To evaluate possible genetic links and/or evolution of the lavas from the GB lavas, major, and trace elements are plotted against SiO_2 (Figure 3.4, Harker 1909, Rollinson 1998). The decrease of TiO_2 , Fe_2O_3 and V with increasing SiO_2 illustrates the importance of Fe-Ti oxide minerals as a fractionating phase for all sample suites. All lavas, except those from Clan Alpine and Desatoya Mountains, have Al_2O_3 and Sr

concentrations that increase with increasing SiO₂ until ca.57 wt% SiO₂, at which point Al₂O₃, CaO and Sr values decrease with increasing SiO₂ that are consistent with the fractionation of plagioclase. MgO, Cr, Ni, Co and Fe₂O₃ all decrease with increasing SiO₂. Na₂O contents increase steadily with SiO₂ for the basalts, basaltic andesites and basaltic trachyandesites, then scatter for the lavas with SiO₂ > 57 wt%. CaO/Al₂O₃ and Sc decrease with SiO₂, consistent with the crystallization of clinopyroxene and/or calcic hornblende. P₂O₅/K₂O and TiO₂/K₂O also decrease with increasing SiO₂. For GB lavas, apatite is a potential crystallizing phase for melts with SiO₂ > 57 wt% (Green & Watson 1982).

All lavas show enrichment in LREEs, moderate slope in the middle REEs (MREEs), and most lavas show flat profiles in the HREEs with the exception of andesite from Bell Mountain (04-LT-45), a dacite from Stillwater Range (04-LT-43) and a trachyandesite from Clan Alpine Range (11-CN-11) (Figure 3.5). Mildly alkaline lavas have an overall higher abundance of REEs and larger negative Eu-anomalies compared to subalkaline lavas (Eu anomalies are denoted Eu/Eu*, and calculated as

$$(Eu/Eu^*)_{pmn} = Eu_{pmn} / ((Sm_{pmn} + Gd_{pmn}) / 2).$$

Three ash flow tuffs from two units in the Desatoya Mountains are included in this study. Samples 11-CN-16 and 17 were collected from the unit identified as TS1 (latite ash flow tuff), and sample 11-CN-18 from the unit TS3 (ash flow tuff) on the Barrows (1971) map of Southern Desatoya mountains. For the purpose of this paper, these volcanic rocks are named based on their chemistry: 11-CN-17 is a trachydacite (SiO₂ = 67.78 wt%, Na₂O+K₂O = 10.164 wt%), whereas 11-CN-16 and 18 are rhyolites (SiO₂ = 71.07, 72.83 wt% respectively, Na₂O+K₂O = 10.056, 9.669 wt% respectively).

Samples 11-CN-16 and 17 are the only rocks from this study with positive Eu-anomaly (ca.1.2). Other felsic rocks show larger negative Eu-anomalies compared to the mafic and intermediate lavas. A dacite (04-LT-43) and two basaltic trachyandesites (11-CN-07a, 11-CN-07b) from the Stillwater Range have a steepening HREE profile relative to chondrites, and both 07a and 07b have a negative Eu-anomaly. Ce-anomalies are also almost non-existent with values between 0.95 to 1 (Ce/Ce anomalies are denoted $Ce/Ce^* = Ce_{pmn}/((La_{pmn} + Pr_{pmn})/2)$). Outliers ($Ce/Ce^* < 0.9$) include an andesite xenolith in a dacite from the Desatoya Mountains (11-CN-22b), and a dacite from Stillwater Range (04-LT-43). Normalized trace element abundance variation diagrams of the lavas from the GB (Figure 3.6) show slightly higher abundances in LILEs (e.g. Ba and Pb) compared to adjacent REEs, as well as depleted HFSEs (e.g. Nb, Ta and Ti). These profiles show that all lavas have a subduction signature.

Initial $^{87}Sr/^{86}Sr$ values for GB lavas range from 0.704 to 0.706 for all compositions, with the exception of the trachyandesites and rhyolites from Clan Alpine Mountains (0.706 to 0.708) and the basaltic trachyandesite from Rainbow Mountains, Lahontan Mountains (0.7076). Whole-rock initial ϵNd values vary from +2.32 to -5.34, and generally increase with decreasing initial $^{87}Sr/^{86}Sr$ (Figure 3.7), with most lavas possessing initial ϵNd values between +2.32 and -2. The trachyandesites from Clan Alpine have initial ϵNd values of between -3 and -5.34. The Pb isotopic compositions plot to the right of the geochron on a $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ plot, and form an array with a positive slope that trends away from the Northern Hemisphere Reference Line (NHRL). However, the Pb isotope ratios parallel the NHRL in a $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ plot. Lavas from the westernmost part of the GB are notably more radiogenic

than the lavas from the central part of the GB. Also, the upper bounds for both $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ increase with increasing age.

3.3.2 *Ancestral Cascades Arc (ACA)*

One hundred and sixty-four samples from the ACA region of the study area were analyzed for this study. Similar to GB lavas, ACA lavas are mostly subalkaline mafic to felsic rocks, including basalts, basaltic andesites, andesites, dacites and rhyolites (Fig. 3.3). The eastern ACA lavas also include minor basaltic trachyandesites and trachytes. Curiously, unlike the GB lavas, the eastern ACA and western ACA lavas have a notable “gap” in the chemical array for various major and trace elements (Figure 4). This is discussed in further detail below.

Magnesium numbers reach higher values compared to GB lavas, particularly for the western ACA volcanic rocks (eastern ACA: 0.2 to 0.69, western ACA: 0.23 to 0.74). The highest weight percent MgO samples from western ACA have high Ni (up to 325 ppm) and Cr (up to 980 ppm) contents (Fig. 3.4). ACA lavas have lower weight percent TiO_2 and P_2O_5 compared to GB rocks (<1.2 wt% and <0.6 wt% respectively), with the exception of basaltic andesites, basaltic trachyandesites and trachyandesites from Pyramid Lake (eastern ACA), as well as a basaltic trachyandesite from Carson Range (01-LT-12, eastern ACA), which have higher weight percent TiO_2 and P_2O_5 (0.8 to 2 wt%, and 0.5 to 9 wt% respectively). Mafic lavas from western ACA have lower Al_2O_3 (12 to 19 wt%), higher CaO (up to 12 wt%) and MgO (up to 12 wt%) compared to eastern ACA and GB lavas. Lavas from Pyramid (again, with the exception of the rhyolites) also have higher HREE and Y content (up to 45 ppm) compared to other ACA lavas.

Although eastern ACA volcanic lavas are represented by a complete range of compositions, the eastern ACA includes a geochemical “gap” in Fe_2O_3 , MgO , CaO , K_2O , V and Rb contents (Figure 3.4). For example, Fe_2O_3 exhibits a gap between 2.8 and 4.4 wt%, CaO shows a gap between 2.5 and 3.9 wt%, and K_2O values shows a gap between 3.2 and 4.3 wt%. Western ACA values also show an absence of volcanic rocks with SiO_2 contents between 54 and 57 wt%, as well as between 63 and 75 wt% (Figure 3.4). All dacites plot along the same linear array as the andesites, basaltic andesites and basalts, with the notable exception of the dacites 04-LT-28 and KS99-321, which exclusively plot with the rhyolites.

Zinc values within intermediate lavas from the ACA typically range from 60 to 130 ppm (not shown); however, andesites from Carson Range and Flowery Peak (eastern ACA) have Zn content that trend to lower values (75 to 100 ppm). Unlike GB lavas, REE patterns (normalized to chondrites) in the eastern ACA lavas have steep LREE, more concave up MREE, then flat HREE. Mafic lavas from the eastern ACA have flat overlapping HREE patterns, whereas intermediate lavas vary slightly in their slope. Western ACA intermediate lavas have overlapping REE patterns with elevated LREE and flat HREE profiles. Only the eastern ACA rhyolite and western ACA alkaline lavas show negative Eu-anomalies. ACA lavas have lower Ce/Ce^* and Ce/Pb values, as well as higher Th/Rb values compared to GB rocks. Ladybug Peak scoria have higher Th/Ta contents (>60) compared to the other volcanic rocks (<30). The ACA volcanic rocks have HREE abundances similar to those of their GB counterparts, but have slightly lower HFSE values - with the exception of lavas from Pyramid and Carson Range, which have values similar to the GB lavas. Lavas from the region surrounding the Carson Sink

(Churchill-3 Ma), Churchill-12 Ma, Truckee Range, Hotsprings Mountains and Soda Lakes trachybasalts) have dramatically lower LREE and $(\text{La}/\text{Sm})_{\text{pmn}}$, as well as slightly lower Pb values compared to the other volcanic rocks from the study area. This is discussed further in section 4.4.

Initial Pb isotopic composition of the ACA volcanic rocks (Fig. 3.7) overlap those of the GB lavas, but Sr and Nd isotopic values are more restricted in range (eastern ACA: initial $^{87}\text{Sr}/^{86}\text{Sr}$: 0.7035 to 0.7055, initial ϵNd : 3.7 to -2.5; western ACA: initial $^{87}\text{Sr}/^{86}\text{Sr}$: 0.7036 to 0.7061, initial ϵNd : 3.3 to -4.3).

3.3.3 Oxygen Isotopes

Whole rock oxygen isotope values for GB and ACA rocks are presented in Table 2 and Figure 3.8. Results from the GB and ACA lavas show $\delta^{18}\text{O}$ values between +8.54‰ to +6.3‰, consistently higher than upper mantle-derived magmas of +5.5 to +6.0‰ (Hoefs 2004). GB lavas have the overall highest $\delta^{18}\text{O}$ values (+7.09 to +8.54), whereas eastern ACA lavas have an intermediate range (+7.21 to +8.01) and western ACA lavas include the lowest values and the widest range (+6.3 to +8.04). Figures 3.8A and B shows a scattered, but overall positive correlation of $\delta^{18}\text{O}$ with $^{87}\text{Sr}/^{86}\text{Sr}$; however, only the eastern ACA shows a correlation with SiO_2 , similar to the $^{87}\text{Sr}/^{86}\text{Sr}$ vs. SiO_2 plot (not shown). Eastern ACA lavas show a positive correlation of $\delta^{18}\text{O}$ with $(\text{La}/\text{Sm})_{\text{pmn}}$ (Figure 3.8C), yet a negative correlation with Ti/Zr (Figure 3.8D).

3.4 Discussion

The results of this study recognizes spatial geochemical distinctions for lavas along the east-west transect as well as through time. Our primary concerns are: 1) why these distinctions exist, and whether these differences can provide information on the

chemical profile of the mantle wedge, the subducted Farallon plate, the lithospheric mantle, and the overlying continental crust, and 2) to determine whether compositional variations are due to fractional crystallization and/or assimilation.

3.4.1 Variation over Space and Time

Variations in major and trace elements as well as isotopic ratios versus longitude and age are shown in Figure 3.9. GB lavas can be chronologically and chemically divided into central GB and western GB, and shall be referred to thus herein. Volcanic rocks from central GB increase in age to the east (up to 35 Ma) compared to western GB and ACA volcanic rocks (range from 5 to ca. 15 Ma), with the youngest rocks located in the western part of eastern ACA and western ACA (ca. 3 Ma). An exception to this spatial relationship is a lava from the Virginia City SW (eastern ACA) which has been dated ca. 27 Ma.

Oxides: Western ACA lavas show the greatest range and highest MgO (up to 10 wt%) and CaO/Al₂O₃ (up to 0.8) values compared to other regions in the study area. MgO, CaO/Al₂O₃ and TiO₂/K₂O values steadily decrease from younger to older lavas. Western GB lavas show the least variation for all oxides. K₂O values are highest (up to 6 wt%) within central GB and selected eastern ACA (Pyramid Lake and high-alkali lavas from Carson Range). Lavas within the other regions of the study area show K₂O values <3 wt%. Older lavas (generally >12Ma) have a greater range in K₂O values compared to younger lavas (<12 Ma).

With the exception of Virginia City SW, older lavas are located within central GB, where the higher K₂O and lower TiO₂/K₂O values are the result of low degrees of partial melting within the spinel field of the CLM (low-*F*, where *F* is the melt fraction)

(Chapter 2). It is likely that as rollback progressed through the GB, the shallow angle of subduction resulted in lower temperatures and therefore less dehydration of the slab compared to a “normal” arc system. Lavas extruded within the eastern and western ACA underwent higher- F melting, probably because of greater temperatures from the hot asthenosphere and greater release of slab fluids into the thickening mantle wedge. I can further test influence from the subducted slab by looking to the trace elements.

Trace elements and Isotopic ratios: Progressive subduction leads to the release of groups of temperature-sensitive incompatible elements, which include low temperature elements (from subduction fluids, e.g. Rb, Ba), high temperature elements (from slab-sediment melts, e.g. LREEs, MREEs, Th, P) and ultra-high temperature elements (from slab (crustal) melts, e.g. Nb, Ta, Zr, Hf) (e.g. Pearce & Peate 1995). In this way, comparing fluid-mobile Ba with lesser mobile Nb can be used as a proxy for slab fluids. Although all lavas have elevated Ba/Nb values (>50), lavas from the ACA show the highest values (up to 400). With respect to tracers from sediment melts, Be, Th, U and Pb and Sr isotopes are high in pelitic sediments and greywackes (Hawkesworth et al. 1997, Lackschewitz et al. 2000, Prytulak et al. 2006). Therefore higher Th/Rb values can be used to study sediment melts. Ce/Ce* can also be used as a tracer for slab sediment melts (Hole et al. 1984). Geochemical investigations of pelagic sediments discovered large negative Ce-anomalies in rare earth patterns of seawater, pelagic clays and nannofossil oozes (Hole et al. 1984). Cerium is a LREE characterized by two different redox states: Ce^{3+} or Ce^{4+} . Ce^{3+} can be oxidized by atmospheric oxygen (O_2) to Ce^{4+} under alkaline conditions. Under reducing conditions, Ce^{3+} is relatively soluble while under oxidizing conditions CeO_2 precipitates out in reservoirs such as oceanic sediments.

Comparing Th/Rb and Ce/Ce* (where Ce/Ce* anomalies are calculated $Ce/Ce^* = Ce_{pmn}/((La_{pmn}+Pr_{pmn})/2)$): higher Th/Rb and negative Ce/Ce* values are present in within selected eastern and more so in western lavas, mainly in the more mafic lavas. Older lavas do not show a sediment melt signature whereas younger lavas (<15 Ma) show greater variation in Th/Rb and Ce/Ce* values. Upper Ce/Ce* values do not vary with location, age or silica content; however, Ce/Ce* trend to lower values to the west, with decreasing age and silica content.

Nb, Zr, HREEs and Y are not considered to be mobilized by slab-related aqueous fluids (e.g. Pearce & Peate 1995), therefore Nb/Yb content in mafic rocks can be used to study the relatively enriched or depleted composition of the mantle wedge component. Nb/Yb can also be used as a proxy for contamination from the continental crust (Pearce et al. 1984). Minerals such as titanite, rutile, ilmenite and hornblende, which contain high abundances of HFSEs (e.g. Zr, Ti, Nb, Hf, Ta), stabilize in the altered oceanic crust part of the subducting plate (Thirlwall et al. 1994). Fluids from the oceanic crust will not partition HFSE because they are locked up in those phases. This results in a LIL and REE-rich fluid coming from the slab and diluting the HFSE in the mantle wedge. Another possibility is that low HFSE abundances reflect contamination with continental crust that was previously depleted in HFS elements relative to the REE and LILE, and so magmas contaminated by it would inherit this signature. The LILEs K and Rb, are potentially useful monitors of crust-magma interactions because they are concentrated in early crustal anatectic melts and because the ratio of Rb to K is relatively insensitive to crystal fractionation (Davidson et al. 1987). Partitioning into plagioclase could account for Rb/K variations; however, this would not explain the increase in La/Sm with

differentiation. As established earlier, other than the weathered sample from Rainbow Mountain (sample 11-CN-15), Lahontan Mountains, samples used in this study are fresh. I can therefore compare these values to Rb/K, ^{18}O and silica content. Eastern ACA and GB lavas show higher Rb/K, Nb/Yb, silica and $\delta^{18}\text{O}$ values compared to other regions in the study area. Age does not seem to be a factor for Nb/Yb and Rb/K variation. $\delta^{18}\text{O}$ values steadily increases from west to east in the study area, with increasing age and with increasing silica content. Lavas from the GB are more evolved (higher weight percent SiO_2) and have include a greater percentage of a crustal component (higher $\delta^{18}\text{O}$ values) compared to lavas from the ACA, which may indicate: 1) a thickened crust in the GB (Henry 2009) that inhibited ascent of mafic magma and instead acted as a density filter and causing magma to be ponded into a chamber where extensive fractional crystallization – assimilation occurred that gave rise to more evolved lavas, and/or 2) a strong compositional contrast exists between the crustal rocks and the ascending liquid, thus assimilation of the crust that would cause the magma to be chemically and isotopically modified. Melting of enriched, subduction-modified lithospheric mantle should also result in increasing Sr/Nb, $(\text{La}/\text{Sm})_{\text{pmn}}$ and $^{87}\text{Sr}/^{86}\text{Sr}$, while maintaining low Rb and K concentrations, whereas upper crustal contamination would result in a strong increase in Rb and K content in mafic to intermediate magmas. Pb isotope ratios increase with increasing continental contamination as well as with increasing fluid/sediment melts from the subducted slab. Central GB lavas contain higher Rb/K values and higher radiogenic Pb for the more evolved lavas. Western ACA lavas, however, contain lower Rb/K values yet higher Pb isotope ratios for more mafic lavas. This may indicate that

central GB lavas were subjected to higher continental contamination, and western ACA lavas have higher influence from the subducted slab.

Western GB lavas are chemically distinct compared to other regions in the study area, showing little variation in MgO, K₂O, CaO/Al₂O₅, TiO₂/K₂O, Th/Rb, La/Sm, Rb/K, Ce/Ce*, Nb/Yb, ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd. Western GB lavas do show variation in radiogenic Pb and Ba/Nb values similar to central GB lavas.

Figure 3.10 further explores compositional trends for the GB, eastern and western ACA lavas by comparing $\delta^{18}\text{O}$ values with LREE/HREE and LILE/HFSE ratios.

Comparing Ba/Nb with La/Yb ratios (Figure 3.10): for central GB lavas, Ba/Nb varies little while La/Yb increases with silica content. Unlike lavas from the central GB, subalkaline and alkaline lavas of the western GB shows positive correlations for Ba/Nb and La/Yb, as alkaline lavas trends along a line with lower Ba/Nb values compared to subalkaline lavas. Lavas from eastern ACA region behave similarly to central GB lavas; however the range in Ba/Nb values is much larger (up to 300) with Ladybug Peak scoria possessing the greatest values (ca.565). There is overlap between alkaline and subalkaline lavas, though subalkaline lavas generally have higher Ba/Nb values. For western ACA and westernmost part of the ACA lavas, only mafic (basaltic) lavas show a positive trend (increasing Ba/Nb values with increasing La/Yb values).

3.4.2 *Origin of Melts*

3.4.2.1 Mafic Melts (summary of Chapter 2)

Mafic melts (SiO₂ < 57 wt%, Mg# > 0.55) from the study area were examined in

Chapter 2 (*see Figure 2.9*) that summarizes the variation in components influencing the source melts within the GB and ACA regions. In general, the basaltic lavas from the study area with $Mg\# > 0.55$ closely follow an idealized olivine-clinopyroxene fractionation trend (Harker 1909). Many of the lavas contain phenocrystic olivine and clinopyroxene along with plagioclase implying that the initial magma evolution was at relatively high pressure under hydrous and/or non-hydrous conditions (>8 kbar, Green & Ringwood 1967, Green & Hibberson 1970).

Also noted was a high abundances of LILE and LREE and low abundances of HFSE in for all lavas, indicating a subduction setting and the chemical profile can be attributed to involvement of fluids transported into the mantle wedge from the subducted slab (Bacon 1990, Leeman et al. 1990, Hughes 1990, Baker et al. 1994, Borg et al. 1997). Similarly, correlation between primitive-mantle-normalized Sr/P ($(Sr/P)_{pmn}$) values and $(Sr/LREE)_{pmn}$ previous workers have used higher $(Sr/P)_{pmn}$ values as a proxy for slab-derived components in the mantle wedge (Borg et al. 1997). Increases in $(Sr/P)_{pmn}$ for mafic lavas from western ACA, from Lousetown and sample 01-LT-53 from the Carson Range, are consistent with more intense fluid fluxing within mantle sources overlying the subducted slab. The $(Sr/P)_{pmn}$ values from the eastern ACA samples show a negative correlation with $^{87}Sr/^{86}Sr$, such that the samples with the most radiogenic Sr have the lowest added fluid flux. *Figure 2.9* also compares the data from mafic lavas to the modern south Cascade arc, intraplate lavas of the Mojave Desert, and extension-related volcanic rocks of the Western Great Basin (Cousens et al. 2008 and references therein). Mafic lavas from the GB have very low $(Sr/P)_{pmn}$ values compared to all other regions, indicating that the mantle source of GB lavas had a low fluid flux from the subducting

Farallon plate. Moving westward, $(\text{Sr}/\text{P})_{\text{pmn}}$ values increase, which may indicate increasing contribution from slab fluids to the melts, similar to the modern South Cascade volcanic rocks. In summary, the “slab fluid signature” is strongest for ACA mafic lavas, and less prevalent for GB mafic lavas. The higher fluid content increased the melt- F for ACA lavas. The diminished signature towards central GB could have been formed by lesser metamorphic dehydration of the altered oceanic crust during flat subduction below the CLM (e.g. Hawkesworth et al. 1990, Gallagher & Hawkesworth 1992).

Nd-Sr isotopic data for mafic lavas plot along a mixing line similar to that of Figure 2.15, joining a South Cascade mantle wedge end-member and an isotopically enriched end-member having Sr and Nd isotopic compositions similar to those of the continental crust (e.g. DePaolo & Wasserburg 1979) or an enriched CLM (e.g. Ormerod et al. 1988 1991, Cousens et al. 2008).

3.4.2.2 Intermediate Melts

The intermediate lavas (andesites and dacites) are the most abundant rock type that erupted throughout the study area. Whereas the mafic rocks are likely to retain the characteristics of their mantle source, some modified by low degrees of crystallization, the more evolved rocks have undergone differentiation and possible crustal contamination.

GB and ACA intermediate lavas may be the result of intracrustal fractional crystallization of primary basaltic magmas, which originated by partial melting of mantle peridotite metasomatized by the slab (LILE-enriched) fluids (Tatsumi 1989, Ormerod et al. 1991). Major and trace element characteristics of the intermediate lavas indicate, for the most part, a shared geochemical evolutionary history with the basaltic melts that

originate from a peridotite mantle source (Figure 3.4). Figures 3.5 and 3.6 show that intermediate lavas are recognized for their amphibole-bearing phenocryst assemblages and apatite fractionation, which is greatest within the GB intermediate lavas compared to the ACA lavas. GB and ACA intermediate lavas show parallel REE profiles generally increasing with silica content. Eu-anomalies are largest within intermediate lavas from the central GB compared to western GB and ACA intermediate lavas. Selected GB and eastern ACA intermediate lavas show steepening HREEs ($(\text{Dy/Yb})_{\text{pmn}}$ up to 1.6 for eastern ACA lavas and 1.7 for central GB lavas) compared to western ACA lavas. Geologic evidence for crustal thickening in the GB correlates with trace element support for increasing amphibole to clinopyroxene ratios in residual and fractionating mineral assemblages. Steepening HREE profiles are more likely to indicate partial melting of a garnet-bearing source, which could be the eclogitic lower crust. I shall explore this further in the next paragraph.

High-K intermediate lavas (especially within central GB with K_2O values up to 5.8 wt %), along with high Sr/Y and La/Yb ratios for the GB and selected ACA volcanic rocks, trend to “adakite”-like values. Adakite magmas are felsic to intermediate melts thought to be produced by partial melting of eclogitic subducted slab (Drummond & Defant 1990) or the mafic lower crust (e.g. Rapp et al. 2002). Adakites show the following geochemical and isotopic characteristics: $\text{SiO}_2 \geq 56$ wt%, $\text{Al}_2\text{O}_3 \geq 15$ wt%, MgO normally < 3 wt%, $\text{Sr} \geq 400$ ppm, $\text{Y} \leq 18$ ppm, $\text{Yb} \leq 1.9$ ppm, $\text{Ni} \geq 20$ ppm, $\text{Cr} \geq 30$ ppm, $\text{Sr/Y} \geq 20$, $\text{La/Yb} \geq 20$, and $^{87}\text{Sr}/^{86}\text{Sr} \leq 0.7045$ (Defant & Drummond 1990). Key adakitic geochemical signatures, such as low Y and Yb concentrations and high Sr/Y and La/Yb ratios, is shown in Figure 3.12. The P-T conditions of the Farallon plate between 3 and 40

Ma would not have been sufficient for melting of the subducted slab (Rapp et al. 1999), especially in the GB. Higher-K melts may also result from partial melting of garnet peridotites (Van Kooten 1980, Ducea & Saleeby 1997, Putirka & Busby 2007), which would require melting depths of >70 km (Kinzler 1997). Trace element data, however, indicate that melting occurred at a depth within the spinel peridotite field, between 70 and 35 km. Underplating of mantle-derived, basaltic melts near or at the crust-mantle boundary may also be the cause of crustal growth within the southwestern North American plate providing a transitional zone which grades from lower crustal mafic rocks in granulite facies to eclogites at near-upper mantle depths (Griffin & O'Reilly 1987, Toft et al. 1989, Rapp & Watson 1995). Partial melting of the thickened mafic (lower) crust (amphibolite, garnet amphibolite or eclogite) is a possible mechanism for the generation of intermediate lavas, which would result in a steepening HREE pattern I see in selected intermediate lavas. For example, isolated GB lavas have $(Dy/Yb)_{pmn}$ as high as 1.6 (namely an andesite from Bell Mountain (04-LT-45), a dacite from Stillwater Range (04-LT-43) and a trachyandesite from Clan Alpine Range (11-CN-11)), which may indicate some added component from the lower crust. Mafic melts mixing with dacitic partial melts of thickened eclogitic lower continental crust would result in increased K_2O , LREE and Nb values but decreased HREE and Y to produce intermediate compositions.

3.4.3 Assimilation vs. Fractional Crystallization

Coupled assimilation-fractional crystallization provides a possible explanation for the observed trace element and isotopic properties observed in many of the GB and ACA magmas. Olivine, plagioclase, Fe-Ti oxides and pyroxene are involved for all lavas during fractional crystallization as seen from the trace element patterns of Ni, V, Sc and

Sr when compared against SiO₂. All mafic lavas with SiO₂ > 52 wt% show an increase in (La/Sm)_{pmn} values with increasing silica content. Amphibole and garnet influence the slope of the REE pattern because garnet incorporates the HREEs and amphibole preferentially incorporates the MREEs with respect to both LREE and HREE. Slopes for both MRE and HRE elements are highest in the central GB lavas.

As mentioned earlier, all lavas contain varying degrees of enrichment in LIL and LRE elements as well as a depletion in HFS elements, which suggests geochemical influence from slab fluids. The primary melts may also be modified by variable degrees of partial melting and/or mixing with an enriched lithospheric mantle and/or overlying continental crust, which largely consists of Sierra Nevada granitoids with distinctively low P₂O₅/K₂O, high present-day ⁸⁷Sr/⁸⁶Sr, and high Rb/Sr compared to ACA and GB mafic rocks.

The question of contamination at the source versus from the crust can be discriminated using Sr, Nd, Pb and O isotope data. Whereas radiogenic isotopes exhibit the characteristics of the melt at the source (radiogenic isotopes are not altered by crystal-liquid equilibria such as crystal fractionation), oxygen isotopes will show changes in the isotope ratio with crystal fractionation (Rollinson 1998, Faure 2005). High δ¹⁸O values (>+9 ‰) can ultimately be produced only as a result of the action of surface or near-surface processes during sedimentation, diagenesis, or hydrothermal alteration at relatively low temperatures since oxygen isotope fractionation is temperature-dependent (Faure 1986). The upper mantle (asthenosphere) has a restricted O-isotopic composition with a δ¹⁸O value of ca.+5 to +6‰ (Hoefs 2005). Closed-system differentiation through crystal fractionation of a parental basaltic magma at igneous temperatures will produce evolved melts enriched in δ¹⁸O by no more than about 1 ‰ (Kempton & Harmon 1992).

Thus the mafic lavas from this study with $\delta^{18}\text{O}$ values of +7 to +8.5 cannot have been derived from the asthenospheric mantle through a simple partial melting-fractional crystallization process.

In continental arc systems the differences in O-isotopic composition can be generated by variations in mineralogy, variations in temperature of crystallization, fluid/rock interaction (i.e. metasomatism), and difference in end-member isotopic inhomogeneity in the mixing of two (or more) magmas. Processes that involve variations in mineralogy or magma crystallization have little effect in generating the higher O-isotopic values I see for the ACA and GB lavas (Hoef 2005). Plausible primary mixing phenomena can be subdivided into: (a) direct mixing of magmas; (b) partial to extensive assimilation of country rocks by magmas; (c) mixing within the source materials prior to or during melting; (d) isotopic exchange between the magmas and their country rocks, without physical assimilation; (e) any combination or permutation of the above (Faure 1986).

To distinguish if the compositional variation of the Cenozoic magmas were affected by these phenomena (assimilation) and/or fractional crystallization, I compare O-isotopic data with $^{87}\text{Sr}/^{86}\text{Sr}$ as well as with $\text{CaO}/\text{Al}_2\text{O}_3$, and Rb/K with Rb (Figure 3.11). Positive correlations of $\delta^{18}\text{O}$ with both $^{87}\text{Sr}/^{86}\text{Sr}$ (*assimilation*) and $\text{CaO}/\text{Al}_2\text{O}_3$ (*fractional* crystallization) for GB and ACA lavas are a result of the two different mechanisms: fractional crystallization and mixing with a higher $\delta^{18}\text{O}$ component at some time prior to extrusion (AFC: assimilation-fractional crystallization; Tyler 1980, DePaolo 1981, Thompson et al. 1990). Note that the $\delta^{18}\text{O}$ data is from mafic lavas only, which indicates that the $\delta^{18}\text{O}$ enrichment is obtained from the source. Limitations to diagrams

A and B are lack of $\delta^{18}\text{O}$ information from intermediate lavas. Figure 3.11C, however, does include Rb/K information from mafic and intermediate lavas from all regions in the study area. The concave-down pattern, particularly with central GB lavas, cannot be produced if only fractional-crystallization processes are involved with magma evolution. The pattern seen in Figure 3.11C from central GB and (to some extent) eastern ACA lavas requires the combined of fractional crystallization and assimilation with crustal materials (Davidson et al. 1987). Combined with major and trace element data indicate that the co-genetic mafic to intermediate rocks from central GB and eastern ACA developed by crystal-liquid fractionation associated with a minor amount of assimilation. The lack of large volumes of mafic compositions in the GB may be due to the inability for mafic melts to penetrate through the thick crust, resulting in greater time for melts to evolve and potentially achieve greater degree of assimilation, which is consistent with what I see in Figure 3.11 (Putirka et al. 2003, Putirka & Busby 2007, Putirka et al. 2012).

The Sr-O isotopic heterogeneity of the melts within the ACA and central GB can be attributed to the magma-crust interaction. The lavas from the study area are situated, for the most part, above Phanerozoic crust (opposed to the stable Precambrian crystalline craton, Kistler & Peterman 1978, Farmer & DePaolo 1981), as established by the 0.706 line shown in Figure 3.1 (Kistler & Peterman 1978, Wooden et al. 1999). The metasedimentary and metaigneous basement rocks of the GB and ACA were tectonically thickened by Mesozoic continental subduction (much like present-day Andes, Isacks 1988, Dickenson 2006, Henry 2008), the Laramide orogeny (Humphreys 1995) and the western ACA region had the addition of voluminous granitic plutons of the Sierra Nevada Batholith. It is also likely that deep-seated magmas may have also been

emplaced underneath the GB due to mafic underplating (e.g. Kempton et al. 1990, Surpless et al. 2002, Wannamaker et al. 2004). I propose that it is this process of AFC magmatic evolution, which includes the interaction between asthenosphere-derived melts, the lithospheric mantle and the continental crust, explains the results I see in Figure 3.11. Melts derived within the Western GB, however did not seem to be subjected to the same level of AFC (if at all) compared to other GB lavas and selected eastern ACA lavas. Elevated Ba/Nd suggests some influence from slab fluids, and variable $^{87}\text{Sr}/^{86}\text{Sr}$ ratios indicate contributions from the lithospheric mantle. Other major, trace element and isotopic ratios seen in Figure 3.9, however, suggests that GB extension affected the western GB resulting in thinner or fractured lithosphere, beneath which mantle-derived melts are able to make it to the surface.

Figure 3.12 summarizes the various stages for magmatic generation and evolution across the east-west transect that may explain the geochemical result presented in this chapter. Ca. 35 Ma, rollback of the Farallon plate in the central GB underneath thickened crust (Figure 3.12A) generated melts within the deep lithospheric mantle (as deep as the lowermost spinel-stability field). Magma chambers are situated at the crustal-lithospheric mantle boundary as well as in the deep Proterozoic crust where magma evolution proceeded by AFC. Magma chambers are periodically replenished by basaltic melts, producing a wide variety of mafic, intermediate and felsic magmas. By ca. 12 Ma extension is active within the westernmost GB, Carson Range (12 Ma) and Pyramid Lake area, and rollback is well established in the western GB. Lavas with notably enriched signatures (e.g. higher Ba/Nb and La/Yb ratios) reflects contributions from an enriched (hydrated) lithospheric mantle. A thinner, (perhaps fractured) crust accelerates extrusion

of the magmas to the surface. The slab continues to roll back and steepen beneath the ACA (Figure 3.12C). Larger volumes of mafic to intermediate magmas are generated in the eastern ACA by partial melting at the asthenospheric-lithospheric mantle boundary then subject to fractional crystallization and less affected (if at all) by assimilation of the continental crust. The resurgence of more mafic volcanism in the western and westernmost part of the ACA possess depleted isotopic signatures (Sr, Nd and O) and are progressively younger, suggesting deeper sources (Farmer et al. 1989, Cousens et al. 2011), consistent with the findings presented by Lee et al. (2001). Interaction between mafic melts and younger, less enriched sub- Sierra Nevada lithospheric mantle in westernmost part of the ACA results in lower Sr-isotopic values compared to other regions in the study area

3.4.4 *Compositional Gap*

We have noted earlier a compositional “gap” for melts extruded within the ACA (a small but notable gap within the eastern ACA as well as a larger gap within the western ACA, Figure 3.4). This absence of compositions with SiO₂ values between 66 and 68 wt% for eastern ACA lavas (a small but notable gap), as well as for western ACA lavas, 55 to 57 wt %, and between 65 to 70 wt%, may be due to a mini-form of a “Daly Gap”. Is this compositional gap due to fractionation within two distinct compositional suites on either side of the gap, or did the fractionation span the gap yet certain fractionation-produced liquids fail to reach the surface? I observe that mantle-derived mafic extrusives are more voluminous in the ACA than in the GB, and that these melts have undergone AFC processes to form intermediate and felsic magmas, with comparable ranges in incompatible trace elements (Ba/La, La/Nb, and Sr) and radiogenic isotopes.

The major element data suggest that to bridge the mini-gap in the fractionating assemblage would involve clinopyroxene ($\text{CaO}/\text{Al}_2\text{O}_3$), plagioclase ($\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O}$), Fe-Ti oxides (Fe_2O_3 and TiO_2) and apatite (P_2O_5). Grove & Donnelly-Nolan (1986) have recognized this form of compositional gap in lavas at Medicine Lake Volcano in California, and, similar to the lavas from western ACA, the workers noted that lavas from Medicine Lake Volcano underwent fractional crystallization as well as assimilation of continental crust. Grove & Donnelly-Nolan (1986) suggested that these gaps resulted from a flattening of the solidus curve in temperature-composition space; that is, large changes in composition during fractional crystallization over a small temperature interval. This observation has been supported by other workers (e.g. Rutherford et al. 1985), such that the solidus slope changes when olivine is replaced by low-Ca pyroxene or amphibole in the fractionating assemblage. Although I see no discernable petrographical evidence for this gap in the mineral assemblage (i.e. the compositional gaps are very small), it is possible that these compositional gaps result from the free energy surface of the liquid and does not therefore depend on the solid phases involved (Grove & Donnelly-Nolan 1986). The frequent occurrence of zoned plagioclase phenocrysts as well as the resorption textures seen in many of the phenocrysts phases suggest that disequilibrium conditions took place during the evolution of the melt, with evidence for additional pulses of MgO-rich magma (Cousens et al. 2008). The liquid line of descent is interrupted by the injection of a fresh batch of hot, undifferentiated magma, causing the system to convect. The change in composition caused rapid crystallization of mineral phases within a small temperature range, rather than sizable changes in temperature.

3.5 Conclusions

Volcanic rocks between 35 and 3 Ma from 51 locations across an east-west transect spanning from the central Great Basin in Nevada to the Sierra Nevada in California were analyzed for their major, trace element and Sr-Nd-Pb-O isotopic geochemistry. I observe that there is no simple ingredient that can be mixed with a primary mafic magma to produce the observed trace element and isotopic compositions of intermediate to felsic lavas from the study area. The geochemical data, however, do provide us with the following observations:

1. Lavas from the study area can be chemically divided into five distinct regions along the east-west transect: Central GB, Western GB, eastern ACA, western ACA and westernmost part of western ACA.
2. Most magma originated from mantle within the spinel stability field that was variably modified by the subducted slab fluids, including sub-continental lithospheric mantle, after whichj crustal components were added by assimilation. The lavas follow an olivine-pyroxene-oxide+/-hornblende fractionating trend.
3. All lavas have an “arc signature”, which is strongest in the west (ACA lavas) and weakest in the east (central GB lavas).
4. Western GB lavas are chemically distinct compared to other regions in the study area, showing little variation in MgO, K₂O, CaO/Al₂O₅, TiO₂/K₂O, Th/Rb, La/Sm, Rb/K, Ce/Ce*, Nb/Yb, ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd. Western GB lavas do show variation in radiogenic Pb and Ba/Nb values similar to central GB lavas.
5. Oxygen isotope results from the GB and ACA lavas show $\delta^{18}\text{O}$ values between

+8.54‰ to +6.3‰, consistently higher than upper mantle values (+5.5 to +6.0, Hoefs 2004). GB lavas have the overall highest $\delta^{18}\text{O}$ values (+7.09 to +8.54), whereas eastern ACA lavas have an intermediate range (+7.21 to +8.01) and western ACA lavas include the lowest values (+6.3 to +8.04). The overall $\delta^{18}\text{O}$ range of up to +3‰ above MORB-mantle values demonstrate that primary melts were mixing with, or (more likely) derived from sources with higher oxygen isotopic values than modern upper mantle. There is a synchronous increase in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and decrease in $^{143}\text{Nd}/^{144}\text{Nd}$ with increasing $\delta^{18}\text{O}$. Incorporation of higher $\delta^{18}\text{O}$ values into mafic magmas is thought to originate from mixing with the modified lithosphere.

6. Evolution of central GB and (to a lesser extent) eastern ACA lavas were subject to AFC processes in which fractional crystallization is accomplished by differentiation within the magma chamber and subsequent mixing with melts from the garnet-bearing lower crust (higher $(\text{Dy}/\text{Yb})_{\text{pmn}}$ values) and/or upper crust (decreasing Rb/K with increasing Rb values).
7. Both mafic and intermediate lavas from the western GB shows little variation in incompatible trace element and Sr-Nd-isotope ratios. Despite this, increases of LILEs with increasing LREEs in combination with higher $^{87}\text{Sr}/^{86}\text{Sr}$ in basalts with lower Sr/P values suggest that western GB lavas were still subject to contributions from an enriched lithospheric mantle and a dehydrating slab. Further interpretation of this data suggests a thinning lithosphere and faulted crust.
8. Mafic and intermediate lavas from the westernmost part of the ACA were originated from primary melts are derived from the mantle wedge then mixed

with low Rb/Sr components from the sub- Sierra Nevada lithospheric mantle that resulted in a different mixing array: lower $^{87}\text{Sr}/^{86}\text{Sr}$ values for equal $^{143}\text{Nd}/^{144}\text{Nd}$ values compared to the other lavas from most of the study area.

9. A small but notable compositional gap exists for eastern ACA and western ACA lava suites, a mini “Daly Gap”. I suggest that these compositional gaps formed during fractional crystallization within multi-leveled magma chambers located at the crustal-mantle boundary and/or within the deep Proterozoic crust.

Figure 3.1 Digital elevation map of eastern California and western Nevada showing the study area.

The region is divided into three parts: Great Basin (GB), eastern Ancestral Cascades Arc (Eastern ACA) and western Ancestral Cascades Arc (Western ACA). The symbols represent the various compositions of the volcanic samples included in the study (see legend). The western edge of the Precambrian continental basement lies just outside of the study area, as is indicated by the 0.706 isopleth (modified from Kistler & Peterman 1978, Wooden et al. 1999). Nevada Caldera Belt obtained from Henry & John (2013), edge of Ancestral Cascade Arc obtained from Cousens et al. (2008), and southern edge of Farallon Plate (Juan de Fuca Plate) obtained from Atwater & Stock (1998).

Figure 3.2 (A) Looking up a mafic lava flow in the region of the Stillwater Mountain Range (sample 04-LT-42). (B) Series of basaltic trachyandesite lava flows ca. 12 Ma in the Truckee Range (04-LT-02). Portion of hammer tip is about 10 cm. (C) Andesite porphyry mound within the city of Sparks (04-LT-30) (D) 3.6 Ma Andesite from Ellis Peak, Sierra Nevada in California (04-LT-55).

Figure 3.3 Alkali-silica diagram (Le Bas et al. 1986) for lavas from the GB (open plus sign), Eastern ACA (solid triangles) and Western ACA (open squares).

LEGEND

Western ACA

△ Stanford/Twin Peaks	✦ Lowell Ridge
△ Stampede Reservoir	✦ Boreal Ridge
□ Verdi Lookout	✦ Castle Peak
■ Squaw	✦ Ladybug
◇ Sierraville-Portola	✦ Bald Mountain
◆ Serene Lakes	▽ Dog Valley
○ Sawtooth	▽ Henness Pass
● Castle Peak Trail	○ Portola
✦ Ellis Peak	● Susanville
★ Pond Terrace	
★ Mt. Lincoln	
✦ Devil's Peak	

Eastern ACA

△ Sparks	✦ Flowery Peak
△ Lake Tahoe	▽ Carson Range
■ Reno	
◇ Reno East	
◆ SW Virginia City	
○ Virginia City	
● Pyramid	
✦ Pyramid South	
✦ Kate Peak	
✦ Clark Mountain	
✦ Rattlesnake	
✦ Lousetown	

GB

△ Clan Alpine	✦ Virginia Range
△ Desatoya Mountains	○ Soda Lake
▽ Desatoya Latite	● Hotsprings Mountains
□ Stillwater Range	
■ Bell Canyon	
◇ Bell Mountain	
◆ Lone Rock	
● Table Mountain and Churchill Butte	
✦ Lahontan Mountains	
✦ Truckee Range	
✦ Churchill (8 Ma)	
✦ Churchill (12 Ma)	

Figure 3.4 Harker diagrams (Harker 1909) showing variations in major and trace elements with silica content for lavas from the GB (right column), eastern ACA (middle column) and western ACA (left column). Major elements and trace elements are presented in weighed percent and parts per million respectively. Symbols represent the locations within each region (see legends).

Figure 3.5 Chondrite normalized rare-earth element plots (Sun and McDonough 1989) for mafic and intermediate rocks from the GB (right column), Eastern ACA (center column) and Western ACA (left column).

Figure 3.6 Primitive mantle normalized incompatible element diagrams (Sun & McDonough 1989) for mafic and intermediate rocks from the GB (right column), Eastern ACA (center column) and Western ACA (left column).

Figure 3.7 A: Diagram showing Nd-Sr isotope variations for volcanic lavas across the study area. Symbols represent the 5 regions identified in the text. On the left-hand side column is the effect of varying proportions of Sierra Nevada Batholith (from Rotberg 2008, northern transect granodiorites sampels G06, G09, G10) with MORB values outside the field of view (from Workman & Hart 2004).

B: $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ plot showing the field for GB, Eastern ACA and Western ACA lavas. Symbols respresent the various compositions (see legend). NHRL = Northern Hemisphere Reference Line (Zindler & Hart 1986).

Figure 3.8 Plots of $\delta^{18}\text{O}$ compared to: A) initial $^{87}\text{Sr}/^{86}\text{Sr}$ B) SiO_2 , C) Ti/Zr , and D) $(\text{La}/\text{Sm})_{\text{pmn}}$, where pmn = primitive mantle normalized. The symbols represent the various regions across the study area (See legend in Figure 3.S3): open plus sign = GB, closed triangles = Eastern ACA, and open squares = Western ACA. See text for discussion.

LEGEND

- ▲ Basalt
- Basaltic Andesite
- Basaltic Trachyandesite
- ◆ Andesite
- ◇ Trachyandesite
- Dacite
- Trachyte
- ✕ Rhyolite

Figure 3.9 Graphs comparing major, trace element and isotopic ratios with longitude and age for the entire study area. Symbols represent composition as shown in the legend in Figure 5. Major elements are presented in weighted percent. See text for discussion.

Figure 3.10 Plots of A) $\delta^{18}\text{O}$ as well as B) Ba/Nb versus La/Yb for ACA and GB lavas. Symbols represent composition (see legend). See text for discussion.

Figure 3.11 Plots of (A) $\delta^{18}\text{O}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ (*assimilation*) highlighting the five regions within the study area, (B) $\delta^{18}\text{O}$ versus $\text{CaO}/\text{Al}_2\text{O}_3$ (*assimilation and/or fractional crystallization*) and (C) Rb/K vs. Rb (ppm). Positive correlations of $\delta^{18}\text{O}$ with both $^{87}\text{Sr}/^{86}\text{Sr}$ and $\text{CaO}/\text{Al}_2\text{O}_3$ (*fractional crystallization*), and the strong trends evident for Rb/K fractionation with increasing Rb for GB and ACA lavas are a result of varying degrees of two different mechanisms: fractional crystallization and mixing with a crustal-like component at some time prior to extrusion (AFC: assimilation-fractional crystallization; Tyler 1980, DePaolo 1981, Thompson et al. 1990). See text for further discussion.

Figure 3.12: Cartoon showing stages of melting across the study area: (A) rollback of the Farallon plate ca. 35 Ma in the GB underneath thickened crust. Melts are generated within the deep lithospheric mantle and possibly accumulate at the crust-mantle boundary forming mafic underplating. Magma chambers are situated in the deep Proterozoic crust where they underwent magma-lower crust interaction as differentiation proceeds through complex AFC, which mainly takes place at the crust-lithospheric mantle boundary. Magma chambers are replenished by basaltic material, producing a wide variety of (some mafic), intermediate to felsic melts. (B) rollback continues in the wGB ca. 14 to 8 Ma, notably enriched signatures (e.g. higher Ba/Nb and La/Yb ratios) reflects contributions from an enriched (hydrated) lithospheric mantle. A thinner, (perhaps fractured) crust accelerates extrusion of the melts to the surface. (C) The slab continues to descend ca. 10 to 5 Ma and mafic melts are generated by partial melts at the asthenospheric-lithospheric mantle boundary as well as at the crust-lithospheric boundary. In the case of the wARC and wwARC, the lithospheric mantle may have been thinned and melts are sourced deeper in the asthenosphere and form multi-levelled magma chambers where magmatic evolution takes place through FC processes.

Table 2.1 $^{40}\text{Ar}/^{39}\text{Ar}$ Ar ages for selected Tertiary lavas from the Great Basin and Eastern ACA.

Sample*	Rock Type	Location	Latitude	Longitude	Material	Plateau		Inverse Isochron		$^{40}\text{Ar}/^{39}\text{Ar}_i$		MSWD	
						age (Ma)	$\pm 2\sigma$	$^{39}\text{Ar}(\%)^{\dagger}$	age (Ma)	$\pm 2\sigma$	$\pm 2\sigma$	$\pm 2\sigma$	$\pm 2\sigma$
11-CN-02	Basaltic andesite	CCQ Virginia Range	39.4677333	119.209267	Sandstone	11.80	0.44	90.2	11.8	1.0	292	27	1.9
11-CN-04	Andesite	CCQ East	39.2801667	118.397700	Whole Rock	6.60	0.20	55.0	6.60	0.18	287	9	1.19
11-CN-05a	Basaltic andesite	CCQ East	39.2970167	118.323417	Whole Rock	8.21	0.52	94.5	8.12	0.7	296	23	1.3
11-CN-06	Basaltic andesite	Churchill 12	39.2715167	119.174933	Whole Rock	13.20	1.00	100	13.30	1.6	293	19	0.094
11-CN-11	Trachyandesite	Clan Alpine Mountains	39.5615167	117.829667	Whole Rock	24.02	0.49	79.3	24.40	1.3	270	39	3.00
11-CN-15	Basaltic trachyandesite	Rainbow Mountain	39.4055333	118.539967	Whole Rock	9.06	0.52	80.3	10.60	1.5	277	16	0.82
08-LT-17	Andesite	Lake Tahoe East	39.2391000	117.774050	Biotope	9.37	0.16	83.8	9.46	0.23	289	11	0.89
11-CN-18	Rhyolite	Desotoya Mountains	39.2404333	117.783867	Whole Rock	26.09	0.32	84.7	26.16	0.41	297	48	2.9
11-CN-26A [§]	Andesite	Stillwater Mountains	39.9172833	117.974367	Whole Rock	137.20	2.80	70.8	142.8	2.70	233	14	1.5
11-CN-26B [§]	Andesite	Stillwater Mountains	39.9172833	117.974367	Whole Rock	145.60	2.10	100.0	154.0	4.90	232	21	5.7

Note: MSWD = mean square of weighted deviates

*The samples were analyzed at the Noble Gas Laboratory, Pacific Centre for Isotopic and Geochemical Research, University of British Columbia, Vancouver, BC, Canada (Koppers 2002, Ludwig 2003, Kuiper et al. 2008).

[†] ^{39}Ar = percentage of ^{39}Ar used to define plateau age.

§ Samples have the age >40 Ma, which is out of range for this study and therefore not included in the database. Results are presented for publication. 11-CN-26A: the Inverse Isochron Age is the best estimate of age due to initial ratio lower than atmospheric. 11-CN-26B: not a clear result. The Inverse Isochron Age is probably a more valid age because the initial argon ratio is much lower than air argon; however, the MSWD is >1, indicating scatter around the isochron. The plateau age is calculated using air initial argon, so will be inaccurate if the trapped argon has a value differing from air.

Sr, Nd and Pb analyses were completed for 11-CN-26A: Sr = Nd = $^{206}\text{Pb}/^{238}\text{Pb}=20.1613$, $^{207}\text{Pb}/^{235}\text{Pb}=15.6654$, $^{208}\text{Pb}/^{232}\text{Pb}=39.8331$

Sr, Nd and Pb analyses were completed for 11-CN-26B: Sr = Nd = $^{206}\text{Pb}/^{238}\text{Pb}=19.6389$, $^{207}\text{Pb}/^{235}\text{Pb}=15.5955$, $^{208}\text{Pb}/^{232}\text{Pb}=39.9670$

Table 2.2 Oxygen isotopic data from selected Tertiary lavas across the study area.

Sample	Location	Rock Type	Age Ma*	$\delta^{18}\text{O}$ (‰ VSMOW)	Reference
GB					
11-CN-01	CCQ Virginia Range	Basaltic Trachyandesite	11.8	7.87	This Study
04-LT-51	Bell Canyon	Basaltic Andesite	13	7.86	This Study
11-CN-09	Stillwater Range (La Plata Canyon)	Basalt			This Study
04-LT-09	Hotsprings Mtns	Basaltic Trachyandesite	9.8	8.07	This Study
04-LT-42	Stillwater Range	Basalt	20.02	7.69	This Study
GD-03-10	Lone Rock Carson Sink	Basaltic Trachyandesite	9.97	7.39	Arehart & Coolbaugh 2006
04-LT-03	Truckee Range	Basaltic Trachyandesite	9.6	7.09	Cousens et al. 2008
11-CN-13	Salt Wells Lahontan Mtns	Basaltic Andesite	4.23	7.47	This Study
eARC					
01-LT-50	Carson Range	Trachyandesite	Unknown	8.01	Cousens et al. 2008
01-LT-53a	Carson Range	Basalt	12	7.21	Cousens et al. 2008
01-LT-47	Carson Range	Basaltic Trachyandesite	Unknown	7.56	Cousens et al. 2008
01-LT-58b	Lousetown	Basalt	7.55	6.73	Cousens et al. 2008
wARC					
97-LT-90	Squaw	Basaltic Andesite	5	6.3	Cousens et al. 2008
04-LT-17	Boreal Ridge	Basaltic Trachyandesite	7.4	7.61	Cousens et al. 2008
Towle#1	Sawtooth	Basalt	3.82	6.3	Cousens et al. 2008
01-T-39	Mt. Lincoln	Basalt	7	7.41	Cousens et al. 2008
Towle#2	Lowell Ridge	Basaltic Andesite	16.34	8.04	Cousens et al. 2008
01-LT-26	Ladybug scoria	Basalt	10.4	7.7	Cousens et al. 2008
97-LT-82	Ladybug	Basaltic Andesite	10	7.1	Cousens et al. 2008
01-LT-33	Dog Valley Babbitt Peak	Basalt	4	6.32	Cousens et al. 2008
04-LT-83	Portola	Basalt	10	6.69	Cousens et al. 2008

Standards and duplicate analyses located in Appendix E

Sample analyses for this study were completed at the Laboratory for Stable Isotope Science (L.S.I.S.),
University of Western Ontario, Ontario, Canada.

* Whole numbers are geologic ages. Decimal numbers are radiometric ages.

$$\delta^{18}\text{O} = ((\delta^{18}\text{O} / \delta^{16}\text{O})_{\text{sample}} / (\delta^{18}\text{O} / \delta^{16}\text{O})_{\text{VSMOW}} - 1) \times 1000$$

Location		⁸⁷ Sr/ ⁸⁶ Sr	¹⁴³ Nd/ ¹⁴⁴ Nd	²⁰⁸ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁶ Pb/ ²⁰⁴ Pb	d18O	Ba/Nb	Ba/La	Th/La	Th/Ta	(Sr/P) pmn	Zr/Yb	(La/Sm) pmn	Nb/U
Central GB	Max	0.70567	0.51272	38.797	15.677	19.084	8.5	188.2	49.1	0.3	18.5	4.5	106.0	3.6	22.6
	Min	0.70411	0.51253	38.376	15.549	18.849	7.4	27.7	26.6	0.1	2.0	0.9	52.8	2.2	3.3
	Ave	0.70488	0.51264	38.586	15.604	18.960	7.9	104.0	34.8	0.1	7.3	1.7	74.2	2.9	9.5
Western GB	Max	0.70764	0.51271	38.641	15.627	18.941	8.1	251.8	71.3	0.1	6.2	4.7	105.0	3.1	20.5
	Min	0.70432	0.51262	38.348	15.555	18.825	7.1	46.2	26.5	0.1	2.3	0.6	61.0	2.4	6.6
	Ave	0.70477	0.51268	38.453	15.575	18.885	7.6	116.5	38.4	0.1	4.5	2.0	85.4	2.7	11.8
Eastern ACA	Max	0.70519	0.51280	38.802	15.659	19.050	7.6	551.1	63.6	0.4	36.4	4.6	147.9	4.8	24.3
	Min	0.70413	0.51261	38.322	15.533	18.851	6.7	41.7	21.4	0.0	2.3	0.7	41.9	2.1	0.9
	Ave	0.70464	0.51273	38.593	15.613	18.932	7.2	172.2	39.1	0.2	12.6	2.6	73.4	2.9	5.0
Western ACA	Max	0.70610	0.51281	38.801	15.687	19.125	7.7	423.6	53.9	0.5	65.5	5.0	81.9	4.4	7.5
	Min	0.70429	0.51257	38.464	15.573	18.890	6.3	100.2	26.7	0.1	5.5	1.3	42.7	2.1	0.7
	Ave	0.70490	0.51269	38.649	15.621	18.977	7.3	205.5	42.1	0.2	23.0	3.4	59.3	3.0	4.1
Westernmost ACA	Max	0.70426	0.51281	38.865	15.684	19.000	8.0	197.3	42.0	0.4	26.3	4.9	66.1	3.8	4.5
	Min	0.70366	0.51254	38.301	15.600	18.854	6.3	81.0	12.4	0.2	9.7	2.2	49.4	2.3	1.9
	Ave	0.70399	0.51265	38.578	15.629	18.916	7.3	142.8	27.8	0.2	16.5	4.2	55.7	2.8	3.2

Table 2.3: Maximum, Minimum and Average isotope and trace element ratios for Central GB, Western GB, Eastern ACA, Western ACA and Westernmost ACA.

4 Chapter: (PAPER 3) Arc to Post-Arc Related Cenozoic Volcanism in Central GB, Nevada to Sierra Nevada, California: A Comparative Geochemical Study

4.1 Introduction

Magmatism has been a major component of the geological evolution of the southwestern United States over the past 40 Ma. The variable contributions of slab-metasomatized mantle wedge, metasomatized lithospheric mantle, subducted slab and overlying continental crust to these igneous events is not clearly understood. Was magmatism triggered by slab decent into the mantle and upwelling of asthenosphere? How do the processes change as magmatism swept southwestward from central Great Basin (GB), across the Ancestral Cascade Arc (ACA) and into the Sierra Nevada? Were any of these processes the cause of postsubduction mantle melting, or are other factors involved?

The purpose of this study is to combine the trace element data and Sr-Nd-Pb and O isotopic characteristics from mafic to intermediate lavas across an east-west transect from central Great Basin to the Sierra Nevada that range in age from ca. 40 to <1 Ma. I examine the importance of crust-mantle interaction as a function of distance and geological time induced by flat-slab subduction, slab rollback and the opening of a slab window associated with formation of the San Andreas transform fault system (Atwater & Menard 1970, Cousens et al. 2008, 2011). The geochemical data for this large area of Cenozoic volcanism can provide a powerful tool in discriminating among the relative role of mantle sources, reveal the composition of the lower lithosphere, evaluate of the

structure of the magma-lithosphere interaction in ACA magmas, and reveal magmatic evolution over time and space.

I have compiled published major and trace element, Sr, Nd, Pb and O isotopic data, as well as Ar-Ar geochronology filling in what once were geochemical “gaps” for Cenozoic magmatic events extending from the central GB in Nevada through to ACA in the Sierra Nevada (SN) mountains in California (ca. latitude 37°). The data reveal the changing tectonic environment over the past ca. 40 Ma, including: 1) flat-slab subduction of the Farallon plate underneath the thickened North American crust (e.g. Kistler et al. 1981), 2) slab rollback and southwestward migrating ignimbrite and ACA magmatism (Colgan et al. 2008, Dickinson 2006, Du Bray et al. 2009, Farmer & DePaolo 1983, Farmer et al. 1989, Feuerbach et al. 1993, Henry et al. 1998, Humphreys et al. 2003, Humphreys 1995, Perry et al. 1993, Ryskamp et al., 2008; Valentine et al. 2006, Wooden et al. 1998), 3) extensional magmatism as the East Pacific Rise reaches the North American Plate margin replacing compression and subduction with shear stress and a transform plate boundary (that includes the San Andreas Fault and the Walker Lane) (Clynne 1990, Dickinson 1997, Atwater & Stock 1998, Stewart 1988, Best et al. 1989, Christiansen & Yeats 1992)., 4) post-ACA magmatism (Omerod et al. 1988, Elkins-Tanton & Grove 2003, Cousens et al. 2011, 2012) following the northward migration of the Pacific-Juan de Fuca (remnant of the Farallon Plate)-North American triple junction north of the study area, such that the current southernmost expression of the modern ACA volcanism (Cascades) is located at the Lassen Volcanic Region (e.g. Borg et al. 1997, Bacon et al. 1997). The youngest volcanic activity in the GB is mostly concentrated at the margins of the Great Basin (DePaolo & Daley 2000), specifically

along the western margin of the Colorado Plateau (Conway et al. 1997, Johnsen et al., 2010, Lee 2005, Smith et al. 1999, Tanaka et al. 1986), in southern Nevada (Feuerbach et al. 1993, Valentine et al. 2006), along the eastern margin of the Sierra Nevada (Ormerod et al. 1988, Rogers et al. 1995) and lesser so within margins of the Great Basin (Cousens & Henry 2008, Dickson 1997, McKee 1970, Smith et al. 2002, Stickney 2004, Valentine et al., 2006, Yogodzinski et al. 1996).

Between 35 and 3 Ma, the compositions of volcanic rocks in the western Great Basin range from mafic to felsic with intermediate lavas being the most abundant rock type. These lavas have been interpreted to be the result of fractional crystallization of primary basaltic magmas, which originate by partial melting of mantle peridotite metasomatized by a slab-derived large-ion lithophile (LIL)-enriched hydrous fluid (Cousens et al. 2008, Rapp & Watson 1995, Tatsumi 1989, Stevens 2013, Timmermans et al. *in preparation*). Post-ACA magmatism (<3 Ma) consists of intermediate to primarily mafic lavas that geochemically reflect a slab-window setting, the result of post-subduction melting of a sub-Sierra Nevada lithospheric mantle source (Cousens et al. 2011). The post-ACA magmas consist of a greater proportion of melt from an enriched mantle component and are less influenced by slab fluids from the subducting slab compared to the older ACA magmas (Cousens et al. 2011). From west to east (eastern California to central Nevada), this lithospheric mantle source signature disappears in < 3 Ma volcanic centres and is replaced by intraplate, asthenospheric mantle sources (Cousens et al. 2012, 2013). Some geochemical variation also may be due to assimilation of crustal material that is the cause of additional regional trace element and isotopic variation.

Our goal is to further understand nature of the relationship between the compositions of the source melts to the subsequent magmatic evolution and assimilation with the surrounding rock over space and time. The variety of possible components influencing the original melts is complex and changes over time and space: these include the subducting Farallon slab, the continental lithospheric mantle (CLM), convecting upper mantle, and the accreted or cratonic upper and lower crust. I utilize geochemical data for magmatic products from the Eocene to Pleistocene to assess the overall trends seen through space (from the Fish Creek Mountains in central GB through to west of the Lake Tahoe region into the Sierra Nevada) and time (from ACA volcanism (35 to 3 Ma) to post-ACA volcanism (<3 Ma).

4.2 Geological Setting

4.2.1 Regional Tectonic Setting

The Cenozoic geological setting for the region is described by Dickinson 2006 and references therein. The post-subduction geological setting is described in Cousens et al. (2011 2012 2013). Cenozoic volcanism began at ca. 40 Ma and included ash-flow tuffs associated with the southward-migrating “ignimbrite flare-up” (Henry & John (2013) and references therein). Calc-alkaline volcanism began in the central GB ca. 35 Ma, then migrated southwestwards settling within the ACA. Detailed investigations of volcanic ash-flow tuffs flowing down paleovalleys in the GB and SN (e.g. Henry et al. 2003) and paleobotanical evidence from species that exist at known climates (e.g. Wolfe et al. 1998) have indicated that during the ignimbrite flare-up the GB was at a higher elevation compared to the Sierra Nevada at the time of eruption. In western Nevada ignimbrite volcanism terminated by 22 Ma, followed by the early development of the

Walker Lane, a zone of dextral faulting in the northwestern Great Basin that accommodates nearly 15%–25% of the Pacific–North American plate motion (Fosdick & Colgan 2008, Atwater & Stock 1998, Faulds et al. 2005). Bimodal volcanism has been linked to GB extension that began as early as ca. 13 Ma within the study area (Stewart 1988, Best et al., 1989, Christiansen & Yeats 1992). Between 13 and 3 Ma, coincident with the northward migration of the Mendocino triple junction and associated termination of subduction, ACA volcanism retreated northwestward, Basin & Range normal faulting advanced westward (Dilles & Gans 1995, Henry & Perkins 2001, Surpless et al. 2002), and strike-slip faulting advanced into the northern Walker Lane. At the latitude of the study area (ca. 37° Latitude), initiation of strike-slip faulting within the Walker lane began at 9 Ma and continued into the Holocene (e.g. Dilles & Gans 1995, Faulds et al. 2005). Within the study area, major faults include the Pyramid Lake, Warm Springs Valley, Honey Lake and Mohawk Valley faults (Figure 4.1) (Faulds et al. 2005). Further to the west major dextral faults merge southward with a system of east-dipping normal faults, which coalesce southward to form the Sierra Nevada frontal fault system (Putirka et al. 2012). Note that the main phase of extension across the GB began east of the Walker Lane in the middle Miocene (Fosdick & Colgan 2008).

4.2.2 Local Geological Setting

At about 40 Ma, high-K intermediate magmatism began migrating southwestward across southern Idaho, central Oregon and into northern Nevada and Utah (Dickinson 2006). Voluminous explosive eruptions and caldera collapse events occurred along the Nevada Caldera Belt beginning at 34.4 Ma (Henry & John 2013). By 24 Ma magmatism changed to include mafic cinder cones, low shield volcanoes, isolated lava

flows and viscous rhyolitic domes (Christiansen 2010). Basalt to basaltic andesite flows along with extrusive rhyolitic flow dome complexes around the Fish Creek Mountains (FCM) were emplaced ca. 35 Ma (Varve 2012, Stevens 2012).

Calc-alkaline intermediate lavas are the most abundant volcanic rock types throughout the Great Basin, capped locally by younger basaltic and rhyolitic rocks (Best & Christiansen 1991). The calc-alkaline samples from the FCM show significant similarities in both the petrographic and geochemical signatures to the calc-alkaline rocks found in the Sulphur Springs Range in central Nevada (Ryskamp et al. 2008), the North Clan Alpine Mountains (as will be presented later in this paper) and to a lesser degree, the Stillwater Range of central Nevada, the Western Great Basin (WGB) (Ormerod et al. 1988 1991) and areas of the ACA (Cousens et al. 2008; Stoffers 2010, Clark 2011). Regional extension as well as bi-modal volcanism began ca. 13 Ma within the westernmost GB and eastern ACA areas (John 2001, Fitten et al. 1991, Christiansen & Lipman 1972). Mafic to intermediate volcanism continued westward into the SN as the Farallon plate hinge line continued to rollback and the angle of subduction of the slab increased.

Magmatic activity that produced the SN batholith occurred episodically from the Triassic until ca. 80 Ma, at which point Mesozoic arc magmatism ceased in the region in response to the low-angle subduction of the Farallon Plate. Igneous activity resumed in the Late Cenozoic in the southern SN consisting of small-volume trachybasalts to rhyolites that erupted in three discrete pulses in the Miocene, Pliocene, and Quaternary (Farmer et al. 2002). Magmatism in the northern SN was more voluminous and widespread. Oligocene volcanic rocks consist largely of distal pyroclastic flow deposits

that originated from the caldera-forming eruptions to the east in central Nevada, and are now preserved as basal deposits in paleocanyons that drained this area (Hagan et al. 2009, Henry 2008). Miocene volcanic rocks range from intermediate to felsic in composition that developed discontinuously from northeastern-most California south to Sonora Pass (Busby et al. 2008, Henry 2008). Intermediate arc volcanism ceased after ca. 3 Ma in the northern SN and was succeeded by smaller volume, and more geographically restricted, post-arc basaltic andesites to trachyandesites.

Predominantly mafic post-arc volcanism (<3 Ma) is found along the eastern margin of the Sierra Nevada (Western Great Basin) and in the Lake Tahoe region (Tahoe-Truckee volcanic field) (Beard & Glazner 1995, Blondes et al. 2008, Cousens 1996, Cousens et al. 2011, Ormerod et al., 1988). Unlike the older arc volcanic rocks, the post-3 Ma suite includes only small-volume volcanic centers that lack the highly plagioclase-porphyrific rocks and common volcanoclastic deposits that dominate the arc volcanic centers (Cousens et al. 2008). TTVF lava flows were also emplaced along the course of the Truckee River from Truckee to Boca Ridge and in the northern Carson Range. This transition from voluminous, older than 3 Ma, calc-alkaline volcanism to smaller volume, younger than 3 Ma, basaltic andesites and andesites in the northern Sierra Nevada correlates roughly with the timing of passage of the subducted Mendocino Fracture Zone beneath this region and the opening of a slab window (Atwater & Stock 1998, Cousens et al. 2008).

To compare, our post-ACA sample set also includes olivine basalts from the Big Pine Volcanic Field (BPVF, Ormerod et al. 1991) of the Western Great Basin, which erupted well to the south of the TTVF (TTVF ca.39° latitude, BPVF ca.37° latitude)

(Ormerod et al. 1991). The BPVF was active during the Quaternary east of the San Andreas transform system in a within-plate tectonic setting. Ormerod (1988) determined that the BPVF melts were almost entirely derived from within the lithospheric mantle, and that the lithospheric source is characterized by high $^{87}\text{Sr}/^{86}\text{Sr}$ (ca. 0.706) and by high LILE/HFSE ratios reflecting the metasomatic contributions from previous subduction events that ceased 5 Ma prior to eruption (Ormerod et al. 1991).

4.2.3 Previous Work

Data were compiled from our own fieldwork guided by existing geologic and topographic maps, and from public databases (Morrison 1964, Page 1964, Jones 1997, et al. 1997, Henry 1996, Stewart & Carlson 1976, Green et al. 1991).

The geochemical characteristics of Cenozoic volcanic rocks from the Tobin, western Shoshone and Fish Creek Mountain ranges can be found in Stevens (2013); the central GB and ACA areas are described in Chapters 2 and 3; ACA to post-ACA in the Lake Tahoe region of the Ancestral Cascades Arc are presented in Cousens et al. (2008) and Cousens et al. (2011, 2012) and Big Pine post-ACA extension-related volcanism is described in Ormerod (1988) and Ormerod et al. (1991).

The distinction between the asthenosphere and CML is best represented by the isotope and trace element ratios, as established by Leeman (1970, 1974) and Hedge & Noble (1971) by recognizing elevated $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in alkali basalts due to partial melting of the CML (Ormerod et al. 1991, Bradshaw et al. 1993, Beard & Glazner 1995, Rogers et al 1995, Cousens 1996, Beard & Johnson 1997, Blondes et al. 2008, Putirka et al. 2012) that has been isolated from the convective asthenospheric mantle for > 1 Ga. The enriched CML contains abundant fluid mobile LILEs (e.g. Rb, Ba, Sr, Th, U, and Pb)

relative to HFSEs (e.g. Nb, Ta and Zr) may have been transferred to the lithosphere by the dehydration of previous subducted slabs (Rogers et al. 1995, Humphreys et al. 2003, Lee 2005, Beard & Glazner 1995). It has also been suggested that major faulting in the region would result in low degrees of decompression melting that is also seen in the chemistry, including elevated TiO_2 , Na_2O , K_2O and P_2O_5 at high MgO values (e.g. Putirka et al. 2012).

Beneath the southern SN, it has been hypothesized that slow removal or delamination of the CML has occurred over the past 10 Ma, represented in the chemistry by lower $^{87}\text{Sr}/^{86}\text{Sr}$ values as well as trace elements profiles (e.g. Ducea & Saleeby 1998, Farmer et al. 2002, Jones et al. 2004, Putirka et al. 2012). Another study of ACA volcanism from Lake Tahoe north to the Lassen volcanic region showed that the contribution of the ancient lithospheric mantle source diminishes northward, as the northern edge of the Sierra Nevada Batholith is approached (Stoffers, 2010).

4.2.4 Data Mining

Our objective is to analyze the interplay of Cenozoic volcanism through a changing tectonic environment by generating volcanic space-time composition patterns from central GB to central SN. I have acquired major, trace element as well as Sr, Nd, Pb and O isotopic data from several volcanic sequences that allow us to construct a profile from east to west across the GB and north to south along the Sierra Nevada for the last 35 Ma. The geochemical data for lavas from the study region was sourced from the following: 1) GB: Tobin Range, Shoshone Range and Fish Creek Mountains from Stevens (2013), 2) GB, eastern and western ACA from Timmermans et al. (*Chapter 2*), and Cousens et al. (2008), 3) post-ACA SN and TTVF from Cousens et al. (2011, 2012),

4) Big Pine VF from Ormerod et al. (1991). I have also included major and trace element data from the modern Cascades for further comparative discussion (Grove et al. 1988, Donnely-Nolan et al. 1991, Baker et al. 1994 and USGS public archives).

As true primitive lavas ($Mg\# > 0.7$, where $Mg\# = Mg/(Mg + Fe^{2+})$) are rare in the study area, mafic lavas have been filtered to include only lavas with $SiO_2 < 57$ wt.% and $Mg\# > 0.55$. These criteria should, for the most part, provide an effective filter against crustal assimilation for most isotopes and trace elements (Leeman 1970, Fitton et al. 1991, Farmer et al. 2002, Blondes et al. 2008). Intermediate lavas include andesitic and dacitic magmas, and felsic material include rhyolitic lavas and volcanoclastic rocks.

4.3 Geochemistry: Relationships Over Space and Time

For our purposes, to compare the chemical changes in space I have regionally and geochemically divided the data into the following groups: 1) **central GB**, which includes lavas from Tobin Range, Fish Creek Mountains and Shoshone Range. Basaltic trachyandesites from the northern Clan Alpine Range are chronologically and chemically similar to those of the central GB and therefore it is suspected that these melts share similar history; 2) **western GB**, which includes lavas from the mid- to southern-Clan Alpine Range, Stillwater Range, Desatoya Range, Lone Rock (Carson Sink), Bell Mountains, Bell Canyon, and eruptives from the Carson City Quadrangle (Table Mountain, Churchill Butte); 3) **westernmost GB**, which includes lavas from the Truckee Range, Hotsprings Mountains, Lahontan Mountains (Seehoo, Salt Wells and Rainbow Mountains), Virginia Range and Soda Lake area (Carson Sink); 4) **eastern ACA**, which includes lavas from Reno area, Carson Range, Lousetown basalts, Pyramid Lake region, Sparks, Clark Mountain, Rattlesnake Mountain (Huffaker Hills), Virginia City, eastern

Lake Tahoe, and Flowery Peak; 5) *western ACA*, which includes lavas from Sawtooth, Portola (Portola/Blairsden), Dog Valley (Babbitt and Crystal Peak), Ladybug Peak (including two scoria samples), Henness Pass, Stanford/Twin Peaks, Boreal Ridge, Verdi Lookout, Castle Peak, Bald Mountain Range, Sierraville, and Stampede Reservoir; 6) *westernmost* ACA, which includes lavas from Mt. Lincoln, Devil's Peak, Lowell Ridge, Squaw, Pond Terrace, Serene Lakes and Susanville; 7) *post-ACA* (post-ACA volcanic rocks from the northern region of the study area), which includes lava from the TTVF, McClellan Peak, New Empire quad, Upsal Hogback, Rattlesnake Hill, and Soda Lake maar; 8) *Big Pine Volcanic Field* (post-ACA, extension-related olivine basalts to the south of the study area).

Figure 4.1 includes an alkali-silica diagram (Le Bas et al. 1986) and an AFM ternary diagram (Irving & Baragar 1971) for the regions specified above. Data from the modern Cascades are included in Figure 4.1A. GB lavas transition from subalkaline for mafic lavas to alkaline towards intermediate to felsic lavas. Compositions include basalts, trachybasalts, basaltic andesites, basaltic trachyandesites, andesites, trachyandesites, dacites, trachytes, to rhyolites (Figure 4.1A). ACA lavas are mostly subalkaline mafic to felsic rocks that include basalts, basaltic andesites, andesites, with only rare dacites and rhyolites. The eastern ACA lavas also include basaltic trachyandesites and trachytes. Modern Cascade lavas are mostly subalkaline, overlapping the ACA lavas. Central GB and Post-ACA lavas are more alkaline compared to the western GB and ACA lavas, and are generally more mafic in composition compared to alkaline lavas of the GB.

Geochemical distinctions between the ACA and post-ACA volcanic suites were discussed in Cousens et al. (2011). The older suite forms a nearly continuous array of

medium-K volcanic rocks from basalts to basaltic trachyandesites and andesites.

Younger post-ACA volcanic rocks span a restricted range of bulk compositions from trachybasalts to basaltic trachyandesites, and show step increases in weight percent K_2O with decreasing weight percent MgO . Most have $K_2O/Na_2O > 0.6$ at 50% SiO_2 . The younger rocks all have higher weight percent Na_2O (ca. 3.0 wt% to ca. 4 wt%), K_2O (ca. 1.5 wt% to 3.0 wt%) and TiO_2 (ca. 1.4 wt% to 1.7 wt%), and lower weight percent CaO than the older volcanic suite over an equivalent range of weight percent MgO .

To understand and quantify the processes that take place over distance and time, elements with distinct behaviors are used. Figure 4.2A shows incompatible elements (K_2O , Zr, Ba and Nb) plotted against silica content for mafic to intermediate lavas from the GB (central GB, western GB and westernmost GB), ACA (eastern ACA, western ACA and westernmost ACA), post-ACA (<3 Ma) and in some cases, the modern south Cascades. Evolved lavas (intermediate and felsic lavas) are included in Figure 4.2B, comparing K_2O with SiO_2 . Evolved lavas from the modern Cascades include medium to high-K andesites, dacites and rhyolites; however, western ACA lavas, eastern ACA and westernmost GB lavas have higher K_2O values. Lavas showing the highest K_2O values include the northern Clan Alpine (western GB), Tobin, Shoshone and Fish Creek Mountains. Post-ACA lavas also show overall higher K_2O values compared to ACA and Cascade lavas (Cousens et al. 2011). For mafic lavas, concentrations of many of these elements vary by the highest factors in the western GB and Post-ACA lavas and by the lowest factors in westernmost ACA lavas. All lavas increase in K_2O content with increasing silica content, and the central GB lavas have consistently higher concentrations of K_2O compared to other lavas to the west within the study area.

Central GB mafic to intermediate lavas also have, on average, higher Ba and Nb concentrations that do not vary with increasing silica content, whereas westernmost ACA have the lowest values that also do not vary with increasing silica content. Post-ACA lavas contain higher K₂O, Ba, Zr and Nb compared to ACA and GB lavas. Nb concentrations are lower for western ACA lavas that do not vary with increasing silica. Post-ACA lavas, however, trend to higher Nb values (up to 40 ppm) with Rattlesnake Hill lavas reaching the highest levels (up to 60 ppm). Lavas from the central GB increase in K₂O with increasing silica, but they do not vary considerably in Ba or Nb with increasing silica. Western GB lavas contain a wide variation of K₂O, Ba, Zr and Nb values with no significant trend with increasing silica. With one exception, westernmost GB lavas behave more uniformly, with lesser variation in K₂O, Ba and Nb (the exception is the basaltic trachyandesite from Rainbow Mountains with uniquely high LOI and ⁸⁷Sr/⁸⁶Sr (>0.708) values as well as petrographical evidence of high degree of weathering). Eastern ACA lavas increase in K₂O and Ba concentrations with increasing silica, and do not show any trends in Zr or Nb with increasing silica, whereas western ACA lavas increase in K₂O, Ba and Zr but do not vary in Nb with increasing silica. Westernmost ACA lavas do not vary in K₂O, Ba, Zr or Nb with increasing silica.

In general, concentrations of LILE such as Ba are notably higher in ACA systems compared to HFSEs such as Zr and Nb, due to the observation that LILEs are readily released into the hydrous slab fluids whereas HFSEs are held back in the slab residue (e.g. Pearce & Peate 1995). Considering the lavas from the study area, it has been noted that not only has this subduction signature exist far into the continental margin (i.e. central GB) (Chapter 2), but also within Post-ACA lavas, demonstrating that trace

element-enriched CLM may possess some of the chemical features of subducted-related mantle sources (e.g. Cousens et al. 2011, Ormerod et al. 1988). This ghost subduction signature attests to the influence of previous subduction episodes in the geochemical development of the lithospheric mantle beneath the GB and SN. I thus compare the extent of this signature by plotting mafic lavas on the graph Ba/Zr versus Nb/Zr as well as $^{87}\text{Sr}/^{86}\text{Sr}$ (Figure 4.3). Note that Ormerod et al. (1991) flagged the XRF-derived low Nb values for Big Pine as data that may have a high percentage of error and therefore included with caution. Most lavas possess Ba/Zr <10 and Nb/Zr <0.075. Western and westernmost ACA mafic lavas trend to high Ba/Zr with little variation in Nb/Zr values. Post-ACA lavas, however, trend to higher Nb/Zr with little variation in Ba/Zr values. Westernmost GB, eastern ACA and Big Pine lavas have less variation in both ratios, and western GB and central GB lavas scatter to higher Ba/Zr and Nb/Zr values.

Radiogenic Isotopic Signatures: Initial values for the older volcanic lavas (GB and ACA) range from 0.7035 to 0.7080 and show no obvious correlation with the rock composition. The central GB lavas have an overall higher range (0.706 to 0.708), and westernmost ACA lavas have an overall lower range (0.7035 to 0.7045, Figure 4.4A). High abundances of LILE and LREE and low abundances of HFSE in lavas erupted in an arc system can be attributed to involvement of fluids transported into the mantle wedge from the subducted slab (Bacon 1990, Leeman et al. 1990, Hughes 1990, Baker et al. 1994, Borg et al. 1997). Similarly, by confirming good correlation between $((\text{Sr}/\text{P})_{\text{pmn}})$ and $(\text{Sr}/\text{LREE})_{\text{pmn}}$ previous workers have used higher $(\text{Sr}/\text{P})_{\text{pmn}}$ values as a proxy for slab-derived, Sr-rich components in the mantle wedge (Borg et al. 1997). $^{87}\text{Sr}/^{86}\text{Sr}$ values decrease with increasing $(\text{Sr}/\text{P})_{\text{pmn}}$ (Cousens et al. 2011, Chapter 3?). This method was

used by Borg et al. (1997) at Lassen Peak in the south Cascades to identify volcanic rocks that may have been derived from mantle that was metasomatized by slab-derived fluids. Whole-rock $^{143}\text{Nd}/^{144}\text{Nd}$ values increase with decreasing $^{87}\text{Sr}/^{86}\text{Sr}$ and increasing $(\text{Sr}/\text{P})_{\text{pmn}}$. ACA volcanic rocks have Pb isotopic compositions that are uniformly radiogenic and plot to the right of the geochron on a $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ plot. Lavas from the GB region are less radiogenic compared to ACA lavas. Lava from older ACA volcanic rocks trend away from the Northern Hemisphere Reference Line (NHRL; Hart 1984) in the $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ plot, whereas they trend essentially parallel to the NHRL in the $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ plot.

The Sr, Nd and Pb isotopic compositions of the younger post-ACA volcanic rocks overlap those of the ACA and GB volcanic rocks (Cousens et al. 2011). The $^{87}\text{Sr}/^{86}\text{Sr}$ values range from 0.7049 to 0.7057 and the Pb isotopic compositions generally are at the radiogenic end of the trends defined by the older volcanic rocks. Big Pine shows greater variation in Ba/Zr values for lavas with $^{87}\text{Sr}/^{86}\text{Sr} > 0.706$. Post-ACA lavas exhibit a positive trend between $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and Ba/Zr.

4.4 Assimilation-Fractional Crystallization

The trends of major elements such as K_2O , Al_2O_3 and CaO , with SiO_2 suggest that fractional crystallization has played a role in GB, ACA (Timmermans et al. *unpublished*), Cousens et al. 2008) and (though lesser so in) Post-ACA lavas (Cousens et al. 2011). I am interested in why the compositional distinctions exist over space (east-west transect across the GB and ACA) as well as between the older and younger volcanic rocks. These differences provide information on the chemical influence of subduction pre-, syn-, and post- subduction of the Farallon plate, and the evolution of the magmas over space and

time. The lack of well-defined relationships amongst the major element and isotopic compositions of all major regional groups may indicate that compositional distinctions are the result of variable degrees of crustal assimilation (Cousens et al. 2008, 2011). Isotopic variability in these rocks is more likely inherited from the mantle source regions of the mafic magmas from which both volcanic suites were derived, as indicated by the most mafic volcanic rocks with higher MgO (>ca.5.5 wt%) and high Ni contents (>150 ppm), which are consistent with melting of ultramafic source rocks (even if none are primary melts) (Timmermans et al. *in preparation*).

Considering the components involved during melt generation and evolution, geochemical trends observed in GB and Post-ACA lavas suggest the lavas are strongly influenced by two distinct end-member types. One extreme contains lower $^{87}\text{Sr}/^{86}\text{Sr}$, lower concentrations of HFSEs and lower LREE/HREE values. Lavas then trend towards higher $^{87}\text{Sr}/^{86}\text{Sr}$, HFSEs and LREE/HREE values, with lavas from different regions forming separate arrays. The relationship between the initial Sr isotopic ratio and the ratio Sr/Zr can help determine the role of fractionation or assimilation – fractional crystallization (AFC) processes, as the Sr/Zr values will decline because Zr is a highly incompatible element in plagioclase whereas Sr is compatible (Rudnick et al. 1986, Griffin et al. 1987). Figure 4.5A shows a negative correlation for central GB lavas (northern Clan Alpine, Tobin, Shoshone and Fish Creek Mountains), which may indicate that these lavas were more affected by fractionation/AFC processes compared to other GB, ACA and Post-ACA lavas, which contain variable $^{87}\text{Sr}/^{86}\text{Sr}$ values with increasing Sr/Zr. Figure 4.5B compares $^{87}\text{Sr}/^{86}\text{Sr}$ with $(\text{La}/\text{Lu})_{\text{pmn}}$, which should not vary significantly with AFC processes but instead reveal the degree of melting and/or

compositional diversity between the lava groups. Lavas from the westernmost ACA and westernmost GB have the least variation in $^{87}\text{Sr}/^{86}\text{Sr}$ and $(\text{La}/\text{Lu})_{\text{pmn}}$ values. Post-ACA and Big Pine lavas show a slight positive correlation between Sr isotopic ratios and $(\text{La}/\text{Lu})_{\text{pmn}}$, which suggests that variation in bulk rock composition may be tied to the Sr-isotopic ratio and thus long-term source enrichment.

Now that I have proposed that AFC processes were also involved for the lavas from the western GB, central GB and post-ACA (Figure 4.4A), I can further test this by presenting examples of assimilation-fractional crystallization (AFC) model curves (Figure 4.5, DePaolo 1981) on a graph comparing $^{143}\text{Nd}/^{144}\text{Nd}$ with La/Sm values. The symbols represent composition (see legend). The AFC model describes the chemical evolution of a magma as it crystallizes in the magma chamber and concurrently assimilates crustal material along chamber walls. The change in concentration of a trace element in the evolving magma depends on distribution coefficient (D, fractionation of that element between crystallizing minerals and magma), the ratio of the rate (mass/unit time) of assimilation to crystallization (r), the initial concentration of the element in the parent magma and in the assimilant, and the mass fraction of magma remaining after a certain period of time (F , mass magma/mass initial magma) (DePaolo 1981). $^{143}\text{Nd}/^{144}\text{Nd}$ in the magma is not changed during fractional crystallization since minerals do not fractionate heavy isotopes from the magma, but assimilation of crustal material may dramatically change isotope ratios in the evolving magma if there is a difference in isotopic composition between magma and wallrocks. The AFC model in Figure 4.5 assumes a fractionating assemblage of olivine, clinopyroxene, Fe-Ti oxides and plagioclase in the proportions of 20%:30%:5%:45%; bulk D values of 0.19, 0.31 and

0.29 for La, Sm and Nd respectively (GERM). For the western GB, an initial composition from westernmost GB was selected (sample 11-CN-13, La/Sm = 3.6, $^{143}\text{Nd}/^{144}\text{Nd} = 0.512704$) as it has been shown that lavas from the westernmost GB have not been subject to assimilation to any large degree. The rhyolite from the Clan Alpine Range is selected to represent the lava with highest crustal influence, and therefore representative as the western GB end-member (sample 11-CN-12b, La/Sm = 9.8, $^{143}\text{Nd}/^{144}\text{Nd} = 0.51255$) and r-values of 0.6 and 1. For lavas from the central GB, the initial composition is more evolved than western GB. A basalt from the Stillwater Range was selected to represent the initial composition (sample 11-CN-08, La/Sm = 3.4, $^{143}\text{Nd}/^{144}\text{Nd} = 0.51256$), and a sample from the FCM was selected as the contaminant lava most influenced by a crustal contaminant (sample 10-BV-48B, La/Sm = 8.2, $^{143}\text{Nd}/^{144}\text{Nd} = 0.51232$), and an r-value of 1. For post-ACA lavas, the initial composition from a basalt from Upsal Hogsback (sample GD-03-04, La/Sm = 3.9, $^{143}\text{Nd}/^{144}\text{Nd} = 0.51277$), and an andesite from Lake Tahoe was selected to represent the contaminant (sample 10-BV-48B, La/Sm = 8.0, $^{143}\text{Nd}/^{144}\text{Nd} = 0.51251$), and an r-value of 1. The AFC 1 curve for western GB follows the data array for the Stillwater Range, Bell Mountain, Bell Canyon, Truckee Range, Desatoya Mountains, Hot Springs, Table Mountains and Churchill Butte, Soda Lake and the southern Clan Alpine Mountains. The curve shows that the westernmost GB lavas were least affected by AFC processes compared to other GB lavas, and that the west GB lavas followed AFC evolution with an assimilant with higher in $^{143}\text{Nd}/^{144}\text{Nd}$ values compared to central GB lavas. The AFC 2 curve for central GB goes through lavas from the older and more easterly positioned Tobin Range, FCM, Shoshone Range and northern Clan Alpine Range. The two

anomalous basaltic andesites from Tobin Range (10-BV-42) and FCM (10-BV-16) notably trend towards the lower and upper crust, very similar to lavas from the BPVF (discussed later in this paragraph). The AFC 3 curve for Post-ACA lavas begins in the region of Upsal Hogsback, then AFC increases to the west towards New Empire Quad, Soda Lake, Truckee then Tahoe. Olivine basalts from BPVF are understandably not greatly affected by AFC processes, as their mafic composition represents primary melts sourced from the lithospheric mantle. The AFC modeling supports the supposition that the intermediate lavas from the study region were derived from mafic parent magmas that were modified by interaction with crustal rocks at varying degrees before their eruption. Crustal rocks vary in composition according to region: older and thickened easternmost crustal rock versus accreted crustal rock from western GB versus crustal rock within the SN for Post-ACA lavas.

4.5 Summary

Figure 4.6 presents a space-time diagram of volcanic events from 40 to <1 Ma in the Great Basin and the Sierra Nevada.

The results of this comparative study are summarized below:

1. The study area can be chemically divided into five broad regions here listed from east to west: Central GB, West GB, and Westernmost GB, Eastern ACA, Western ACA and Westernmost ACA. Lavas from Central GB are the oldest (up to 35 Ma) compared to lavas from West GB (up to 25 Ma), Westernmost GB (up to 21 Ma), Eastern ACA (up to 14 Ma, with the exception of lavas from SW Virginia City, which are 27 Ma) and Western ACA (up to 10 Ma, with the exception of

lavas from Lowell Ridge, which are 16 Ma). All Cenozoic ARC lavas have lower alkalinity compared to Post-ACA and BPVF lava, which are mostly alkaline.

2. Lavas from the northern Clan Alpine Mountains are chemically, isotopically and petrographically similar to lavas from Central GB (Shoshone, Tobin and FCM).
3. Trace element HFSE and REE arc patterns within ACA lavas and, to a lesser extent GB lavas, show that magmatism during slab rollback were enrichment processes and melting conditions varied directly from the subducted Farallon plate, and that Post-ACA lavas are enriched by the metasomatised CLM.
4. Central GB and post-ACA intermediate lavas were produced by AFC processes in which fractional crystallization is accomplished by differentiation within the magma chamber and subsequent mixing with melts from the garnet-bearing lower crust (higher $(\text{Dy/Yb})_{\text{pmn}}$ values) and/or upper crust (higher Rb/K values).
Selected western GB lavas were produced by AFC processes, mixing with an assimilant higher in $^{143}\text{Nd}/^{144}\text{Nd}$ values. Westernmost GB lavas were least affected by AFC processes.

Figure 4.1 (A) Total alkali versus silica diagram (Le Bas et al. 1986) for the GB, ACA and Post-ARC (including Big Pine) lavas. Data from the modern Cascades has been included for comparison (see legend). The arced line separates alkaline and subalkaline lavas (Irvine & Baragar 1971). (B) Ternary diagram plotting MgO , FeO^{t} and $\text{Na}_2\text{O}+\text{K}_2\text{O}$ (wt%) values for GB, ACA and Post-ARC lavas (including Big Pine olivine basalts) (Irvine & Baragar 1971).

Figure 4.2 Total variation in SiO_2 values in weighted percent (wt%) of GB, ACA and Post-ARC lavas (including Big Pine) with respect to (A) K_2O , (B) Ba, (C) Zr and (D) Nb. Trace elements are presented in ppm. Data for the modern Cascades is included in diagram (A). Legend for the data is shown in Figure 4.2A. See text for discussion.

Figure 4.3 Variation of selected trace elements along with initial Sr-isotopic values for GB, ACA and Post-ARC mafic lavas (including Big Pine): (A) Ba/Zr vs. Nb/Zr, (B) $^{87}\text{Sr}/^{86}\text{Sr}$ vs. Ba/Zr, and (C) $^{87}\text{Sr}/^{86}\text{Sr}$ vs. Nb/Zr. The dashed line highlights $^{87}\text{Sr}/^{86}\text{Sr} = 0.706$. The circled western GB mafic lava with unusually high Nb/Zr values compared to other western GB mafic lavas is a basaltic andesite from Hotsprings Mountains (04-LT-12). Sample 11-CN-15 (Rainbow Mountains) is also highlighted – its anomalously high $^{87}\text{Sr}/^{86}\text{Sr}$ values due to a high-degree of weathering. Insert in (A) shows Ba/Zr vs. Nb/Zr with a smaller scale. Average upper and lower crust (UC, LC, Wedepohl 1995) is plotted as black stars to show that melting of, or assimilation (contamination) by such material cannot exclusively explain the values seen in ACA and western GB mafic lavas.. See text for further discussion.

Figure 4.4 Series of LILE/HFSE (column A) and LREE/HREE (column B) vs. Sr- isotopic plots separated by space (rows 1 and 2) and time (row 3).

Figure 4.5 Variation of selected A $^{143}\text{Nd}/^{144}\text{Nd}$ vs. La/Sm plot for GB (left) and Post-ARC (including Big Pine) (right) lavas. The AFC curves represent assimilation-fractional crystallization models. The AFC 1 shows a model for $r=0.6$ and $r=1$ between two eastern and western GB lavas at different points along the assimilation-fractional crystallization trend. The lava representing the “parental” basaltic magma, represented by sample 11-CN-13, are simultaneously fractionating and assimilating with a component with lower $^{143}\text{Nd}/^{144}\text{Nd}$ and higher La/Sm values, represented by sample 11-CN 12b. The easternmost GB lavas (including lavas from the northern Clan Alpine Mountain range) follow a different AFC path, shown as AFC 2 curve ($r=1$). Trending towards the upper and lower crustal end members (grey circles), the curve trends between the “parental” magma represented by sample 11-CN-08 and the component with much lower $^{143}\text{Nd}/^{144}\text{Nd}$ with slightly higher La/Sm values (Sample 10-BV-48B). Post-ARC lavas follow the AFC 3 curve between the “parental” magma, represented by sample GD-03-04, and the component with lower $^{143}\text{Nd}/^{144}\text{Nd}$ and higher La/Sm values, represented by 10-BV-48B. Big Pine lavas do not overlap with Post-ARC lavas, but instead trends down towards the lower and upper crustal values. Tick marks on the AFC curves with $r=0.6$ indicate F (mass magma remaining/mass initial magma) from 1 to 0.1, in increments of 0.1. Tick marks on the AFC curves with $r=1$ indicate F from 0 to 5 in increments of 1. See text for further discussion.

Figure 4.6 A space-time diagram of volcanic events from 40 to <1 Ma in the Great Basin and the Sierra Nevada. For clarity only representative volcanic centres are included in the diagram. The examples are follows: CENTRAL GREAT BASIN: FCM = Fish Creek Mountains, TR = Tobin Range, SR = Shoshone Mountain Range; WEST GREAT BASIN: BM = Bell Mountains, BC = Bell Canyon, SR = Sillwater Mountain Range, CA = Clan Alpine Mountains, DM = Desatoya Mountains; WESTERNMOST GREAT BASIN: TM = Table Mountain, Carson City Quadrangle, CH = Churchill, C12 = Churchill for lavas 12 Ma, HM =Hotspring Mountains, TR = Truckee Range, SL= Soda Lake; EASTERN ACA: KP = Kate Peak, L = Lousetown, VC = Virginia City, RM = Rattlesnake Mountains, ELT = East Lake Tahoe, P = Pyramid, FP = Flowery Peak, CR = Carson Range, R = Reno, SWVC = Southwest Virginia City; WESTERN ACA: BR = Boreal Ridge, CP = Castle Peak, DV = Dog Valley, EP = Ellis Peak, HP = Heness Pass, ML = Mount Lincoln, VL = Verdi Lookout, S = Squaw, Stanford/Twin peaks; POST-ACA: TTVF – Tahoe-Truckee Volcanic Field, NE = New Empire Quadrangle, MP = McClellan Peak (Chalk Hills), VC = Virginia City, RH = Rattlesnake Hill (Fallon), UH = Upsal Hogsback, SL = Soda Lake

5 Chapter: Conclusions

5.1 Introduction

This chapter presents the conclusions of this thesis with results from all chapters as well as a discussion of the tectonic and magmatic evolution of the southwestern United States with reference to the Cenozoic southwestward magmatic sweep. Section 5.2 presents conclusions from chapters 2, dealing with investigations on mafic magmas for the purpose of understanding melt generation and the components involved: asthenospheric mantle wedge, subducted slab, continental lithospheric mantle (CLM) and the continental crust. Section 5.3 discusses the results from chapter 3, evaluating the genetic evolution of mafic to intermediate lavas across the study area. Subsequent sections 5.5 integrate conclusions in context of adjacent tectonomagmatic regions as well as the transition from arc to post-arc related volcanism. Section 5.6 presents suggestions for future work.

5.2 Geochemical study of 25 to 2.5 Ma mafic lavas representing the southwestward magmatic sweep from the Central Great Basin to Ancestral Cascade Arc in Sierra Nevada, southwestern United States

The trace element and isotopic geochemical results presented in this thesis includes XRF and ICP-MS data as well as Sr, Nd, Pb radiogenic isotope data from 56 mafic lavas in the Central Great Basin (GB) and Ancestral Cascade Arc (ACA) (Figure 2.1). Data results were combined with previous work forming a basis for interpreting the nature of the Farallon plate subduction, regional extension and resultant southwestward magmatic sweep.

The study area is geochemically, chronologically and spatially divided into three broad regions: central GB (age range 5 to 35 Ma), eastern and western ACA (age range 2.5 to 16 Ma) (Figure 2.2). As primitive lavas ($Mg\# > 0.7$, where $Mg\# = Mg/(Mg+Fe^{2+})$) are rare to non-existent in the study area, I have filtered our data to lavas with $SiO_2 < 57$ wt.% and $Mg\# > 0.55$, which limits the eastern reach of the east-west transect to the Stillwater Mountain Range within central GB.

Mafic Lavas are subalkaline trending to alkaline towards the east end of the study area (Figure 2.4). Basalt and basaltic andesite lavas from all lavas within the study area follow olivine-clinopyroxene + plagioclase fractionating phases, with clinopyroxene noted as the dominant phase. The effects of plagioclase fractionation are minimal for all mafic lavas, though greatest in the GB mafic lavas compared to ACA lavas (see Figures 2.5 and 2.6).

Trace element models show that compositions of all mafic melts possess subduction zone signature (see Figures 2.8 and 2.9). This subduction signature, which includes negative Ta, Nb and Ti anomalies and LREE + LILE enrichment, is weakest in GB (older) mafic lavas when dip angle and dehydration from the slab was the lowest. The subduction signature is strongest in western ACA (younger) mafic lavas, when the dip angle and slab dehydration was greater. ACA lavas, particularly the western ACA lavas, show contributions from slab sediment melts with higher Th/Nb, Pb/Ce and Ce/Ce* values (see Figure 2.13). $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ values for western ACA values are higher compared to GB lavas for equal $^{143}Nd/^{144}Nd$ values. It is therefore likely that the higher radiogenic Pb were sourced from melted sediment as opposed to recycled crustal Pb.

Most mafic melts are dominated by a lithospheric mantle component that is revealed in normalized incompatible element patterns and in Sr and Nd isotopic compositions (Figure 2.10). The westernmost ACA lavas, located within the western ACA region of the study area, are recognized by their lower $^{87}\text{Sr}/^{86}\text{Sr}$ values for equal $^{144}\text{Nb}/^{143}\text{Nb}$ values, probably because the lavas erupted over less enriched lithospheric mantle compared to the CLM underneath the rest of the study area.

Mafic lavas from central GB and selected eastern ACA (Pyramid Lake) lavas are enriched in K_2O , TiO_2 , P_2O_5 , HREE and Nb contents for equal silica and lower Mg# values compared to ACA lavas. Central GB mafic lavas are generally older than ACA mafic lavas (15 to 25 Ma), erupting during the early stages of slab rollback. Geochemical results from central GB mafic lavas are consistent with low degrees of partial melting due to low temperatures, pressure conditions and low water (volatile) abundances generated from the shallow slab. With regard to Pyramid Lake mafic lavas (eastern ACA), tensile forces related to regional extension most likely triggered the low- F melting. The Pyramid Lake Fault (PLF), part of the northern Walker Lane, is situated through the Pyramid Lake volcanic field. Although the age of PLF is not certain, it is at least 9 Ma or older. The late Cenozoic Walker Lane belt marks the boundary between the Great Basin province and the Sierra Nevada, and is characterized by northwest-striking transcurrent faults and coeval dip-slip faults. Within the central Walker Lane belt, located in the region of western GB and the eastern part of the eastern ACA, faulting began between 15 and 10 Ma. Clearly the region surrounding Pyramid Lake was stressed, and therefore plausible that volcanism was triggered by these extension-related tensile forces.

5.3 Magmatic evolution of mafic and intermediate lavas

Mafic and Intermediate volcanic rocks between 35 and 3 Ma from 51 locations across an east-west transect spanning from the central Great Basin in Nevada to the Sierra Nevada in California (Figure 2.1) were analyzed for their major, trace element and Sr-Nd-Pb-O isotopic geochemistry. I observe that there is no simple ingredient that can be mixed with the primary magma to produce the observed trace element and isotopic compositions from the study area. The geochemical data, however, do provide us with new interpretations of the evolution of melts as magmatism migrated southwestward.

New geochemical data allows the study area to be further divided into five distinct regions along the east-west transect: Central GB, Western GB, eastern ACA, western ACA and westernmost part of western ACA. Most magma originated from mantle within the spinel stability field that was variably modified by the subducted slab fluids (Figures 3.5 and 3.6), including sub-continental lithospheric mantle, after which lower crustal components were added by assimilation. The lavas follow an olivine-pyroxene-oxide+/-hornblende fractionating trend (Figure 3.4).

Mafic and felsic lavas have increasing subduction signatures as volcanism migrated southwestward; that is, the arc signature is weakest in the older lavas to the east (central GB lavas) and strongest in younger lavas to the west (ACA lavas) (Figure 6). Western GB lavas are chemically distinct compared to other regions in the study area, showing little variation in MgO, K₂O, CaO/Al₂O₅, TiO₂/K₂O, Th/Rb, La/Sm, Rb/K, Ce/Ce*, Nb/Yb, ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd. Western GB lavas do show wide variation in radiogenic Pb values, and the low Ba/Nb values are similar to central GB lavas (see

Figure 3.9).

Oxygen isotope results from the GB and ACA lavas show $\delta^{18}\text{O}$ values between +8.54‰ to +6.3‰, consistently higher than upper mantle values (+5.5 to +6.0, Hoefs 2004). GB lavas have the overall highest $\delta^{18}\text{O}$ values (+7.09 to +8.54), whereas eastern ACA lavas have an intermediate range (+7.21 to +8.01) and western ACA lavas include the lowest values (+6.3 to +8.04). The overall $\delta^{18}\text{O}$ range of up to +3‰ above MORB-mantle values demonstrate that primary melts were mixing with, or (more likely) derived from sources with higher oxygen isotopic values than modern upper mantle. There is a synchronous increase in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and decrease in $^{143}\text{Nd}/^{144}\text{Nd}$ with increasing $\delta^{18}\text{O}$. Incorporation of higher $\delta^{18}\text{O}$ into mafic magmas is thought to originate at the source (from mixing with the lithosphere) (Figure 3.8)

Evolution of central GB and (to a lesser extent) eastern ACA lavas were subject to AFC processes in which fractional crystallization is accomplished by differentiation within the magma chamber and subsequent mixing with melts from the garnet-bearing lower crust (higher $(\text{Dy}/\text{Yb})_{\text{pmn}}$ values) and/or upper crust (decreasing Rb/K with increasing Rb values) (Figure 3.11)

Both mafic and intermediate lavas from western GB shows little variation in incompatible trace element and Sr-Nd-isotope ratios. Despite this, increases of LILEs with increasing LREEs in combination with higher $^{87}\text{Sr}/^{86}\text{Sr}$ in basalts with lower Sr/P values suggest that western GB lavas were still subject to contributions from an enriched lithospheric mantle and a dehydrating slab. Further interpretation of this data suggests a thinning lithosphere and faulted crust.

Mafic and intermediate lavas from the Westernmost part of the ACA were originated from primary melts are derived from the mantle wedge then mixed with low Rb/Sr components from the sub- Sierra Nevada lithospheric mantle that resulted in a different mixing array: lower $^{87}\text{Sr}/^{86}\text{Sr}$ values for equal $^{143}\text{Nd}/^{144}\text{Nd}$ values compared to the other lavas from most of the study area.

5.4 A magmatic model for the evolution of the Cenozoic southwestward magmatic sweep.

The Eocene Mio–Pliocene geological history of volcanism in the Central Great Basin to northern Sierra Nevada is complicated by overlapping volcano- tectonic settings, including arc volcanism resulting from subduction and rollback of the Farallon (Laramide) plate (e.g. Best & Christiansen 1991, Lipman 1992, Dickinson 1997) and the incursion of Basin and Range extension westward into the Sierra Nevada (Guffanti et al., 1990, Henry & Perkins, 2001). The geochemical results from this thesis are used to enhance our geological knowledge of the southwestward magmatic sweep at ca. 39 to 40° latitude, as summarized below.

At 45 Ma, a high rate of convergence of the Farallon plate (14 cm/yr, Leeman 1983) resulted in flat-slab subduction (Liu et al. 2008, DeCelles 2004) underneath the North American plate that thickened the lithosphere and amplified the relief in the Sierra Nevada and in what is now the Great Basin (Henry 2009, DeCelles 2004). The Pacific Rise was ca. 200 km from the edge of the North American plate and the thermal structure of the Farallon plate was influenced by its young age, shear heating from the flat slab subduction (Peacock et al. 1994, Peacock 1996) and fast subduction rate, allowing

incompatible elements to be released from the slab (i.e. dehydration) and chemically enrich the overlying CLM.

Flat slab subduction was most likely caused by 1) a high rate of convergence of the overlying plate, and/or 2) the buoyancy of thickened oceanic crust of moderate to young age (Gutscher et al. 2000). In the flat-slab scenario for the Farallon Plate, it has been argued that there is no asthenospheric gap between the lithospheric mantle and the Farallon plate (Liu et al. 2008, DeCelles 2004). This caused a delay in the basalt to eclogite transition by up to 8 to 10 Ma (Gutscher et al. 2000) due to the cool thermal structure of two overlapping plates (Gutscher et al. 2000, Arcay et al. 2007). Dehydration due to frictional heat took place from serpentinized metabasaltic oceanic crust directly enriching the CLM; however, no melting took place.

High intraplate coupling may have scraped much of the sediments at the wedge, possibly explaining the absence of a sediment-sourced chemical signature in the GB lavas. As subduction progressed, the serpentinized metabasaltic oceanic crust and oceanic lithospheric mantle underwent metamorphic transformation far into the North American plate, which would have increased the density of the subducted slab. As the hydrous minerals continued to break down they would have released substantial amounts of H₂O and other fluid-mobile elements into the CLM, thereby altering the rheological properties of the boundary between the slab and CLM (Achray et al. 1990), which would have reduced the intraplate coupling above a flat slab segment (Gutsher et al. 2000). As convergence rate decreased and density of the slab increased (by up to 10% once the metabasalt was transformed to eclogite), the lithospheric plate to collapse and the slab to

sink down, at which point slab detachment from the base of the North American plate was possible (Spencer 1994) and volcanism began.

As the slab hinge point rolled back at 35 Ma, hot asthenosphere moved in between the North American and subducted Farallon plates, initiating dehydration of the slab releasing aqueous fluids into the mantle wedge triggering low- F partial melting at the CLM boundary. Low- F mafic melts of the central GB were generated within the spinel-field of the upper mantle where they were enriched in incompatible elements including the REEs, K, P, Ti and HFSEs. 35 Ma lavas from the northern Clan Alpine Mountains are chemically, isotopically and petrographically similar to lavas from Central GB (Shoshone, Tobin and FCM) and are therefore interpreted to be from the same magmatic sequence.

Magmatism moved southwestward as the Farallon slab hinge point continued to roll back and high-K magmatism of central-west GB erupted ca. 25 to 15 Ma. The similarities in phenocryst compositions, REE and isotopic signatures amongst GB mafic compositions further support the derivation of their primary magmas from similar source regions, with variations in chemistry due to a wide range of contributions from the CLM and variable degrees of partial melting (F). Alkaline melts (basaltic trachyandesites) within the GB represents melting higher in the CLM. AFC processes within central and central-west GB lavas produced intermediate melts, which became the dominant lava-type for the region. Alkaline lavas originated by melting further within the CLM.

Simultaneously to the south west, the Pacific plate margin collided with the North American Plate at ca. 34° latitude at ca. 25 Ma, initiating a right-lateral strike-slip fault near the present site of Los Angeles (Schellart et al. 2010), creating the Mendicino Triple

Junction (MTJ) that began migrating northward relative to stable North America at about 33 mm/yr (Atwater & Stock 1998). Intermediate volcanism migrated southwestward across Nevada as the Farallon Plate hinge point rolled back and dipped more steeply into the mantle, increasing P, T and resultant dehydration (aqueous fluid) from the slab. Extensional stress affected the chemistry of the melts starting ca. 14 Ma within the region of what is now identified as the Walker Lane. An episode ca. 12 Ma was particularly voluminous and extensive as major andesitic stratovolcanos developed around the western GB and eastern part of the eastern ACA (e.g. Pyramid Lake and Carson Range). This episode was coeval with a major episode of extension recognized along much of the eastern margin of the Sierra Nevada (Stewart 1992, Stockli et al. 2000; Henry & Perkins, 2001).

By 10-12 Ma, the rate of subduction slowed as well as the rate of east-west migration, and higher volumes of mafic magmatism erupted in the eastern ACA. As the angle of subduction increased, heating of the slab resulted in larger contributions from the slab-derived fluids into the widening mantle wedge. Concurrently the slab window was expanding to the south of the study area (latitude ca. 31°) as the Mendicino Triple Junction continued to migrate northward (Schellart et al. 2010, Atwater & Stock 1998) at a rate of about 52 mm/yr (Atwater & Stock 1998). Extension continued to fracture and thin the lithosphere in northern and southern B&R (Schellart et al. 2010, Henry 2009, Dickinson 2002) as well as increasing lithospheric tensile stress between eastern ACA and western GB (from Sparks, around Pyramid Lake, Lousetown, Coal Valley and Carson Range). The angle of subduction increased and, west of longitude 120°, and P-T conditions are high enough to produce sediment melt components from the Farallon slab

to infiltrate the mantle wedge. By 5 Ma, the rate of subduction slowed to 8 cm/yr (Leeman 1982) and the slab angle equilibrated in the mantle (Figure 2.16D). Slab components continued to infiltrate the mantle wedge ($(\text{Sr}/\text{P})_{\text{pmn}} = 2\text{--}5$) and melting resulted in mafic extrusives in the western ACA (Stampede Reservoir, Ladybug region, Portola and Mt. Lincoln). A distinct, less enriched lithospheric mantle component contributed to magmas in the westernmost part of the ACA (Sierra Nevada) including lavas of Squaw, Pond Terrace, Devil's Peak and Lowell Ridge, resulting in lower overall $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios (Putirka et al. 2012). ACA lavas evolved mainly by fractional crystallization, and less so by AFC processes.

5.5 Future Work

Now that work has been completed on mafic and intermediate melts (magma source and evolution), I recommend looking to felsic magmatism (Ignimbrite flare-up, caldera complexes). That is: what is going on in the upper crust and how does the story connect with intermediate and mafic lavas?

A problem that should be further explored is the relationship between extension and subduction that generated the Pyramid Lake volcanism. ICP-MS trace element data as well as Sr, Nd, Pb and O isotopic data will better identify magmatic generation and evolutions of the Pyramid Lavas, and their possible connection to the early formation of the Walker Lane.

Future work should also investigate magmatism due to subduction-related backarc versus Basin and Range extension. Large volumes of low-K basalts and basaltic andesites in the Lousetown, Carson Range (12 Ma) and Truckee Range, for example,

erupted ca. 8 to 12 Ma, at a time of regional extension. To compare, high-alumina olivine tholeiite or low-K tholeiite are common mafic rocks in the modern Cascades that are interpreted to represent near-primary melts of a relatively dry subarc to backarc mantle or unmetasomatized lithospheric mantle (Guffanti et al. 1990, Hughes 1990, Baker et al. 1994, Bacon et al. 1997, Conrey et al. 1997, Hart et al. 1997, Leeman et al. 2005). Isotopic data suggests the Lousetown, Carson Range (12 Ma) and Truckee Range melts were generated from a modified CLM; however, trace element data confirms a thinning or fractured lithosphere. Detailed comparative geochemical analyses should attempt to isolate specific trace element and isotopic signatures that can distinguish backarc extension from other tectonic forces.

My final suggestion is to further investigate volcanism surrounding Virginia City. Virginia City volcanics are generally andesitic in composition and range in age from 15.2 to 15.9 Ma (Castor et al. 2005). One magmatic event, however, erupted ca. 27 Ma, which is highly unusual when considering the chronological model that supports magmatism due to slab rollback. Is the 27 Ma magmatic event related to the southwestward migration that plagued the study area? To help answer this question, investigative ICP-MS trace element as well as isotopic analyses should be completed.

Appendices

Appendix A MAJOR- AND TRACE-ELEMENT COMPOSITIONS FOR MAFIC ROCKS

	Great Basin										
SAMPLE LOCATION	04-LT-48 Bell Canyon	04-LT-51 Bell Canyon	04-LT-41 Stillwater Mtns	11-CN-08 Stillwater Mtns	11-CN-09 Stillwater Mtns	04-LT-08 Truckee Rg	04-LT-05 Truckee Rg	04-LT-02 Truckee Rg	04-LT-06 Truckee Rg	04-LT-10 HotSprings Mtns	04-LT-09 HotSprings Mtns
Latitude	39.144	39.169	39.395	39.274	39.508	39.730	39.726	39.725	39.726	39.768	39.768
Longitude	-118.170	-118.226	-118.304	-118.403	-118.408	-119.276	-119.283	-119.283	-119.284	-118.983	-118.983
SiO2	53.32	50.40	53.37	48.15	49.19	53.56	52.98	52.82	55.32	53.20	53.79
TiO2	0.83	1.51	1.20	1.75	1.46	1.33	1.19	1.34	1.04	1.42	1.41
Al2O3	16.16	17.33	16.89	16.48	15.90	17.00	17.81	17.20	17.10	16.85	16.84
Fe2O3t	5.09	10.40	8.84	10.99	9.77	8.91	9.06	9.29	8.07	8.59	8.97
MnO	0.09	0.15	0.16	0.16	0.17	0.14	0.15	0.14	0.13	0.11	0.14
MgO	1.98	4.43	4.17	5.34	6.59	4.27	4.36	4.53	3.95	4.06	4.21
CaO	5.39	8.72	7.66	9.73	7.98	7.19	7.46	7.55	6.76	6.97	6.85
Na2O	4.43	3.53	3.44	3.01	3.21	3.78	3.77	3.68	3.76	3.97	3.94
K2O	2.58	1.33	1.64	1.14	1.42	1.87	1.76	1.70	2.11	2.02	2.07
P2O5	0.27	0.60	0.45	0.60	0.63	0.55	0.62	0.54	0.50	0.62	0.63
L.O.I.	1.30	1.50	2.00	1.99	2.88	0.90	0.80	0.40	0.50	1.80	0.90
Total	91.91	100.39	100.32	99.57	99.45	100.02	100.47	99.71	99.77	100.12	100.25
V	103	247	196	264.26	212.56	184	187	192	157	177	164
Cr	10	68	52	135	211	66	52	72	55	46	49
Co	13	28	26	34.9	35.5	35	28	33	22	27	24
Ni	7	35	64	47	122	112	90	240	75	60	59
Zn	74	115	98	107	104	110	113	111	103	119	119
Ba	1066	1143	757	763	870	972	1069	911	1077	1105	1118
La	28.2	30.0	23.0	25.0	30.7	30.6	34.2	28.6	34.2	41.3	42.1
Ce	58.0	64.8	50.7	56.4	67.3	65.9	74.7	62.1	72.9	88.8	90.5
Pr	6.9	9.0	6.6	7.8	8.9	8.4	9.5	8.0	9.2	11.3	11.4
Nd	27.2	38.1	28.2	33.9	37.8	34.5	39.1	34.0	37.3	45.7	46.7
Sm	5.1	8.0	5.7	7.4	7.8	7.0	7.7	6.8	7.2	8.9	9.0
Eu	1.4	2.1	1.5	2.1	2.1	1.8	2.0	1.8	1.8	2.1	2.1
Gd	4.4	7.0	5.1	6.7	6.9	6.0	6.3	5.9	5.9	7.6	7.6
Tb	0.6	1.0	0.7	1.0	1.0	0.9	0.9	0.8	0.8	1.1	1.1
Dy	3.8	5.8	4.1	5.8	5.7	4.8	5.0	4.8	4.7	6.2	6.3
Ho	0.8	1.1	0.8	1.2	1.1	0.9	1.0	0.9	0.9	1.2	1.2
Er	2.2	3.1	2.3	3.2	3.1	2.7	2.8	2.7	2.6	3.5	3.5
Tm	0.3	0.4	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5
Yb	2.1	2.9	2.1	2.9	2.8	2.5	2.5	2.4	2.4	3.2	3.3
Lu	0.3	0.4	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5
Rb	67.5	21.2	36.3	19.8	23.0	33.6	25.6	29.3	39.6	26.1	36.2
Sr	615	911	695	671	670	734	820	734	748	733	707
Nb	12.2	11.7	8.1	15.5	12.9	13.5	11.9	12.8	10.7	21.9	22.1
Cs	2.3	0.6	1.1	0.4	0.5	0.4	0.7	0.7	0.9	1.0	0.8
Hf	5.4	4.5	3.5	3.9	4.6	5.1	5.4	4.9	5.6	7.3	7.4
Ta	0.7	0.6	0.4	0.9	0.7	0.7	0.6	0.7	0.5	1.0	1.1
Th	7.1	3.4	3.1	1.8	2.8	2.4	3.0	2.2	3.2	3.0	3.1
U	2.9	1.8	1.1	0.9	1.0	0.9	1.0	1.0	1.3	1.2	1.2
Y	21.1	30.3	22.0	30.7	29.9	26.5	26.8	25.8	26.3	33.2	33.7
Zr	223	190	140	160	195	227	239	214	254	336	341
Sc	12.9	26.4	20.7	33.9	26.2	19.8	18.7	20.9	18.6	18.6	17.8
Pb	14.9	9.5	9.8	5.0	8.1	11.1	10.7	10.4	12.9	11.4	11.1
(⁸⁷ Sr/ ⁸⁶ Sr) _i	0.704607	0.704711	0.705295	0.705040	0.704518	0.704834	0.704686	0.704773	0.704476	0.704700	0.704694
(¹⁴³ Nd/ ¹⁴⁴ Nd) _i	0.51270	0.51266	0.51272	0.51256	0.51268	0.51264	0.51270	0.51265	0.512642	0.51264	0.51265
(²⁰⁸ Pb/ ²⁰⁴ Pb) _i	38.764	38.690	38.376	38.488	38.438	38.463	38.428	38.423	38.426	38.452	38.472
(²⁰⁷ Pb/ ²⁰⁴ Pb) _i	15.663	15.639	15.549	15.578	15.563	15.574	15.569	15.563	15.570	15.569	15.576
(²⁰⁶ Pb/ ²⁰⁴ Pb) _i	18.979	18.972	18.881	18.920	18.925	18.905	18.876	18.883	18.875	18.913	18.915

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SAMPLE LOCATION	Eastern Ancestral Cascade Arc					Western Ancestral Cascade Arc								Precision (% Average Difference, except isotope ratios that are 2-sigma standard deviations)
	04-LT-32 Sparks	04-LT-31 Sparks	04-LT-25 Lousestoun	04-LT-24 Lousestoun	04-LT-01 Ladybud	04-LT-87 Portola	04-LT-83 Portola	04-LT-102 Pond Terrace	04-LT-21 Andesite Ridge	04-LT-103 Devils Peak	Towle #2 Lowell Ridge	Towle #1 Sawtooth	04-LT-68a Henness Pass	
Latitude	39.579	39.558	39.394	39.394	39.486	39.770	39.686	39.219	39.343	39.281	39.250	39.200	39.506	
Longitude	-119.701	-119.703	-119.607	-119.609	-120.047	-120.463	-120.495	-120.329	-120.351	-120.444	-120.792	-120.667	-120.829	
SiO ₂	53.13	52.65	52.74	52.06	52.86	52.56	49.28	54.14	52.75	51.26	52.26	48.93	51.32	0.5
TiO ₂	0.93	0.75	0.95	0.80	0.74	0.71	0.66	0.67	0.78	0.67	0.78	0.66	0.77	1.9
Al ₂ O ₃	16.87	16.35	18.31	17.99	17.02	16.33	14.97	13.47	16.74	14.34	16.76	15.19	17.81	1.2
Fe ₂ O ₃ t	8.89	8.81	8.70	8.66	8.40	8.38	9.62	8.97	8.82	9.04	8.07	9.47	9.97	1.6
MnO	0.15	0.16	0.15	0.15	0.14	0.14	0.15	0.16	0.15	0.14	0.13	0.16	0.18	3.4
MgO	6.26	6.92	4.29	5.64	7.48	8.24	12.08	7.62	6.03	10.61	6.92	11.97	6.24	1.7
CaO	8.27	9.33	8.78	9.91	8.64	8.62	9.28	10.35	9.60	9.83	9.08	10.04	8.55	1.9
Na ₂ O	3.52	3.05	3.47	3.16	3.17	3.21	2.33	2.27	2.55	2.35	2.40	2.22	2.81	2.7
K ₂ O	1.04	0.79	1.16	1.01	0.80	0.71	0.91	1.09	1.33	0.93	1.28	0.51	1.00	6.5
P ₂ O ₅	0.23	0.16	0.32	0.18	0.17	0.19	0.15	0.17	0.14	0.17	0.23	0.15	0.32	5.0
L.O.I.	0.20	0.00	0.90	0.10	0.40	1.20	0.30	1.60	1.00	0.70	1.10	0.00	0.40	5.0
Total	100.09	99.61	100.29	100.24	100.47	100.97	100.47	101.15	100.49	100.76	99.66	100.03	99.95	
V	188	216	172	234	195	177	197	232	268	194	213	226	184	4.0
Cr	186	236	26	109	314	452	862	312	95	620	222	983	188	6.4
Co	36	32	29	31	37	40	51	32	37	37	27	48	31	16.0
Ni	90	89	34	39	172	154	325	56	61	186	57	292	122	16.7
Zn	95	89	107	83	85	86	79	82	85	84	85	80	96	3.1
Ba	634	421	691	468	447	405	537	500	538	337	316	254	589	7.5
La	13.4	9.5	29.9	14.7	9.9	9.2	13.3	14.9	12.6	11.8	17.7	8.1	20.7	3.3
Ce	28.7	20.6	62.4	29.7	21.3	19.9	23.5	31.1	26.9	24.8	36.1	17.7	39.3	3.4
Pr	3.8	2.7	7.9	3.9	2.9	2.7	3.3	4.1	3.6	3.5	5.2	2.5	5.4	3.8
Nd	16.8	11.9	31.8	16.6	12.9	12.2	13.7	17.4	15.3	14.7	22.2	10.8	22.4	3.1
Sm	3.7	2.9	6.0	3.6	2.9	2.7	2.9	3.6	3.5	3.2	4.4	2.5	4.6	2.7
Eu	1.2	0.9	1.8	1.1	0.9	0.9	0.9	1.0	1.0	1.0	1.3	0.8	1.5	7.3
Gd	3.4	3.0	4.7	3.4	2.8	2.7	3.0	3.0	3.3	3.0	3.9	2.7	4.3	7.3
Tb	0.5	0.5	0.6	0.5	0.4	0.4	0.5	0.4	0.5	0.4	0.6	0.5	0.6	6.5
Dy	3.1	2.9	3.5	2.9	2.7	2.5	2.8	2.5	3.0	2.7	3.2	2.7	3.5	4.3
Ho	0.6	0.6	0.7	0.6	0.5	0.5	0.6	0.5	0.6	0.6	0.7	0.6	0.7	3.0
Er	1.7	1.8	1.9	1.7	1.6	1.5	1.8	1.4	1.8	1.6	1.8	1.7	1.9	4.7
Tm	0.2	0.3	0.3	0.2	0.2	0.2	0.3	0.2	0.3	0.2	0.3	0.3	0.3	6.5
Yb	1.6	1.7	1.7	1.6	1.5	1.4	1.7	1.3	1.7	1.5	1.7	1.7	1.8	4.5
Lu	0.2	0.3	0.3	0.2	0.2	0.2	0.3	0.2	0.3	0.2	0.3	0.3	0.3	5.3
Rb	17.1	10.0	14.1	12.6	12.1	14.0	16.5	15.0	27.3	12.4	14.7	11.0	21.4	3.5
Sr	732	500	1436	719	640	652	479	793	576	750	911	425	628	2
Nb	4.5	2.6	3.2	2.5	3.0	2.5	2.6	2.6	2.8	2.8	3.9	2.9	4.6	8.1
Cs	0.5	0.2	0.2	0.4	0.7	0.7	0.9	0.8	1.2	0.3	0.5	0.3	0.5	9.0
Hf	2.5	1.9	2.6	2.1	2.1	1.9	2.0	1.9	2.4	2.0	2.6	1.6	2.6	7.5
Ta	0.2	0.1	0.2	N.D.	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.3	14.6
Th	2.1	1.1	6.6	4.1	1.7	0.9	3.4	3.3	3.2	2.1	2.9	1.2	3.4	7.1
U	0.8	0.4	2.1	1.3	0.7	0.5	1.5	1.2	1.5	0.7	0.9	0.4	1.0	6.1
Y	16.3	16.4	18.7	16.1	15.0	14.3	19.6	12.9	16.6	15.1	17.5	15.2	19.5	6.3
Zr	96	72	92	76	77	68	74	71	87	76	96	59	99	4
Sc	23.9	34.2	18.2	31.4	28.0	27.3	34.2	34.9	38.0	32.8	37.7	40.7	21.3	3.5
Pb	8.7	5.9	16.6	5.9	8.4	6.6	11.9	7.1	7.6	3.7	5.5	3.6	5.5	1.0
(⁸⁷ Sr/ ⁸⁶ Sr) _i	0.704591	0.704332	0.704530	0.704139	0.704719	0.704573	0.704913	0.703939	0.704727	0.704063	0.704264	0.706101	0.704629	0.000018
(¹⁴³ Nd/ ¹⁴⁴ Nd) _i	0.51271	0.51276	0.51274	0.51277	0.51269	0.51271	0.51271	0.51267	0.51273	0.51260	0.51254	0.51242	0.51264	0.043
(²⁰⁸ Pb/ ²⁰⁴ Pb) _i	38.661	38.675	38.322	38.323	38.464	38.618	38.801	38.736	38.451	38.865	38.301	38.726	38.697	0.013
(²⁰⁷ Pb/ ²⁰⁴ Pb) _i	15.641	15.652	15.533	15.536	15.573	15.620	15.645	15.647	15.567	15.684	15.626	15.687	15.619	0.010
(²⁰⁶ Pb/ ²⁰⁴ Pb) _i	18.949	18.894	18.882	18.851	18.909	18.932	19.050	18.952	18.906	19.000	18.933	19.125	19.016	0.05

Note: Major-element oxides (wt%) and trace elements V through Ba (ppm) were analyzed by X-ray fluorescence; La through Pb (ppm) were analyzed by acid-dissolution-inductively coupled plasma-mass spectrometry. Fe₂O₃t—total iron expressed as Fe₂O₃; LOI—loss on ignition; Precisions are based on repeat analyses of duplicate rocks over 5 yr time period.

Appendix B MAJOR- AND TRACE-ELEMENT COMPOSITIONS FOR VOLCANIC ROCKS FROM THE STUDY AREA WITH IDENTIFIERS 04-LT AND 11-CN.

Region SAMPLE Latitude Longitude	Westernmost ACA					Western ACA			
	04-LT-103	Towle #2	04-LT-102	04-LT-38	04-LT-94a	04-LT-17	04-LT-18	04-LT-23	04-LT-22
Latitude	39.281	39.250	39.219	39.306	40.403	39.331	39.330	39.366	39.359
Longitude	-120.444	-120.792	-120.329	-120.413	-120.838	-120.343	-120.349	-120.354	-120.364
SiO ₂	51.26	52.26	54.14	75.22	62.14	53.77	58.28	57.90	57.28
TiO ₂	0.67	0.78	0.67	0.12	0.50	1.23	1.06	0.59	0.75
Al ₂ O ₃	14.34	16.76	13.47	13.08	15.28	17.48	16.64	18.04	18.52
Fe ₂ O _{3t}	9.04	8.07	8.97	1.08	4.84	9.12	7.39	6.70	6.52
MnO	0.14	0.13	0.16	0.02	0.10	0.16	0.16	0.14	0.13
MgO	10.61	6.92	7.62	0.15	1.87	3.44	2.21	3.21	1.80
CaO	9.83	9.08	10.35	0.72	4.72	6.85	4.80	6.90	7.24
Na ₂ O	2.35	2.40	2.27	3.49	3.28	3.61	4.26	3.84	4.24
K ₂ O	0.93	1.28	1.09	4.64	2.43	2.21	3.12	1.31	1.73
P ₂ O ₅	0.17	0.23	0.17	0.02	0.14	0.47	0.53	0.23	0.30
L.O.I.	0.70	1.10	1.60	1.60	4.65	1.10	1.10	1.70	1.30
Total	100.76	99.66	101.15	100.38	100.39	99.90	99.95	101.08	100.19
V	194	213	232	5	89	230	105	131	128
Cr	620	222	312	18	8	-4	5	46	4
Co	37	27	32	5	18	26	15	18	14
Ni	186	57	56	5	4	58	28	35	35
Zn	84	85	82	32	60	107	109	93	97
Ba	337	316	500	718	803	902	1194	852	874
La	11.8	17.7	14.9	58.0	19.1	33.7	39.2	19.3	14.5
Ce	24.8	36.1	31.1	84.0	37.0	72.1	84.6	38.1	30.0
Pr	3.5	5.2	4.1		4.2	9.6	10.7	4.6	4.2
Nd	14.7	22.2	17.4	29.0	16.2	39.3	43.7	18.1	17.6
Sm	3.2	4.4	3.6		3.2	8.1	8.9	3.4	3.8
Eu	1.0	1.3	1.0		0.8	1.7	1.9	1.0	1.0
Gd	3.0	3.9	3.0		3.0	7.1	7.6	2.9	3.3
Tb	0.4	0.6	0.4		0.5	1.0	1.1	0.4	0.5
Dy	2.7	3.2	2.5		3.0	6.1	6.7	2.7	2.8
Ho	0.6	0.7	0.5		0.6	1.2	1.4	0.5	0.6
Er	1.6	1.8	1.4		1.9	3.5	4.0	1.6	1.6
Tm	0.2	0.3	0.2		0.3	0.5	0.6	0.2	0.2
Yb	1.5	1.7	1.3		1.9	3.4	3.8	1.6	1.5
Lu	0.2	0.3	0.2		0.3	0.5	0.6	0.3	0.2
Rb	12.4	14.7	15.0		61.1	72.8	100.3	24.5	31.6
Sr	750	911	793		289	606	514	634	798
Nb	2.8	3.9	2.6		5.7	8.0	10.5	5.5	5.0
Cs	0.3	0.5	0.8			5.6	7.0	0.8	0.6
Hf	2.0	2.6	1.9		3.0	6.2	7.9	3.1	3.9
Ta	0.2	0.3	0.2		0.5	0.4	0.6	0.3	0.3
Th	2.1	2.9	3.3	30.0	7.9	9.8	12.5	3.0	3.3
U	0.7	0.9	1.2	15.0	3.0	3.9	7.1	1.1	1.1
Y	15.1	17.5	12.9			33.4	37.2	15.9	14.9
Zr	76	96	71		106	236	307	128	150
Sc	32.8	37.7	34.9		12.0	24.3	17.5	16.3	5.6
Pb	3.7	5.5	7.1	38.0	13.5	16.4	22.3	9.8	10.0
(⁸⁷ Sr/ ⁸⁶ Sr) _i	0.704063	0.704264	0.703939	0.704152	0.704098	0.704527	0.704565	0.704559	0.705275
Epsilon Nd	-0.84	-1.95	0.70	-1.83	-0.70	1.60	1.38	-1.25	2.44
(¹⁴³ Nd/ ¹⁴⁴ Nd) _i	0.512595	0.512538	0.512674	0.512544	0.512602	0.512720	0.512709	0.512574	0.512763
(²⁰⁸ Pb/ ²⁰⁴ Pb) _i	38.865	38.301	38.736	38.595	38.550	38.492	38.581	38.625	38.772
(²⁰⁷ Pb/ ²⁰⁴ Pb) _i	15.684	15.626	15.647	15.618	15.610	15.577	15.592	15.616	15.654
(²⁰⁶ Pb/ ²⁰⁴ Pb) _i	19.000	18.933	18.952	18.900	18.875	18.921	18.933	18.946	18.995

continued...

Region	Western ACA								
SAMPLE	04-LT-55	04-LT-56	04-LT-68a	04-LT-65	04-LT-01	04-LT-83	04-LT-87	04-LT-85	04-LT-90
Latitude	39.067	39.067	39.506	39.466	39.486	39.686	39.770	39.772	39.857
Longitude	-120.230	-120.197	-120.829	-120.761	-120.047	-120.495	-120.463	-120.441	-120.546
SiO2	58.70	59.12	51.32	57.50	52.86	49.28	52.56	59.30	57.32
TiO2	0.63	0.71	0.77	0.54	0.74	0.66	0.71	0.61	0.69
Al2O3	18.64	16.98	17.81	17.61	17.02	14.97	16.33	17.22	18.01
Fe2O3t	6.21	6.28	9.97	7.01	8.40	9.62	8.38	5.82	6.81
MnO	0.10	0.11	0.18	0.14	0.14	0.15	0.14	0.11	0.11
MgO	2.36	3.59	6.24	3.86	7.48	12.08	8.24	3.27	3.53
CaO	6.39	6.00	8.55	6.73	8.64	9.28	8.62	6.34	7.16
Na2O	4.13	3.65	2.81	3.36	3.17	2.33	3.21	4.08	3.89
K2O	1.71	2.36	1.00	1.38	0.80	0.91	0.71	1.58	1.34
P2O5	0.31	0.27	0.32	0.33	0.17	0.15	0.19	0.19	0.25
L.O.I.	0.70	0.80	0.40	0.30	0.40	0.30	1.20	1.00	n.d.
Total	100.33	100.42	99.95	103.76	100.47	100.47	100.97	100.07	99.11
V	108	135	184	114	195	197	177	124	143
Cr	-1	69	188	123	314	862	452	100	39
Co	20	24	31	23	37	51	40	18	22
Ni	23	51	122	20	172	325	154	53	38
Zn	91	77	96	84	85	79	86	78	89
Ba	1043	1206	589	756	447	537	405	845	731
La	19.1	25.0	20.7	27.7	9.9	13.3	9.2	16.1	24.5
Ce	33.8	48.2	39.3	53.0	21.3	23.5	19.9	33.1	44.2
Pr	4.5	5.9	5.4	6.8	2.9	3.3	2.7	4.0	5.7
Nd	17.6	22.6	22.4	26.4	12.9	13.7	12.2	15.9	22.7
Sm	3.2	4.2	4.6	4.8	2.9	2.9	2.7	3.1	4.2
Eu	0.8	1.0	1.5	1.4	0.9	0.9	0.9	0.9	1.2
Gd	2.6	3.4	4.3	3.9	2.8	3.0	2.7	2.6	3.5
Tb	0.4	0.5	0.6	0.6	0.4	0.5	0.4	0.4	0.5
Dy	2.1	2.7	3.5	3.2	2.7	2.8	2.5	2.1	2.7
Ho	0.4	0.5	0.7	0.6	0.5	0.6	0.5	0.4	0.5
Er	1.2	1.5	1.9	1.8	1.6	1.8	1.5	1.2	1.5
Tm	0.2	0.2	0.3	0.3	0.2	0.3	0.2	0.2	0.2
Yb	1.1	1.5	1.8	1.8	1.5	1.7	1.4	1.1	1.4
Lu	0.2	0.2	0.3	0.3	0.2	0.3	0.2	0.2	0.2
Rb	39.2	56.6	21.4	37.2	12.1	16.5	14.0	32.5	26.6
Sr	819	637	628	693	640	479	652	726	951
Nb	6.8	8.3	4.6	5.5	3.0	2.6	2.5	3.7	3.8
Cs	1.2	1.9	0.5	1.5	0.7	0.9	0.7	2.0	0.9
Hf	4.0	4.4	2.6	3.8	2.1	2.0	1.9	2.8	2.6
Ta	0.4	0.5	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Th	3.3	8.4	3.4	5.8	1.7	3.4	0.9	2.9	7.5
U	1.6	2.9	1.0	1.9	0.7	1.5	0.5	1.3	2.8
Y	11.7	14.8	19.5	18.4	15.0	19.6	14.3	11.4	15.5
Zr	163	174	99	154	77	74	68	104	102
Sc	6.8	13.3	21.3	15.9	28.0	34.2	27.3	13.7	15.2
Pb	11.1	12.7	5.5	10.0	8.4	11.9	6.6	13.4	13.8
(⁸⁷ Sr/ ⁸⁶ Sr) _i	0.704667	0.705740	0.704629	0.705565	0.704719	0.704913	0.704573	0.704583	0.704802
Epsilon Nd	-2.65	-1.50	0.04	0.04	0.92	1.35	1.40	0.96	1.23
(¹⁴³ Nd/ ¹⁴⁴ Nd) _i	0.512502	0.512561	0.512640	0.512640	0.512685	0.512707	0.512710	0.512687	0.512701
(²⁰⁸ Pb/ ²⁰⁴ Pb) _i	38.692	38.939	38.697	38.961	38.464	38.801	38.618	38.609	38.668
(²⁰⁷ Pb/ ²⁰⁴ Pb) _i	15.628	15.688	15.619	15.696	15.573	15.645	15.620	15.611	15.637
(²⁰⁶ Pb/ ²⁰⁴ Pb) _i	18.983	19.083	19.016	19.083	18.909	19.050	18.932	18.957	18.948

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Region	Western ACA								Eastern ACA	
SAMPLE	04-LT-91	Towle #1	04-LT-80	04-LT-82	04-LT-81	04-LT-97	04-LT-92	04-LT-95	04-LT-69	04-LT-72
Latitude	39.887	39.200	39.537	39.577	39.561	40.475	40.355	40.400	39.274	39.264
Longitude	-120.521	-120.667	-120.264	-120.281	-120.253	-120.749	-120.560	-120.838	-119.731	-119.672
SiO2	63.61	48.93	57.66	59.83	59.92	57.19	61.72	63.96	57.48	57.66
TiO2	0.39	0.66	0.64	0.56	0.52	0.83	0.65	0.52	0.93	0.76
Al2O3	17.35	15.19	17.72	17.27	17.14	17.30	17.11	16.47	17.92	17.77
Fe2O3t	4.13	9.47	7.28	6.47	6.00	7.33	6.31	4.97	6.97	6.81
MnO	0.09	0.16	0.12	0.13	0.11	0.11	0.11	0.06	0.11	0.12
MgO	1.74	11.97	3.36	2.99	2.56	3.87	1.60	1.49	3.62	4.13
CaO	4.68	10.04	6.64	6.43	5.44	6.57	4.69	4.64	6.96	7.19
Na2O	4.44	2.22	3.48	3.60	3.48	3.63	4.10	3.73	4.09	3.69
K2O	1.57	0.51	1.65	1.67	1.85	1.69	2.12	2.37	1.60	1.68
P2O5	0.21	0.15	0.19	0.18	0.18	0.29	0.17	0.14	0.32	0.19
L.O.I.	1.60	0.00	0.80	1.10	3.00	1.30	1.30	1.30	3.00	1.70
Total	100.29	100.03	100.05	100.73	100.68	100.65	100.25	100.05	103.00	101.70
V	58	226	156	131	83	160	108	102	185	166
Cr	19	983	11	21	10	71	5	10	23	68
Co	14	48	22	21	16	23	20	10	23	28
Ni	29	292	30	31	25	44	28	16	45	48
Zn	73	80	80	78	75	77	67	61	100	74
Ba	877	254	699	726	754	763	822	776	687	667
La	18.0	8.1	17.5	18.1	19.1	31.1	17.4	21.5	18.4	16.5
Ce	33.6	17.7	35.6	35.5	36.4	45.1	35.0	36.6	40.1	32.7
Pr	4.1	2.5	4.3	4.3	4.5	8.1	4.2	5.0	5.3	4.2
Nd	15.4	10.8	17.7	16.5	17.0	33.3	17.0	19.1	22.0	16.9
Sm	2.7	2.5	3.6	3.2	3.3	6.6	3.4	3.8	4.5	3.6
Eu	0.8	0.8	1.0	0.9	0.9	1.8	1.0	1.0	1.3	1.1
Gd	2.2	2.7	3.1	2.8	2.8	5.8	3.1	3.5	3.9	3.2
Tb	0.3	0.5	0.5	0.4	0.4	0.8	0.5	0.5	0.5	0.5
Dy	1.7	2.7	2.8	2.5	2.5	4.8	2.8	3.2	3.0	2.9
Ho	0.3	0.6	0.6	0.5	0.5	1.0	0.6	0.7	0.6	0.6
Er	1.0	1.7	1.7	1.6	1.5	2.8	1.7	2.1	1.7	1.7
Tm	0.1	0.3	0.3	0.2	0.2	0.4	0.3	0.3	0.2	0.3
Yb	0.9	1.7	1.7	1.5	1.5	2.6	1.8	2.2	1.7	1.7
Lu	0.1	0.3	0.3	0.2	0.2	0.4	0.3	0.3	0.3	0.3
Rb	32.2	11.0	38.2	35.4	39.5	41.2	46.5	70.0	27.4	35.9
Sr	750	425	604	578	543	548	416	344	860	585
Nb	4.5	2.9	4.4	4.5	4.9	6.8	4.9	5.9	4.7	4.0
Cs	1.6	0.3	1.2	1.2	0.8	1.7	1.3	2.3	0.5	1.7
Hf	2.4	1.6	2.9	2.2	2.2	3.6	3.7	3.1	3.2	2.9
Ta	0.3	0.2	0.3	0.3	0.3	0.4	0.3	0.4	0.3	0.3
Th	3.0	1.2	4.3	4.5	5.0	4.2	5.1	7.5	3.2	3.8
U	1.3	0.4	1.8	1.8	1.6	1.5	2.1	2.8	1.2	1.6
Y	10.3	15.2	17.4	14.8	14.7	27.3	16.0	19.2	16.5	16.3
Zr	90	59	110	80	80	147	142	112	118	111
Sc	6.5	40.7	16.2	16.5	13.7	18.8	13.1	13.5	15.7	18.0
Pb	14.7	3.6	7.7	9.8	11.9	9.4	13.7	12.8	16.8	10.5
(⁸⁷ Sr/ ⁸⁶ Sr) _i	0.704573	0.706101	0.704754	0.704663	0.704491	0.704613	0.704336	0.704404	0.704088	0.704704
Epsilon Nd	1.35	-4.29	2.62	2.61	2.61	2.13	3.26	0.02	2.51	2.50
(¹⁴³ Nd/ ¹⁴⁴ Nd) _i	0.512707	0.512418	0.512789	0.512781	0.512772	0.512747	0.512805	0.512639	0.512792	0.512766
(²⁰⁸ Pb/ ²⁰⁴ Pb) _i	38.633	38.726	38.893	38.597	38.729	38.764	38.701	38.797	38.601	38.607
(²⁰⁷ Pb/ ²⁰⁴ Pb) _i	15.626	15.687	15.664	15.610	15.646	15.638	15.639	15.655	15.638	15.629
(²⁰⁶ Pb/ ²⁰⁴ Pb) _i	18.969	19.125	19.142	18.943	18.978	18.919	18.962	19.063	18.867	18.897

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Region	Eastern ACA								
SAMPLE	04-LT-36	04-LT-26	04-LT-28	04-LT-27a	04-LT-27b	04-LT-24	04-LT-25	04-LT-35b	04-LT-34
Latitude	39.465	39.405	39.406	39.406	39.406	39.394	39.394	39.472	39.472
Longitude	-119.744	-119.569	-119.564	-119.563	-119.563	-119.609	-119.607	-119.755	-119.757
SiO2	59.31	60.82	68.14	72.98	73.45	52.06	52.74	56.08	58.03
TiO2	0.80	0.85	0.56	0.29	0.35	0.80	0.95	0.90	0.78
Al2O3	17.86	17.25	17.13	14.22	14.26	17.99	18.31	17.79	17.49
Fe2O3t	6.32	5.84	2.61	1.74	1.50	8.66	8.70	7.56	6.81
MnO	0.12	0.10	0.06	0.04	0.02	0.15	0.15	0.12	0.12
MgO	2.65	2.84	1.03	0.43	0.28	5.64	4.29	2.99	2.74
CaO	6.49	5.55	2.53	2.01	1.68	9.91	8.78	7.06	6.43
Na2O	4.21	3.92	2.96	3.64	3.84	3.16	3.47	4.07	4.12
K2O	1.99	2.53	4.86	4.59	4.54	1.01	1.16	1.74	1.92
P2O5	0.26	0.30	0.13	0.06	0.08	0.18	0.32	0.29	0.24
L.O.I.	1.00	1.40	5.10	1.30	1.30	0.10	0.90	1.20	0.70
Total	101.00	101.40	105.10	101.30	101.30	100.24	100.29	100.26	99.84
V	154	147	40	24	28	234	172	172	139
Cr	8	30	7	8	5	109	26	16	21
Co	22	20	6	9	7	31	29	22	23
Ni	25	67	20	36	22	39	34	22	33
Zn	105	88	60	38	37	83	107	111	110
Ba	844	922	1240	1107	1124	468	691	820	810
La	15.5	25.6	33.7	29.8	31.5	14.7	29.9	16.8	13.6
Ce	31.2	55.5	60.3	57.0	59.6	29.7	62.4	32.6	26.8
Pr	4.1	7.1	7.6	6.2	6.8	3.9	7.9	4.6	3.5
Nd	17.3	28.9	28.9	21.5	24.2	16.6	31.8	19.8	14.8
Sm	3.5	5.7	5.2	3.6	4.1	3.6	6.0	4.0	3.1
Eu	1.0	1.3	1.1	0.6	0.8	1.1	1.8	1.1	0.9
Gd	3.1	4.9	4.1	2.6	3.0	3.4	4.7	3.3	2.8
Tb	0.5	0.7	0.6	0.4	0.4	0.5	0.6	0.5	0.4
Dy	2.6	4.1	3.6	2.3	2.7	2.9	3.5	2.7	2.4
Ho	0.5	0.8	0.7	0.5	0.5	0.6	0.7	0.5	0.5
Er	1.5	2.4	2.2	1.4	1.6	1.7	1.9	1.5	1.4
Tm	0.2	0.4	0.3	0.2	0.3	0.2	0.3	0.2	0.2
Yb	1.4	2.3	2.3	1.6	1.8	1.6	1.7	1.3	1.3
Lu	0.2	0.3	0.4	0.2	0.3	0.2	0.3	0.2	0.2
Rb	47.4	61.6	105.3	144.8	136.8	12.6	14.1	36.7	45.2
Sr	722	652	411	258	282	719	1436	899	731
Nb	4.8	7.0	11.0	8.4	9.0	2.5	3.2	4.6	4.7
Cs	1.1	1.6	7.4	4.7	4.7	0.4	0.2	0.7	0.9
Hf	3.5	4.2	7.0	4.3	4.9	2.1	2.6	3.3	3.5
Ta	0.3	0.4	0.8	0.7	0.7	N.D.	0.2	0.3	0.3
Th	4.0	7.5	17.4	19.9	18.7	4.1	6.6	4.2	3.8
U	1.7	2.8	5.3	6.3	6.3	1.3	2.1	1.9	1.8
Y	14.2	23.2	21.3	13.3	15.5	16.1	18.7	14.2	12.6
Zr	137	160	266	131	162	76	92	125	133
Sc	11.3	15.5	5.8	4.0	4.2	31.4	18.2	12.5	10.6
Pb	10.5	17.2	29.5	25.5	22.6	5.9	16.6	11.3	12.8
(⁸⁷ Sr/ ⁸⁶ Sr) _i	0.704797	0.704806	0.704756	0.704750	0.704840	0.704139	0.704530	0.704617	0.704595
Epsilon Nd	1.31	1.30	0.99	1.17	0.94	2.59	2.07	1.05	0.99
(¹⁴³ Nd/ ¹⁴⁴ Nd) _i	0.512705	0.512686	0.512689	0.512698	0.512686	0.512771	0.512744	0.512692	0.512689
(²⁰⁸ Pb/ ²⁰⁴ Pb) _i	38.658	38.618	38.688	38.764	38.660	38.323	38.322	38.686	38.622
(²⁰⁷ Pb/ ²⁰⁴ Pb) _i	15.637	15.623	15.644	15.668	15.637	15.536	15.533	15.611	15.623
(²⁰⁶ Pb/ ²⁰⁴ Pb) _i	18.920	18.925	18.942	18.956	18.931	18.851	18.882	18.937	18.914

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Region	Eastern ACA									
SAMPLE	04-LT-37a	04-LT-31	04-LT-32	04-LT-30a	04-LT-29a	04-LT-30b	04-LT-29b	04-LT-33a	04-LT-33b	04-LT-70a
Latitude	39.464	39.558	39.579	39.582	39.584	39.582	39.584	39.575	39.575	39.278
Longitude	-119.805	-119.703	-119.701	-119.679	-119.675	-119.679	-119.675	-119.700	-119.700	-119.701
SiO2	59.64	52.65	53.13	59.40	59.67	60.48	60.82	62.25	63.85	57.27
TiO2	0.66	0.75	0.93	0.70	0.69	0.71	0.71	0.65	0.67	0.65
Al2O3	16.75	16.35	16.87	17.63	17.53	17.95	17.87	17.25	17.69	17.73
Fe2O3t	5.64	8.81	8.89	6.20	6.10	5.68	5.60	5.09	4.70	6.89
MnO	0.09	0.16	0.15	0.10	0.10	0.10	0.10	0.10	0.10	0.13
MgO	2.47	6.92	6.26	2.80	2.70	2.85	2.75	0.97	0.99	3.07
CaO	5.89	9.33	8.27	6.16	5.95	6.27	6.06	4.48	4.60	6.56
Na2O	3.74	3.05	3.52	4.33	4.38	4.41	4.46	4.34	4.45	3.70
K2O	2.24	0.79	1.04	1.28	1.36	1.30	1.38	2.54	2.61	1.78
P2O5	0.21	0.16	0.23	0.24	0.24	0.24	0.24	0.34	0.35	0.23
L.O.I.	2.20	0.00	0.20	1.00	0.80	1.00	0.80	1.70	1.70	2.00
Total	100.02	99.61	100.09	100.33	100.01			100.00		100.50
V	126	216	188	118	117	118	117	84	84	125
Cr	21	236	186	48	54	48	54	36	36	22
Co	15	32	36	15	17	15	17	14	14	19
Ni	37	89	90	53	60	53	60	46	46	26
Zn	108	89	95	99	99	99	99	81	81	86
Ba	1203	421	634	761	781	761	781	1278	1278	743
La	20.9	9.5	13.4	15.9	16.2	15.9	16.2	22.8	22.8	15.3
Ce	35.8	20.6	28.7	33.5	33.9	33.5	33.9	45.9	45.9	31.2
Pr	5.3	2.7	3.8	4.5	4.5	4.5	4.5	5.4	5.4	3.9
Nd	22.4	11.9	16.8	19.5	19.1	19.5	19.1	20.8	20.8	16.1
Sm	4.2	2.9	3.7	3.8	3.9	3.8	3.9	3.7	3.7	3.3
Eu	1.1	0.9	1.2	1.2	1.1	1.2	1.1	0.9	0.9	1.0
Gd	4.0	3.0	3.4	3.3	3.2	3.3	3.2	2.8	2.8	2.9
Tb	0.6	0.5	0.5	0.5	0.4	0.5	0.4	0.4	0.4	0.4
Dy	3.3	2.9	3.1	2.5	2.4	2.5	2.4	2.1	2.1	2.5
Ho	0.7	0.6	0.6	0.5	0.4	0.5	0.4	0.4	0.4	0.5
Er	2.0	1.8	1.7	1.3	1.2	1.3	1.2	1.1	1.1	1.5
Tm	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Yb	1.9	1.7	1.6	1.1	1.0	1.1	1.0	1.1	1.1	1.5
Lu	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Rb	52.0	10.0	17.1	16.7	18.1	16.7	18.1	57.7	57.7	47.8
Sr	788	500	732	849	827	881	847	708	691	780
Nb	5.2	2.6	4.5	5.0	5.1	5.0	5.1	9.0	9.0	4.2
Cs	2.7	0.2	0.5	0.7	0.4	0.7	0.4	1.1	1.1	46.5
Hf	3.9	1.9	2.5	3.0	3.1	3.0	3.1	4.0	4.0	3.1
Ta	0.4	0.1	0.2	0.3	0.3	0.3	0.3	0.5	0.5	0.3
Th	5.6	1.1	2.1	1.0	1.1	1.0	1.1	3.7	3.7	3.2
U	2.4	0.4	0.8	0.5	0.6	0.5	0.6	1.9	1.9	1.4
Y	22.0	16.4	16.3	13.0	12.1	13.0	12.1	10.3	10.3	13.8
Zr	147	72	96	117	120	117	120	168	168	115
Sc	11.1	34.2	23.9	12.5	11.9	12.5	11.9	6.7	6.7	11.7
Pb	16.0	5.9	8.7	10.4	10.4	10.4	10.4	15.3	15.3	12.6
(⁸⁷ Sr/ ⁸⁶ Sr) _i	0.703682	0.704332	0.704591		0.704812	0.704813	0.704839	0.704819	0.704825	0.704848
Epsilon Nd	0.64	2.40	1.38	0.68	0.59	0.68	0.59	0.92	0.92	1.62
(¹⁴³ Nd/ ¹⁴⁴ Nd) _i	0.512671	0.512761	0.512709	0.512673	0.512668	0.512673	0.512668	0.512685	0.512685	0.512721
(²⁰⁸ Pb/ ²⁰⁴ Pb) _i	38.607	38.675	38.661	38.872	38.771	38.772	38.771	38.772	38.602	38.689
(²⁰⁷ Pb/ ²⁰⁴ Pb) _i	15.624	15.652	15.641	15.657	15.659	15.659	15.657	15.659	15.622	15.631
(²⁰⁶ Pb/ ²⁰⁴ Pb) _i	18.907	18.894	18.949	19.126	18.989	18.990	18.995	18.992	18.902	18.961

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Region	Eastern ACA			Western/Westernmost GB					
SAMPLE	04-LT-73a	04-LT-71a	04-LT-79a	11-CN-01	11-CN-02	11-CN-06	04-LT-12	04-LT-10	04-LT-09
Latitude	39.262	39.276	39.250	39.468	39.468	39.272	39.786	39.768	39.768
Longitude	-119.670	-119.689	-119.735	-119.209	-119.209	-119.175	-118.937	-118.983	-118.983
SiO ₂	57.47	58.04	58.21	54.55	55.12	53.86	52.26	53.20	53.79
TiO ₂	0.69	0.63	0.74	1.10	1.11	0.93	1.56	1.42	1.41
Al ₂ O ₃	17.15	17.82	17.03	17.56	17.72	17.74	17.56	16.85	16.84
Fe ₂ O _{3t}	6.72	6.58	5.52	8.69	8.31	7.48	9.79	8.59	8.97
MnO	0.13	0.13	0.08	0.14	0.14	0.12	0.16	0.11	0.14
MgO	3.18	2.99	3.06	3.76	3.67	3.65	4.23	4.06	4.21
CaO	6.34	6.41	5.46	6.78	6.75	6.99	7.37	6.97	6.85
Na ₂ O	3.66	4.06	4.07	3.63	3.67	3.73	4.02	3.97	3.94
K ₂ O	1.89	1.42	1.99	1.86	1.75	1.37	1.66	2.02	2.07
P ₂ O ₅	0.20	0.22	0.30	0.34	0.34	0.25	0.59	0.62	0.63
L.O.I.	1.70	1.90	3.70	2.31	2.12	5.11	1.10	1.80	0.90
Total	99.64	100.70	100.71	100.94	100.94	101.44	100.78	100.12	100.25
V	136	119	142	188	186	178	216	177	164
Cr	32	22	17	43	86	68	41	46	49
Co	17	21	18	22	23	23	27	27	24
Ni	26	32	34	20	21	32	69	60	59
Zn	75	83	59	102	104	89	126	119	119
Ba	783	756	780	899	1042	868	877	1105	1118
La	17.2	14.5	28.8	24.1	24.3	16.5	29.1	41.3	42.1
Ce	34.8	29.8	61.9	50.9	51.6	35.3	63.2	88.8	90.5
Pr	4.3	3.7	7.9	6.7	6.8	4.6	8.3	11.3	11.4
Nd	16.8	15.1	30.9	27.7	28.2	19.8	35.5	45.7	46.7
Sm	3.4	3.1	5.1	5.9	6.1	4.4	7.3	8.9	9.0
Eu	1.0	0.9	1.3	1.6	1.6	1.3	2.0	2.1	2.1
Gd	3.1	2.8	3.4	5.2	5.4	3.9	6.5	7.6	7.6
Tb	0.5	0.4	0.4	0.8	0.8	0.6	0.9	1.1	1.1
Dy	2.7	2.4	2.2	4.5	4.6	3.4	5.5	6.2	6.3
Ho	0.6	0.5	0.4	0.9	0.9	0.7	1.1	1.2	1.2
Er	1.6	1.5	1.1	2.5	2.6	1.9	3.1	3.5	3.5
Tm	0.2	0.2	0.2	0.4	0.4	0.3	0.4	0.5	0.5
Yb	1.6	1.4	1.1	2.4	2.5	1.8	2.9	3.2	3.3
Lu	0.2	0.2	0.2	0.4	0.4	0.3	0.4	0.5	0.5
Rb	104.6	41.9	30.8	26.9	25.9	18.6	22.9	26.1	36.2
Sr	577	727	1122	720	721	756	748	733	707
Nb	4.6	4.3	3.9	9.0	9.1	4.9	19.6	21.9	22.1
Cs	24.7	3.0	0.8	0.6	0.6	0.5	0.4	1.0	0.8
Hf	3.2	3.2	3.4	4.7	4.7	3.0	4.8	7.3	7.4
Ta	0.3	0.3	0.2	0.5	0.5	0.3	1.1	1.0	1.1
Th	4.3	3.4	5.5	2.0	2.1	1.6	2.4	3.0	3.1
U	1.8	1.5	1.9	0.9	0.9	0.6	1.0	1.2	1.2
Y	15.4	13.5	11.8	24.9	25.5	18.5	29.7	33.2	33.7
Zr	121	119	124	196	199	114	200	336	341
Sc	14.9	10.1	10.3	20.5	20.8	19.9	19.7	18.6	17.8
Pb	13.2	12.8	5.0	10.4	10.5	9.2	8.2	11.4	11.1
(⁸⁷ Sr/ ⁸⁶ Sr) _i	0.704501	0.704474	0.704530	0.704633	0.704694	0.704717	0.704554	0.704700	0.704694
Epsilon Nd	2.44	1.68	3.73	1.34	1.30	0.97	0.72	0.12	0.21
(¹⁴³ Nd/ ¹⁴⁴ Nd) _i	0.512763	0.512724	0.512829	0.512707	0.512705	0.512688	0.512675	0.512644	0.512649
(²⁰⁸ Pb/ ²⁰⁴ Pb) _i	38.659	38.621	38.520	38.410	38.432	38.480	38.454	38.452	38.472
(²⁰⁷ Pb/ ²⁰⁴ Pb) _i	15.635	15.632	15.612	15.565	15.571	15.582	15.571	15.569	15.576
(²⁰⁶ Pb/ ²⁰⁴ Pb) _i	18.936	18.900	18.849	18.861	18.868	18.880	18.901	18.913	18.915

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Region	Western/Westernmost GB								
SAMPLE	04-LT-11a	04-LT-11b	11-CN-15	11-CN-13	11-CN-30	11-CN-29	11-CN-14	418-33-2270-2280	418-33-2910-2920
Latitude	39.757	39.757	39.406	39.391	39.419	39.423	39.404	39.530	39.530
Longitude	-118.960	-118.960	-118.540	-118.610	-118.597	-118.606	-118.546	-118.870	-118.870
SiO2	58.37	67.02	53.66	53.96	54.72	55.56	69.23	57.83	57.89
TiO2	1.22	0.94	1.51	0.87	0.92	0.90	0.27	0.86	0.84
Al2O3	17.14	13.34	16.24	18.35	17.82	18.04	14.34	17.20	17.01
Fe2O3t	7.67	6.02	9.79	7.87	7.59	7.60	2.27	6.76	6.41
MnO	0.06	0.06	0.09	0.14	0.13	0.13	0.02	0.13	0.12
MgO	1.07	0.67	2.91	3.54	3.45	3.31	0.37	2.52	2.36
CaO	5.78	4.46	5.54	7.79	6.86	6.95	2.00	5.57	5.17
Na2O	4.01	3.10	3.19	3.69	3.90	3.83	3.05	3.85	4.15
K2O	2.92	2.33	2.97	1.09	1.26	1.41	5.67	2.12	2.15
P2O5	0.64	0.49	0.82	0.37	0.40	0.39	0.08	0.42	0.41
L.O.I.	0.40	1.10	4.43	1.75	1.59	1.90	3.09	2.27	2.23
Total	99.51	99.72	101.45	99.63	98.84	100.25	100.62	99.53	98.74
V	165	86	195	161	167	160	19	116	114
Cr	48	48	125	68	53	50	50	63	59
Co	15	17	25	20	21	21	6	13	13
Ni	51	55	42	13	16	16	6	9	7
Zn	100	76	111	95	104	98	37	105	103
Ba	1204	960	1544	608	780	782	1439	1504	1285
La	43.1	34.4	40.7	16.8	20.6	20.1	23.7	27.7	27.4
Ce	92.1	72.1	89.0	37.2	45.2	43.7	42.6	56.9	57.3
Pr	11.5	9.0	11.6	5.0	5.9	5.8	4.6	7.3	7.3
Nd	45.6	35.9	48.2	21.5	25.0	24.6	16.0	29.9	30.0
Sm	8.7	7.0	9.8	4.6	5.2	5.0	2.8	5.9	5.9
Eu	2.0	1.6	2.3	1.4	1.5	1.5	0.6	1.5	1.5
Gd	7.2	5.9	8.3	4.0	4.5	4.4	2.1	4.9	4.9
Tb	1.0	0.8	1.1	0.6	0.6	0.6	0.3	0.7	0.7
Dy	6.0	4.9	6.5	3.4	3.7	3.7	1.9	4.1	4.4
Ho	1.2	1.0	1.2	0.7	0.7	0.7	0.4	0.8	0.9
Er	3.3	2.8	3.4	1.9	2.1	2.0	1.0	2.3	2.5
Tm	0.5	0.4	0.5	0.3	0.3	0.3	0.2	0.3	0.4
Yb	3.2	2.5	3.0	1.8	1.9	1.9	1.1	2.1	2.4
Lu	0.5	0.4	0.4	0.3	0.3	0.3	0.2	0.3	0.4
Rb	59.6	29.2	63.9	10.8	18.2	16.4	150.3	29.0	28.2
Sr	592	484	512	960	895	873	250	644	586
Nb	17.4	13.4	15.7	5.4	6.1	6.0	6.7	8.9	9.0
Cs	1.6	5.0	2.6	0.7	0.4	0.2	7.0	1.4	0.5
Hf	7.6	5.9	5.9	2.8	3.3	3.3	2.9	4.2	5.0
Ta	0.8	0.6	0.8	0.3	0.3	0.3	0.6	0.4	0.5
Th	4.0	3.1	2.9	1.6	1.7	1.7	8.2	1.6	1.8
U	1.4	1.1	1.2	0.8	0.7	0.7	3.1	0.6	0.8
Y	32.5	26.5	34.0	18.3	20.9	19.8	10.5	22.5	24.5
Zr	347	263	260	107	134	130	99	165	209
Sc	19.6	14.8	23.5	17.3	17.4	16.5	4.9	13.0	13.3
Pb	18.8	14.7	9.9	5.7	7.7	6.2	20.3	12.8	9.9
(⁸⁷ Sr/ ⁸⁶ Sr) _i	0.704806	0.704834	0.707642	0.704316	0.704490	0.704516	0.704685		
Epsilon Nd	0.12	0.06	-0.43	1.29	0.82	0.82	1.56		
(¹⁴³ Nd/ ¹⁴⁴ Nd) _i	0.512644	0.512641	0.512616	0.512704	0.512680	0.512680	0.512718		
(²⁰⁸ Pb/ ²⁰⁴ Pb) _i	38.710	38.742	38.578	38.348	38.381	38.478	38.454		
(²⁰⁷ Pb/ ²⁰⁴ Pb) _i	15.645	15.654	15.602	15.555	15.558	15.586	15.583		
(²⁰⁶ Pb/ ²⁰⁴ Pb) _i	18.973	18.980	18.941	18.825	18.853	18.879	18.841		

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Region	Western/Westernmost GB								Central/West GB
SAMPLE	45A-33-2260-2280	04-LT-04	04-LT-02	04-LT-05	04-LT-08	04-LT-07	04-LT-03	04-LT-06	04-LT-51
Latitude	39.530	39.725	39.725	39.726	39.730	39.725	39.725	39.726	39.169
Longitude	-118.870	-119.283	-119.283	-119.283	-119.276	-119.283	-119.283	-119.284	-118.226
SiO ₂	58.33	52.71	52.82	52.98	53.56	53.69	53.85	55.32	50.40
TiO ₂	0.85	1.26	1.34	1.19	1.33	1.20	1.18	1.04	1.51
Al ₂ O ₃	17.14	17.53	17.20	17.81	17.00	17.45	17.46	17.10	17.33
Fe ₂ O ₃ t	6.20	9.28	9.29	9.06	8.91	8.96	8.99	8.07	10.40
MnO	0.11	0.14	0.14	0.15	0.14	0.15	0.14	0.13	0.15
MgO	2.15	4.08	4.53	4.36	4.27	3.97	3.82	3.95	4.43
CaO	5.33	7.48	7.55	7.46	7.19	7.11	7.22	6.76	8.72
Na ₂ O	4.01	3.63	3.68	3.77	3.78	3.88	3.81	3.76	3.53
K ₂ O	2.09	1.86	1.70	1.76	1.87	1.90	1.85	2.11	1.33
P ₂ O ₅	0.43	0.57	0.54	0.62	0.55	0.54	0.54	0.50	0.60
L.O.I.	2.25	1.00	0.40	0.80	0.90	0.50	0.70	0.50	1.50
Total	98.89	100.03	99.71	100.47	100.02	99.83	100.04	99.77	100.39
V	115	190	192	187	184	177	167	157	247
Cr	59	51	72	52	66	58	58	55	68
Co	23	24	33	28	35	31	23	22	28
Ni	13	115	240	90	112	73	88	75	35
Zn	106	110	111	113	110	114	108	103	115
Ba	1343	1045	911	1069	972	1033	1034	1077	1143
La	28.5	34.0	28.6	34.2	30.6	34.2	33.9	34.2	30.0
Ce	58.9	73.2	62.1	74.7	65.9	75.0	72.8	72.9	64.8
Pr	7.6	9.4	8.0	9.5	8.4	9.5	9.3	9.2	9.0
Nd	30.9	39.5	34.0	39.1	34.5	38.8	38.7	37.3	38.1
Sm	6.1	7.7	6.8	7.7	7.0	7.7	7.7	7.2	8.0
Eu	1.6	2.0	1.8	2.0	1.8	1.9	2.0	1.8	2.1
Gd	5.2	6.3	5.9	6.3	6.0	6.4	6.3	5.9	7.0
Tb	0.7	0.9	0.8	0.9	0.9	0.9	0.9	0.8	1.0
Dy	4.4	5.1	4.8	5.0	4.8	5.0	5.0	4.7	5.8
Ho	0.8	1.0	0.9	1.0	0.9	1.0	1.0	0.9	1.1
Er	2.5	2.8	2.7	2.8	2.7	2.8	2.8	2.6	3.1
Tm	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Yb	2.4	2.6	2.4	2.5	2.5	2.6	2.6	2.4	2.9
Lu	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Rb	30.0	32.9	29.3	25.6	33.6	32.7	32.3	39.6	21.2
Sr	650	821	734	820	734	792	798	748	911
Nb	9.3	12.9	12.8	11.9	13.5	12.1	11.6	10.7	11.7
Cs	2.1	0.9	0.7	0.7	0.4	0.5	0.5	0.9	0.6
Hf	5.0	5.3	4.9	5.4	5.1	5.5	5.4	5.6	4.5
Ta	0.5	0.6	0.7	0.6	0.7	0.6	0.6	0.5	0.6
Th	1.9	3.1	2.2	3.0	2.4	3.2	3.2	3.2	3.4
U	0.8	1.2	1.0	1.0	0.9	1.3	1.2	1.3	1.8
Y	24.6	28.0	25.8	26.8	26.5	27.2	27.2	26.3	30.3
Zr	212	242	214	239	227	241	235	254	190
Sc	13.2	19.7	20.9	18.7	19.8	20.2	19.0	18.6	26.4
Pb	11.4	10.1	10.4	10.7	11.1	12.5	10.3	12.9	9.5
(⁸⁷ Sr/ ⁸⁶ Sr) _i	0.705060	0.704525	0.704773	0.704686	0.704834	0.704478	0.704473	0.704476	0.704711
Epsilon Nd	-0.39	1.17	0.23	1.11	0.00	1.27	1.17	1.19	0.43
(¹⁴³ Nd/ ¹⁴⁴ Nd) _i	0.512618	0.512698	0.512650	0.512695	0.512638	0.512703	0.512698	0.512642	0.512660
(²⁰⁸ Pb/ ²⁰⁴ Pb) _i	38.731	38.418	38.423	38.428	38.463	38.420	38.426	38.426	38.690
(²⁰⁷ Pb/ ²⁰⁴ Pb) _i	15.642	15.565	15.563	15.569	15.574	15.568	15.570	15.570	15.639
(²⁰⁶ Pb/ ²⁰⁴ Pb) _i	19.004	18.881	18.883	18.876	18.905	18.872	18.875	18.875	18.972

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Region	Central/West GB								
SAMPLE	04-LT-48	04-LT-50	04-LT-49	04-LT-45	04-LT-47	11-CN-05a	11-CN-25a	11-CN-11[hnd]	11-CN-24
Latitude	39.144	39.162	39.146	39.264	39.251	39.297	39.684	39.562	39.684
Longitude	-118.170	-118.213	-118.181	-118.076	-118.072	-118.323	-117.697	-117.830	-117.697
SiO ₂	53.32	63.05	66.91	58.93	62.30	56.57	54.98	58.06	59.54
TiO ₂	0.83	0.62	0.47	0.81	0.64	0.78	0.93	1.17	0.78
Al ₂ O ₃	16.16	16.76	15.31	16.54	15.89	18.05	14.99	16.66	16.08
Fe ₂ O _{3t}	5.09	4.32	2.77	6.15	5.15	6.99	5.97	7.70	4.70
MnO	0.09	0.11	0.04	0.07	0.09	0.12	0.13	0.24	0.22
MgO	1.98	1.41	0.56	2.47	2.56	3.29	2.20	2.79	1.63
CaO	5.39	3.82	2.69	5.69	4.42	6.80	6.95	5.82	7.07
Na ₂ O	4.43	4.79	3.53	3.84	3.62	3.81	3.42	3.76	3.64
K ₂ O	2.58	3.12	4.23	2.30	2.87	1.36	2.38	2.56	3.10
P ₂ O ₅	0.27	0.24	0.15	0.35	0.23	0.27	0.45	0.63	0.36
L.O.I.	1.30	2.10	4.30	2.60	2.70	1.10	4.18	2.85	4.52
Total	91.91	100.76	101.27	100.21	100.99	99.38	96.92	102.57	101.94
V	103	64	31	86	105	148	174	132	140
Cr	10	6	10	33	43	51	55	60	51
Co	13	7	3	24	17	19	15	36	14
Ni	7	5	2	41	33	15	9	29	5
Zn	74	79	61	86	70	85	84	113	75
Ba	1066	1403	1324	1326	1155	853	1569	1543	1554
La	28.2	21.5	35.4	29.7	25.6	17.9	41.0	52.4	34.9
Ce	58.0	40.5	70.4	58.5	49.3	37.1	83.1	101.2	70.7
Pr	6.9	4.6	7.6	7.1	5.6	4.8	10.2	12.4	8.3
Nd	27.2	17.5	27.0	28.1	20.8	19.9	40.9	46.6	32.0
Sm	5.1	3.3	4.5	4.9	3.7	4.1	7.4	8.1	5.7
Eu	1.4	0.9	0.9	1.3	0.9	1.2	1.8	2.0	1.4
Gd	4.4	2.6	3.3	3.4	2.7	3.6	5.2	6.1	4.2
Tb	0.6	0.4	0.5	0.4	0.4	0.5	0.7	0.8	0.6
Dy	3.8	2.3	2.8	2.1	2.2	3.1	3.6	4.2	3.2
Ho	0.8	0.5	0.6	0.4	0.4	0.6	0.7	0.8	0.6
Er	2.2	1.4	1.7	1.0	1.2	1.8	1.8	2.1	1.7
Tm	0.3	0.2	0.2	0.1	0.2	0.3	0.3	0.3	0.2
Yb	2.1	1.4	1.7	0.9	1.1	1.7	1.6	1.8	1.6
Lu	0.3	0.2	0.3	0.1	0.2	0.3	0.3	0.3	0.2
Rb	67.5	78.5	121.2	53.6	74.5	20.6	41.8	66.1	80.0
Sr	615	507	323	1010	618	913	1291	763	830
Nb	12.2	10.6	16.6	6.7	8.6	5.2	8.3	17.6	9.4
Cs	2.3	2.4	2.3	1.5	1.4	0.4	0.6	1.1	1.3
Hf	5.4	5.8	4.8	3.1	3.4	3.0	4.3	6.2	4.4
Ta	0.7	0.7	1.1	0.4	0.6	0.3	0.5	0.9	0.6
Th	7.1	5.9	13.4	8.1	7.8	1.9	9.2	5.9	8.0
U	2.9	2.8	4.3	2.0	2.9	0.7	2.5	1.9	2.6
Y	21.1	13.0	16.2	10.2	11.8	17.6	18.6	22.2	17.1
Zr	223	253	168	116	123	116	174	278	168
Sc	12.9	5.8	5.1	11.0	11.5	16.3	15.3	15.2	15.7
Pb	14.9	16.2	16.6	17.5	18.9	7.4	12.1	14.9	12.1
(⁸⁷ Sr/ ⁸⁶ Sr) _i	0.704607	0.704683	0.704792	0.704752	0.704665	0.704669	0.705032	0.705026	0.705838
Epsilon Nd	1.15	0.45	0.62	0.86	0.18	0.27	-1.00	-1.17	-3.47
(¹⁴³ Nd/ ¹⁴⁴ Nd) _i	0.512697	0.512661	0.512670	0.512682	0.512647	0.512652	0.512587	0.512578	0.512460
(²⁰⁶ Pb/ ²⁰⁴ Pb) _i	38.764	38.658	38.667	38.679	38.681	38.797	38.611	38.609	38.701
(²⁰⁷ Pb/ ²⁰⁴ Pb) _i	15.663	15.629	15.637	15.634	15.638	15.677	15.599	15.605	15.615
(²⁰⁶ Pb/ ²⁰⁴ Pb) _j	18.979	18.954	18.959	18.953	18.955	18.960	18.997	18.991	19.064

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Region	Central/West GB								
SAMPLE	11-CN-25b	11-CN-23	11-CN-28a	11-CN-12a	11-CN-12b	11-CN-19	11-CN-20	11-CN-22b	11-CN-22a
Latitude	39.684	39.682	39.948	39.595	39.595	39.201	39.193	39.183	39.183
Longitude	-117.697	-117.697	-117.492	-117.786	-117.786	-117.839	-117.842	-117.829	-117.829
SiO2	59.88	61.22	61.96	76.34	81.18	58.46	58.47	60.74	65.79
TiO2	0.98	0.72	0.85	0.11	0.11	0.83	0.83	0.65	0.31
Al2O3	16.40	16.81	15.94	11.77	11.36	15.84	15.90	14.55	13.50
Fe2O3t	6.32	5.17	5.10	0.34	0.42	5.71	5.40	6.33	2.14
MnO	0.15	0.09	0.08	0.00	0.00	0.09	0.09	0.10	0.07
MgO	2.23	1.84	2.08	0.13	0.12	2.81	2.66	2.84	0.65
CaO	7.52	4.58	4.33	0.51	0.46	5.00	5.17	5.22	1.81
Na2O	3.48	3.82	3.00	2.43	2.43	3.28	3.01	2.41	3.27
K2O	2.47	2.93	4.51	4.61	4.42	3.23	2.98	3.08	4.63
P2O5	0.49	0.28	0.35	0.02	0.01	0.32	0.31	0.26	0.11
L.O.I.	1.00	3.25	2.40	2.75	1.91	3.28	3.11	2.28	5.64
Total	101.26	100.96	100.94	99.14	102.55	99.12	98.20	98.66	98.14
V	174	113	106	<10	<10	124	123	143	24
Cr	55	29	50	76	109	78	76	42	38
Co	15	10	12	0	0	16	17	16	3
Ni	8	<3	4	<3	<3	14	18	10	<3
Zn	82	74	93	14	13	86	98	74	55
Ba	1563	1281	1710	706	717	1284	1331	882	1460
La	40.9	31.0	64.0	37.2	35.1	34.1	33.9	17.2	40.7
Ce	82.8	62.9	123.1	66.7	62.7	68.9	68.2	32.5	77.3
Pr	10.2	7.4	14.5	7.2	6.7	8.3	8.2	4.4	8.6
Nd	40.8	28.2	52.7	23.8	21.8	31.4	31.7	17.9	29.8
Sm	7.5	5.1	9.1	3.9	3.6	5.7	5.7	3.6	4.8
Eu	1.8	1.3	1.8	0.5	0.4	1.3	1.4	1.1	0.8
Gd	5.3	3.9	6.6	2.7	2.6	4.2	4.5	3.0	3.3
Tb	0.7	0.5	0.9	0.4	0.4	0.6	0.6	0.4	0.5
Dy	3.6	3.1	5.0	2.5	2.3	3.2	3.5	2.6	2.7
Ho	0.7	0.6	1.0	0.5	0.5	0.6	0.7	0.5	0.5
Er	1.9	1.7	2.7	1.5	1.3	1.6	1.8	1.5	1.5
Tm	0.3	0.3	0.4	0.2	0.2	0.2	0.3	0.2	0.2
Yb	1.7	1.7	2.6	1.6	1.3	1.5	1.7	1.5	1.4
Lu	0.3	0.3	0.4	0.2	0.2	0.2	0.3	0.2	0.2
Rb	41.4	78.0	195.5	153.4	150.7	86.4	81.5	60.3	129.3
Sr	1264	733	729	60	63	686	717	707	344
Nb	8.3	8.8	20.1	10.7	10.4	10.3	10.3	3.6	13.5
Cs	0.6	1.8	9.7	5.9	6.1	2.2	2.0	1.6	4.2
Hf	4.3	4.8	9.1	2.6	2.5	5.2	5.0	2.1	2.3
Ta	0.5	0.6	1.3	1.0	0.9	0.7	0.7	0.2	1.0
Th	9.2	8.3	31.8	18.7	18.0	8.1	7.6	2.4	13.2
U	2.4	2.2	9.0	5.9	6.3	2.8	2.7	2.4	4.5
Y	18.4	17.3	27.0	15.0	13.4	16.5	19.1	15.5	15.1
Zr	170	191	368	76	73	208	195	75	59
Sc	14.6	11.6	11.4	2.2	2.2	14.1	15.2	15.9	4.9
Pb	12.2	14.4	24.4	16.2	14.2	16.4	17.7	10.4	24.4
(⁸⁷ Sr/ ⁸⁶ Sr) _i	0.705029	0.706071	0.706575	0.705461	0.705394	0.704781	0.705045	0.704661	0.705206
Epsilon Nd	-1.34	-4.12	-5.34	-1.82	-1.75	-0.04	-1.01	0.07	-0.67
(¹⁴³ Nd/ ¹⁴⁴ Nd) _i	0.512569	0.512427	0.512364	0.512545	0.512548	0.512636	0.512586	0.512642	0.512603
(²⁰⁸ Pb/ ²⁰⁴ Pb) _i	38.657	38.791	38.794	38.706	38.600	38.551	38.620	38.627	38.607
(²⁰⁷ Pb/ ²⁰⁴ Pb) _i	15.613	15.640	15.636	15.623	15.596	15.588	15.602	15.611	15.598
(²⁰⁶ Pb/ ²⁰⁴ Pb) _i	19.010	19.080	19.181	19.064	19.029	18.967	19.015	18.976	19.004

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Region	Central/West GB								
SAMPLE	11-CN-17	11-CN-21	11-CN-16	11-CN-18	11-CN-08	11-CN-09	11-CN-07a	04-LT-42	11-CN-10
Latitude	39.239	39.188	39.238	39.240	39.274	39.508	39.265	39.395	39.582
Longitude	-117.774	-117.836	-117.723	-117.784	-118.403	-118.408	-118.382	-118.334	-118.359
SiO2	67.78	69.29	71.07	72.83	48.15	49.19	51.06	51.32	51.59
TiO2	0.41	0.29	0.41	0.39	1.75	1.46	1.44	1.59	1.41
Al2O3	14.90	13.28	14.71	14.78	16.48	15.90	16.68	17.54	17.05
Fe2O3t	1.83	1.81	2.34	1.35	10.99	9.77	8.12	9.62	10.16
MnO	0.02	0.03	0.04	0.01	0.16	0.17	0.08	0.17	0.15
MgO	0.08	0.46	0.12	0.06	5.34	6.59	3.58	3.72	4.56
CaO	0.83	1.55	0.82	0.88	9.73	7.98	6.18	8.39	8.14
Na2O	4.47	3.88	4.47	4.14	3.01	3.21	2.76	3.61	3.29
K2O	5.69	3.92	5.59	5.53	1.14	1.42	3.18	1.41	1.51
P2O5	0.09	0.10	0.09	0.07	0.60	0.63	0.62	0.74	0.61
L.O.I.	2.12	1.68	2.52	1.22	1.99	2.88	6.47	1.40	1.09
Total	98.43	100.29	102.40	101.57	99.57	99.45	100.54	99.96	99.82
V	9	21	9	9	264	213	127	228	222
Cr	34	48	31	39	135	211	101	24	80
Co	1	3	1	1	35	36	26	24	27
Ni	2	<3	2	2	47	122	38	34	26
Zn	66	46	52	123	107	104	82	115	113
Ba	1304	1312	1267	2044	763	870	2301	868	869
La	38.2	43.4	37.7	54.9	25.0	30.7	46.8	28.7	32.7
Ce	73.2	79.2	71.9	110.3	56.4	67.3	97.3	65.5	71.9
Pr	8.7	8.5	8.7	13.3	7.8	8.9	11.9	8.8	9.5
Nd	33.4	28.9	32.6	49.7	33.9	37.8	46.6	38.3	39.4
Sm	6.1	4.6	5.9	9.5	7.4	7.8	8.5	7.8	8.2
Eu	2.2	0.8	2.1	2.1	2.1	2.1	1.7	2.1	2.0
Gd	4.4	3.2	4.3	7.1	6.7	6.9	6.5	6.8	7.0
Tb	0.6	0.4	0.6	1.0	1.0	1.0	0.9	1.0	1.0
Dy	3.3	2.6	3.2	5.6	5.8	5.7	4.8	5.3	5.8
Ho	0.6	0.5	0.6	1.0	1.2	1.1	0.9	1.0	1.2
Er	1.6	1.4	1.5	2.8	3.2	3.1	2.4	2.8	3.2
Tm	0.2	0.2	0.2	0.4	0.4	0.4	0.3	0.4	0.4
Yb	1.3	1.3	1.1	2.4	2.9	2.8	1.9	2.6	2.9
Lu	0.2	0.2	0.2	0.3	0.4	0.4	0.3	0.4	0.4
Rb	108.2	120.1	105.2	161.5	19.8	23.0	85.3	24.7	28.6
Sr	44	281	45	121	671	670	685	828	739
Nb	16.2	13.2	14.7	26.4	15.5	12.9	14.6	11.3	12.6
Cs	3.0	3.8	2.9	5.7	0.4	0.5	6.3	0.8	0.6
Hf	2.6	2.3	1.1	8.6	3.9	4.6	3.8	4.1	4.9
Ta	1.1	1.0	1.0	1.8	0.9	0.7	0.9	0.6	0.6
Th	7.3	12.9	7.0	20.3	1.8	2.8	8.8	2.3	3.1
U	2.1	4.2	1.5	5.7	0.9	1.0	2.5	0.9	1.1
Y	16.4	14.3	15.9	27.0	30.7	29.9	24.4	27.4	31.1
Zr	96	57	34	329	160	195	147	170	211
Sc	9.7	4.4	8.2	9.6	33.9	26.2	18.6	23.7	26.2
Pb	37.9	23.2	19.1	33.0	5.0	8.1	18.4	9.3	10.0
(⁸⁷ Sr/ ⁸⁶ Sr) _i	0.705590	0.704957	0.702860	0.706419	0.705040	0.704518	0.705655	0.704800	0.704714
Epsilon Nd	-0.37	-0.90	-0.48	0.27	-1.47	0.90	-2.08	1.35	-0.33
(¹⁴³ Nd/ ¹⁴⁴ Nd) _i	0.512619	0.512592	0.512614	0.512652	0.512563	0.512684	0.512532	0.512707	0.512621
(²⁰⁸ Pb/ ²⁰⁴ Pb) _i	38.483	38.651	38.708	38.678	38.488	38.438	38.636	38.561	38.541
(²⁰⁷ Pb/ ²⁰⁴ Pb) _i	15.612	15.612	15.616	15.609	15.578	15.563	15.595	15.601	15.589
(²⁰⁶ Pb/ ²⁰⁴ Pb) _i	18.914	19.016	19.056	19.058	18.920	18.925	19.069	18.956	18.939

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Region	Central/West GB							Precision (% Average
SAMPLE	11-CN-07b	04-LT-41	04-LT-44b	04-LT-43	04-LT-44a	11-CN-03	11-CN-04	Difference, except
Latitude	39.265	39.395	39.408	39.442	39.408	39.280	39.280	isotope ratios that
Longitude	-118.382	-118.304	-118.342	-118.349	-118.342	-118.398	-118.398	are 2-sigma standard
								deviations)
SiO ₂	51.69	53.37	61.54	65.35	66.15	55.91	58.11	0.5
TiO ₂	1.41	1.20	1.13	0.73	0.80	0.72	0.73	1.9
Al ₂ O ₃	16.35	16.89	17.04	15.45	14.61	18.64	19.29	1.2
Fe ₂ O ₃ t	8.29	8.84	5.04	5.04	4.14	7.18	6.91	1.6
MnO	0.08	0.16	0.03	0.05	0.05	0.12	0.13	3.4
MgO	3.88	4.17	0.59	1.18	0.58	3.24	3.28	1.7
CaO	6.64	7.66	3.77	5.73	3.15	7.49	7.33	1.9
Na ₂ O	2.74	3.44	4.27	3.13	3.61	3.68	3.48	2.7
K ₂ O	3.27	1.64	4.29	1.33	4.19	1.19	1.50	6.5
P ₂ O ₅	0.61	0.45	0.49	0.28	0.34	0.26	0.27	5.0
L.O.I.	5.91	2.00	1.40	0.60	1.90	1.23	2.06	5.0
Total	101.15	100.32	99.79	99.21	99.76	99.87	103.29	
V	125	196	108	90	74	147	146	4.0
Cr	98	52	0	7	6	46	52	6.4
Co	27	26	14	13	14	19	19	16.0
Ni	38	64	12	25	16	12	13	16.7
Zn	89	98	107	69	73	84	91	3.1
Ba	1422	757	1234	733	1109	523	546	7.5
La	46.6	23.0	43.6	25.8	35.5	15.5	16.8	3.3
Ce	95.9	50.7	93.0	47.1	74.4	34.3	36.5	3.4
Pr	11.9	6.6	11.5	6.8	9.1	4.5	4.8	3.8
Nd	46.4	28.2	45.8	28.2	35.5	18.6	19.9	3.1
Sm	8.7	5.7	8.8	5.4	6.8	3.9	4.2	2.7
Eu	1.9	1.5	1.7	1.4	1.2	1.2	1.3	7.3
Gd	6.8	5.1	7.3	4.2	5.6	3.4	3.6	7.3
Tb	0.9	0.7	1.1	0.6	0.8	0.5	0.5	6.5
Dy	5.2	4.1	6.1	3.1	4.7	2.9	3.1	4.3
Ho	1.0	0.8	1.2	0.6	0.9	0.6	0.6	3.0
Er	2.7	2.3	3.5	1.5	2.7	1.6	1.7	4.7
Tm	0.4	0.3	0.5	0.2	0.4	0.2	0.2	6.5
Yb	2.3	2.1	3.3	1.3	2.7	1.5	1.6	4.5
Lu	0.3	0.3	0.5	0.2	0.4	0.2	0.2	5.3
Rb	107.7	36.3	151.0	21.4	151.0	13.6	15.4	3.5
Sr	678	695	463	871	382	1125	1152	2.2
Nb	14.5	8.1	18.4	4.8	13.6	3.8	4.1	8.1
Cs	6.3	1.1	4.5	2.7	4.8	0.2	0.6	9.0
Hf	3.4	3.5	9.2	2.7	7.3	2.6	2.8	7.5
Ta	0.9	0.4	1.1	0.3	0.9	0.2	0.2	14.6
Th	10.8	3.1	16.5	4.5	16.2	1.6	1.9	7.1
U	2.6	1.1	6.2	1.3	5.9	0.6	0.7	6.1
Y	27.0	22.0	34.3	16.2	26.5	15.4	16.7	6.3
Zr	120	140	366	107	283	96	105	3.5
Sc	18.7	20.7	11.6	11.0	9.7	15.8	16.3	3.5
Pb	15.8	9.8	21.4	7.5	20.6	6.2	6.4	1.0
(⁸⁷ Sr/ ⁸⁶ Sr) _i	0.705670	0.705295	0.704418	0.704591	0.704095	0.704112	0.704132	0.000018
Epsilon Nd	-1.98	1.50	1.74	2.32	1.48	1.52	1.50	
(¹⁴³ Nd/ ¹⁴⁴ Nd) _i	0.512537	0.512715	0.512727	0.512757	0.512714	0.512716	0.512715	0.043
(²⁰⁸ Pb/ ²⁰⁴ Pb) _i	38.627	38.376	38.595	38.572	38.740	38.437	38.357	0.013
(²⁰⁷ Pb/ ²⁰⁴ Pb) _i	15.585	15.549	15.634	15.620	15.637	15.580	15.556	0.010
(²⁰⁶ Pb/ ²⁰⁴ Pb) _i	19.084	18.881	18.855	18.881	18.892	18.849	18.831	0.05

Note: Major-element oxides (wt%) and trace elements V through Ba (ppm) were analyzed by X-ray fluorescence; La through Pb (ppm) were analyzed by acid-dissolution-inductively coupled plasma-mass spectrometry. Fe₂O₃t—total iron expressed as Fe₂O₃; LOI—loss on ignition. Precision of isotopic data based on duplicate runs of standards. See text for details.

Appendix C: Sr, Nd and Pb Isotope Standards

Nd Standards 2004/5							
Standard	b-s-i*	Temp.	144Nd intensity**	c 143/144	c 145/144	c 148/144	m 146/144
La Jolla	9	1777	10	0.511847	0.348403	0.241583	0.723030
La Jolla	9	1755	2.8	0.511850	0.348408	0.241575	0.722192
La Jolla	9	1725	3	0.511853	0.348405	0.241590	0.720563
La Jolla	9	1700	2.9	0.511846	0.348406	0.241589	0.721313
La Jolla	9	1695	3.3	0.511850	0.348405	0.241585	0.721707
La Jolla Summary				0.511849	0.348405	0.241584	
2-sigma				0.000006	0.000004	0.000012	
1-sigma				0.000003	0.000002	0.000006	
ppm (2 sigma)				10.842597	10	50	
*blocks, scans, integration time							
**144Nd intensity: 500mV minimum							

Nd Standards 2011/2							
Standard	b-s-i*	Temp.	144Nd intensity**	c 143/144	c 145/144	c 148/144	m 146/144
NdStd	8,13,8	1797	0.57	0.511832	0.348416	0.241587	0.720214
NdStd	8,13,8	1751	1.37	0.511827	0.348421	0.241604	0.721581
NdStd	8,13,8	1720	1.16	0.511834	0.348418	0.241592	0.720524
NdStd	8,13,8	1727	1.07	0.511812	0.348410	0.241597	0.720981
NdStd	8,13,8	1779	1.4	0.511823	0.348410	0.241586	0.719422
La Jolla Summary				0.511826	0.348415	0.241593	
2-sigma				0.000017	0.000010	0.000015	
1-sigma				0.000009	0.000005	0.000007	
ppm (2 sigma)				34.132670	28	62	
*blocks, scans, integration time							
**144Nd intensity: 500mV minimum							

Sr Standards 2004/5					
Standard	files	Temp.	88Sr intensity**	c 87/86	c 84/86
SRM 987	double	1420 3.8V, 38 pA		0.710252	0.056498
SRM 987	double	1420 5.6V, 56 pA		0.710249	0.056484
SRM 987	double	1410 5.1V, 51 pA		0.710238	0.056496
SRM 987	double	1410 5.4V, 54 pA		0.710246	0.056491
SRM 987 Summary				0.710246	0.056492
2-sigma				0.000012	0.000012
1-sigma				6.0208E-06	6.23832E-06
*blocks, scans, integration time					
**88Sr intensity: 1.5V minimum					

Sr Standards 2011/2					
Standard	files	Temp.	88Sr intensity**	c 87/86	c 84/86
E&A	single	6.35		0.707997	0.056489
E&A	single	6.21		0.708008	0.056487
E&A	single	6.43		0.708008	0.056485
E&A	single	6.39		0.708009	0.056494
E&A Summary				0.708005	0.056489
2-sigma				0.000011	0.000008
1-sigma				5.73607E-06	3.99041E-06
*blocks, scans, integration time					
**88Sr intensity: 1.5V minimum					

Pb Standards 2011/2									
Standard	b-s-i*	Temp.	208Pb intensity**	Cup Config.	m 206/204	m 207/204	m 208/204	m 207/206	m 208/206
NBS981	6,10,10	1200	1.7 V	205CC	16.885	15.423	36.486	0.913419	2.160816
NBS981	6,10,10	1180	1.85 V	205CC	16.894	15.434	36.517	0.913578	2.161506
NBS981	6,10,10	1170	1.5 V	205CC	16.892	15.431	36.507	0.913524	2.161250
NBS981	9,10,8	1200	2.5 V	205CC	16.901	15.442	36.545	0.913716	2.162350
NBS981	5,10,10	1170	3 V	205CC	16.896	15.437	36.530	0.913670	2.162050
SRM 987 Summary					16.8935	15.4336	36.5170	0.9136	2.1616
2-sigma					0.0114	0.0144	0.0448	0.0002	0.0012
1-sigma					0.005688409	0.007182479	0.022404508	0.00011795	0.00061458
*blocks, scans, integration time									
**88Sr intensity: 1.5V minimum									

Appendix D: Whole-rock trace element geochemistry internal standard and calculation of precision

Sample No. LOCATION Rock Type Latitude Longitude	LT-2 (internal standard) Loveloy Formation * Basalt 40.243 -120.557	11-CN-09 Stillwater Range Basalt 39.508 -118.408	11-CN-14 Lahontan Mountains Trachyandesite 39.404 -118.546	11-CN-24 Cien Alpine Mountains Trachyandesite 39.684 -117.697
	Measured 2212	Measured 870	Measured 1439	Measured 1554
	Duplicate 2216	Duplicate 847	Duplicate 1462	Duplicate 1538
	%difference 0.2	%difference 2.7	%difference 1.6	%difference 1.0
Ba	1.3	1.4	1.3	1.4
Be	0.0	0.0	0.1	0.0
Bi	0.0	0.0	0.1	0.0
Cd	0.2	0.1	0.1	0.1
Ce	60.7	67.3	42.6	70.7
Cs	1.7	0.5	7.0	1.3
Cu	29.0	28.0	6.0	6.0
Dy	9.0	5.7	1.9	3.2
Er	5.1	3.1	1.0	1.7
Eu	3.8	2.1	0.6	1.4
Ga	19.6	18.1	14.1	18.9
Gd	10.1	6.9	2.1	4.2
Hf	4.1	4.6	2.9	4.4
Ho	1.8	1.1	0.4	0.6
La	27.1	30.7	23.7	34.9
Li	8.7	9.6	45.1	14.1
Lu	0.6	0.4	0.2	0.2
Mo	1.4	1.6	1.2	1.3
Nb	7.4	12.9	6.7	9.4
Nd	40.2	37.8	16.0	32.0
Pb	6.7	8.1	20.3	12.1
Pr	8.5	8.9	4.6	8.3
Rb	40.5	23.0	150.3	80.0
Sb	0.5	0.1	9.1	0.2
Sc	42.0	26.2	4.9	15.7
Sm	9.8	7.8	2.8	5.7
Sn	1.9	1.6	1.0	1.4
Sr	41.0	67.0	25.0	83.0
Ta	0.4	0.7	0.6	0.6
Tb	1.5	1.0	0.3	0.6
Th	4.1	2.8	8.2	8.0
Ti	0.2	0.1	0.9	0.2
Tm	0.7	0.4	0.2	0.2
U	1.6	1.0	3.1	2.6
W	0.6	<0.5	1.5	0.6
Y	48.3	29.9	10.5	17.1
Yb	4.4	2.8	1.1	1.6
Zr	153	195	99	168

*Internal Standard: The Loveloy Formation (also formally known as the Loveloy basalt) is located within the Blaisden Quadrangle, extending northeast towards the escarpment above Honey Lake in the Thomson Peak area. Loveloy consists of as many as 15 flows of olivine basalt. It is a distinctive, unusually hard basalt that is black on fresh surfaces and chocolate brown when weathered. The age of the Loveloy basalt is reported by Page et al. (1995) using Ar/Ar step heating, concluding an age of 16 Ma. Numerous chemical and isotopic analyses from the Loveloy basalt were completed since 1997 (e.g. Garrison 2004), the results of which proved to be surprisingly homogeneous. For this reason, the Loveloy Basalt was submitted as an internal standard for major and trace element analyses. Measured and Duplicate data completed by Geoscience Laboratories, OGS, Sudbury, Ontario

Appendix E: Whole-rock oxygen isotope geochemistry internal standard and duplicate data.

Isotopic Calculations for oxygen in silicates			
Timmermans O13-01			
Date: December 23, 2013			
Sample	18O VSMOW	Yield $\mu\text{mol/mg}$	Accepted Value
October 25, 2013			
Laboratory standard quartz	11.54	15.74	11.5
Laboratory standard kaolinite	21.46	16.34	21.5
04-LT-51	7.86	13.11	
11-CN-09	7.64	12.11	
04-LT-09	8.07	12.94	
04-LT-51 duplicate	7.86	12.73	
11-CN-13	7.47	13.91	
Laboratory standard CO2 II			
	10.35		10.3

For methodology and discussion see Potter, J., Longstaffe, F. J., & Barr, S. M. (2008). Regional 18O-depletion of Neoproterozoic igneous rocks from Avalonia, Cape Breton Island and southern New Brunswick, Canada. *Geological Society of America Bulletin*, 120(3-4), 347-367.

Appendix F: Raw Ar-Ar analyses analyses: data sheet, plateau age, normal isochron and inverse isochron.

Laser	Isotope Ratios		(sample/mineral)											
	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Ca/K	%40Ar atm	f39Ar	40Ar*/39ArK	Age	2σ		
2.30	1857.18	60.90	1.72	0.82	7.110	0.307	3.15	113.12	0.09	243.935	-1803.00 ± 1515.48			
2.60	838.46	21.16	2.39	0.48	3.389	0.119	4.39	119.42	0.18	163.079	-990.87 ± 408.91			
2.90	242.18	3.88	0.79	0.24	0.878	0.027	1.44	107.06	0.16	17.119	-81.91 ± 66.23			
3.30	146.42	1.08	0.82	0.09	0.542	0.013	1.50	109.45	0.60	13.845	-65.96 ± 36.07			
3.60	36.41	0.27	0.39	0.06	0.121	0.003	0.72	97.79	0.90	0.804	3.76 ± 8.14			
4.00	15.44	0.10	0.15	0.02	0.045	0.001	0.28	86.92	3.18	2.019	9.42 ± 3.67			
4.50	4.95	0.06	0.08	0.01	0.010	0.000	0.14	59.83	8.00	1.987	9.27 ± 0.75			
5.00	3.45	0.04	0.06	0.01	0.005	0.000	0.11	43.77	13.00	1.940	9.05 ± 0.43			
5.50	2.55	0.03	0.03	0.00	0.002	0.000	0.06	22.35	17.62	1.980	9.24 ± 0.34			
6.00	2.44	0.02	0.03	0.00	0.001	0.000	0.06	18.04	15.27	2.001	9.34 ± 0.26			
6.50	2.39	0.02	0.03	0.00	0.001	0.000	0.05	14.12	14.34	2.050	9.56 ± 0.25			
7.00	2.45	0.02	0.01	0.00	0.001	0.000	0.03	17.54	11.53	2.022	9.43 ± 0.32			
7.50	2.48	0.01	0.02	0.00	0.001	0.000	0.04	17.26	8.73	2.055	9.59 ± 0.32			
8.00	2.59	0.02	0.03	0.01	0.002	0.000	0.05	21.15	6.40	2.042	9.53 ± 0.30			
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Ca/K	%40Ar atm	f39Ar	40Ar*/39ArK	1σ			
Total/Average	2.675	0.007	0.031	0.002	0.0018	0.0000			100.00	2.019	0.012			
<p>J = 0.0025869 ± 0.0000129 Volume 39Ar/K = 0.534 Integrated Data = 9.42 ± 0.11 Ma Includes 83.8% of the 39Ar steps 5 through 12</p> <p>Plateau age = 9.37 ± 0.16 Ma (2σ, including J-error of 1%) MSWD = 1.05, probability=0.39 Age = 9.46 ± 0.16 Ma</p> <p>Inverse isochron (correlation age) results, plateau steps: Model 1 Solution (49.9%-conf) on 14 points MSWD = 0.89 Probability = 0.6</p>														
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Laser	Isotope Ratios 11CN-268 WFL										(sample/mineral)	
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Ca/K	%40Ar atm	f39Ar	40Ar*/39ArK	Age	2σ
2.30	1061.12	16.72	8.66	1.08	4.096	0.152	15.96	91.44	0.96	91.397	399.30 ± 810.85	
2.60	222.53	1.57	10.06	0.47	0.833	0.019	18.55	88.46	2.59	25.873	122.26 ± 185.17	
2.90	83.06	1.02	14.72	0.45	0.249	0.011	27.23	69.86	7.65	25.298	119.63 ± 59.03	
3.10	52.74	0.74	12.21	0.33	0.099	0.002	22.55	43.10	11.61	30.269	142.24 ± 21.74	
3.40	41.11	0.37	10.10	0.26	0.039	0.002	18.62	25.80	17.40	30.719	144.27 ± 4.88	
3.70	38.15	0.33	12.51	0.31	0.031	0.001	23.11	21.31	23.68	30.290	142.33 ± 4.36	
4.00	37.64	0.26	10.23	0.21	0.027	0.001	18.87	18.81	13.13	30.784	144.56 ± 3.06	
4.50	40.05	0.23	15.49	0.32	0.034	0.001	28.68	21.71	9.12	31.703	148.70 ± 3.02	
5.40	40.35	0.29	24.50	0.69	0.041	0.001	45.67	24.93	10.20	30.822	144.73 ± 3.35	
6.20	44.74	0.39	26.76	0.78	0.055	0.001	49.95	31.35	3.66	31.304	146.90 ± 4.28	
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Ca/K	%40Ar atm	f39Ar	40Ar*/39ArK	1σ	
Total/Average	41.836	0.117	12.281	0.111	0.0388	0.0004			100.00		31.004	0.164
J = 0.0027035 ± 0.0000135 Volume 39ArK = 0.105 Integrated Date = 145.56 ± 1.48 Ma Includes 100% of the 39Ar steps 1 through 10 Plateau age = 145.6 ± 2.1 Ma (2σ, including J-error of 1%) MSWD = 1.02, probability=0.42 Inverse isochron (correlation age) results, plateau step: Model 1 Solution (±95%-conf) on 10 points Age = 154.0 ± 4.9 Ma Initial 40Ar/36Ar = 232 ± 21 MSWD = 5.7 Probability = 0												

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Laser	Isotope Ratios 11CN-26A WR										(sample/mineral)	
Power(%)	40Ar/39Ar	1 σ	37Ar/39Ar	1 σ	36Ar/39Ar	1 σ	Ca/K	%40Ar atm	f39Ar	40Ar*/39ArK	Age	2 σ
2.30	610.06	14.03	15.40	0.91	2.056	0.072	28.51	99.40	1.26	3.729	18.14 $\pm$ 163.30	
2.60	126.74	1.69	19.02	0.58	0.411	0.018	35.32	94.46	5.34	7.121	34.48 $\pm$ 48.28	
2.90	74.74	0.71	18.75	0.63	0.202	0.007	34.80	77.73	12.39	16.864	80.62 $\pm$ 19.63	
3.20	38.72	0.31	5.76	0.19	0.038	0.003	10.60	28.01	27.67	27.990	131.91 $\pm$ 8.69	
3.50	34.47	0.24	10.83	0.23	0.022	0.001	19.99	16.16	28.19	29.121	137.04 $\pm$ 2.74	
3.80	36.03	0.25	46.39	1.20	0.037	0.002	87.83	19.35	14.91	30.044	141.22 $\pm$ 6.90	
4.50	39.70	0.30	87.66	1.98	0.048	0.002	171.14	17.06	10.24	35.098	163.93 $\pm$ 7.53	
Power(%)	40Ar/39Ar	1 σ	37Ar/39Ar	1 σ	36Ar/39Ar	1 σ	Ca/K	%40Ar atm	f39Ar	40Ar*/39ArK	1 σ	
Total/Average	38.679	0.132	9.939	0.136	0.0282	0.0007			100.00	29.446	0.255	
J = 0.0027035 $\pm$ 0.0000135												
Volume 39ArK = 0.022												
Integrated Date = 138.63 $\pm$ 2.31 Ma												
Plateau age = 137.2 $\pm$ 2.8 Ma (2 σ , including J-error of 1%)												
MSWD = 1.4, probability=0.24												
Inverse isochron (correlation age) results, plateau steps: Model 1 Solution ($\pm$ 95%-conf.) on 5 points												
Age = 142.8 $\pm$ 2.7 Ma												
Initial 40Ar/36Ar = 233 $\pm$ 14												
MSWD = 1.5												
Probability = 0.22												

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Laser	Isotope Ratios											
	11CN-26A sericitic plagioclase (sample/mineral)											
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Ca/K	%40Ar atm	f 39Ar	40Ar*/39ArK	Age	2σ
2.30	28.71	0.26	6.04	0.20	0.045	0.002	11.11	45.02	3.62	15.851	75.83 ± 4.83	
2.60	28.27	0.15	8.77	0.26	0.027	0.002	16.16	25.90	11.12	21.080	100.16 ± 6.36	
2.90	24.03	0.13	3.26	0.07	0.005	0.000	5.98	5.35	24.05	22.795	108.08 ± 1.21	
3.20	22.47	0.16	3.10	0.08	0.004	0.000	5.69	3.92	36.61	21.635	102.73 ± 1.51	
3.50	24.18	0.60	5.82	0.19	0.008	0.001	10.71	7.87	6.92	22.371	106.12 ± 5.35	
4.50	24.56	0.14	5.67	0.13	0.010	0.001	10.42	10.23	9.53	22.137	105.04 ± 1.93	
5.50	24.16	0.16	6.10	0.19	0.009	0.001	11.22	8.61	8.15	22.171	105.20 ± 2.12	
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Ca/K	%40Ar atm	f 39Ar	40Ar*/39ArK	1σ	
Total/Average	24.917	0.064	4.065	0.044	0.0047	0.0001			100.00		22.102	0.083
J = 0.0027018 ± 0.0000135 Volume 39ArK = 0.099 Integrated Date = 104.91 ± 0.76 Ma												
Plateau age = no plateau Inverse isochron (correlation age) results, plateau steps: Model 1 Solution (+95%-conf.) on 6 points Age = 106.3 ± 6.4 Ma												
Initial 40Ar/36Ar = 265 ± 220 MSWD = 8.4 Probability = 0												

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Laser	Isotope Ratios 11CN-18 WR											
	(sample/mineral)											
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Cu/K	%40Ar atm	f39Ar	40Ar ^v /39ArK	Age	2σ
2.30	17.13	0.12	0.48	0.02	0.040	0.002	0.87	69.40	3.07	5.245	24.82 ± 4.58	
2.60	5.97	0.04	0.44	0.02	0.001	0.000	0.81	4.06	12.20	5.727	27.09 ± 0.49	
2.90	5.56	0.03	0.40	0.02	0.000	0.000	0.73	1.00	32.36	5.508	26.06 ± 0.30	
3.20	5.66	0.03	0.35	0.02	0.001	0.000	0.63	2.83	32.86	5.505	26.04 ± 0.31	
3.50	5.79	0.04	0.25	0.02	0.001	0.000	0.46	4.13	12.86	5.551	26.26 ± 0.41	
3.80	6.33	0.04	0.35	0.04	0.003	0.000	0.65	14.09	4.19	5.437	25.72 ± 1.35	
4.20	8.23	0.09	0.93	0.11	0.010	0.001	1.71	34.04	1.49	5.434	25.71 ± 4.13	
5.00	11.16	0.18	1.64	0.08	0.017	0.003	3.01	43.09	0.97	6.358	30.04 ± 6.98	
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Cu/K	%40Ar atm	f39Ar	40Ar ^v /39ArK	1σ	
Total/Average	6.079	0.016	0.396	0.008	0.0004	0.0000		100.00		5.542	0.019	
J = 0.0026352 ± 0.0000132 Volume 39ArK = 0.164 Integrated Date = 26.22 ± 0.18 Ma Includes 84.7% of the 39Ar steps 3 through 8												
Plateau age = 26.09 ± 0.32 Ma (2σ, including J-error of 1%) MSWD = 0.48, probability=0.79												
Inverse isochron (correlation age) results, plateau steps: Model 1 Solution (±95%-conf.) on 8 points Age = 26.16 ± 0.41 Ma												
Initial 40Ar/36Ar = 297 ± 48 MSWD = 2.9 Probability = 0.007												

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Laser	Isotope Ratios 11CN-15 WR												
	(sample/mineral)												
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Ca/K	%40Ar atm	f39Ar	40Ar*/39ArK	Age	2σ	
2.30	214.17	1.98	2.60	0.12	0.755	0.024	4.76	104.12	2.57	8.836	-41.72 ± 65.22		
2.60	52.00	0.52	2.66	0.12	0.164	0.009	4.88	92.77	9.28	3.768	17.51 ± 25.38		
2.90	8.57	0.06	2.86	0.12	0.024	0.001	5.26	81.01	8.35	1.630	7.59 ± 3.61		
3.30	6.76	0.04	3.96	0.16	0.018	0.001	7.27	73.58	11.37	1.790	8.34 ± 2.40		
3.80	6.07	0.04	2.90	0.08	0.015	0.000	5.32	67.19	24.94	1.995	9.29 ± 0.91		
4.30	7.48	0.05	3.15	0.08	0.020	0.000	5.78	74.66	22.04	1.901	8.85 ± 1.28		
4.70	9.19	0.05	3.38	0.10	0.026	0.001	6.20	80.40	15.94	1.806	8.41 ± 3.06		
5.20	14.57	0.11	3.74	0.11	0.044	0.002	6.86	86.45	5.50	1.979	9.21 ± 4.85		
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Ca/K	%40Ar atm	f39Ar	40Ar*/39ArK	1σ		
Total/Average	7.761	0.021	3.112	0.036	0.0178	0.0002			100.00		1.931	0.072	
J = 0.0025814 ± 0.0000129 Volume 39ArK = 0.082 Integrated Date = 8.99 ± 0.67 Ma Includes 100% of the 39Ar steps 1 through 8													
Plateau age = 8.99 ± 0.68 Ma (2s, including J-error of 1%) MSWD = 0.63, probability=0.73													
Inverse isochron (correlation age) results, plateau steps: Model 1 Solution (+95%-conf.) on 8 points Age = 9.7 ± 1.3 Ma													
Initial 40Ar/36Ar = 287 ± 14 MSWD = 0.50 Probability = 0.81													

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Laser	Isotope Ratios 11CN15FR (sample/mineral)											
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Ca/K	%40Ar atm	f39Ar	40Ar*/39ArK	Age	2σ
2.00	76.03	0.71	3.72	0.11	0.347	0.013	6.84	134.35	6.37	26.181	-126.53 ± 39.43	
2.30	322.18	6.23	3.00	0.31	1.224	0.040	5.51	112.20	0.35	39.379	-193.84 ± 100.70	
2.70	148.04	2.69	2.61	0.08	0.606	0.015	4.78	120.92	2.44	31.028	-150.96 ± 46.33	
3.20	44.82	0.43	2.77	0.06	0.179	0.004	5.09	117.51	6.00	7.862	-37.08 ± 10.80	
3.50	17.73	0.25	3.17	0.07	0.058	0.001	5.82	95.81	4.53	0.744	3.47 ± 3.97	
3.90	13.61	0.22	3.66	0.11	0.040	0.001	6.73	85.52	5.93	1.977	9.20 ± 3.05	
4.30	8.43	0.05	3.51	0.11	0.023	0.001	6.45	75.88	6.07	2.038	9.49 ± 1.40	
4.70	7.22	0.05	3.56	0.08	0.019	0.000	6.54	72.18	6.75	2.015	9.38 ± 1.20	
5.10	6.76	0.04	3.27	0.10	0.017	0.000	6.00	70.49	8.93	2.000	9.31 ± 1.23	
5.60	6.99	0.04	3.10	0.09	0.018	0.000	5.69	72.32	11.92	1.939	9.03 ± 1.30	
6.10	7.48	0.05	3.13	0.06	0.020	0.000	5.74	76.36	11.34	1.772	8.25 ± 1.24	
6.80	8.05	0.04	3.15	0.06	0.021	0.001	5.79	75.90	12.88	1.945	9.05 ± 2.52	
7.50	8.82	0.05	3.33	0.07	0.024	0.001	6.12	78.90	8.83	1.866	8.69 ± 2.10	
8.50	9.30	0.05	3.52	0.08	0.026	0.001	6.46	78.98	7.66	1.961	9.13 ± 2.12	

Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Ca/K	%40Ar atm	f39Ar	40Ar*/39ArK	1σ
Total/Average	7.900	0.016	3.187	0.021	0.0218	0.0002		100.00		1.893	0.055
J = 0.0025813 ± 0.0000129 Volume 39ArK = 0.346 Integrated Date = 8.82 ± 0.51 Ma Plateau age = 9.06 ± 0.52 Ma (2σ, including J-error of 1%) MSWD = 0.33, probability=0.95 Includes 80.3% of the 39Ar steps 6 through 14 Inverse isochron (correlation age) results, plateau steps: Model 1 Solution (±95%-conf) on 9 points Age = 9.0 ± 2.4 Ma Initial 40Ar/36Ar =296 ± 26 MSWD = 0.38 Probability = 0.91											

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Laser	Isotope Ratios											
11CN11 WZ	(sample/mineral)											
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Ca/K	%40Ar atm	f39Ar	40Ar*/39ArK	Age	2σ
2.30	23.91	0.16	1.37	0.08	0.074	0.004	2.51	90.89	7.17	2.182	10.13 ± 10.81	
2.60	8.38	0.05	2.21	0.08	0.015	0.001	4.06	49.40	13.53	4.249	19.68 ± 2.15	
2.90	7.51	0.05	3.60	0.08	0.009	0.000	6.62	31.55	18.74	5.153	23.84 ± 1.28	
3.20	6.52	0.04	4.56	0.13	0.005	0.000	8.38	19.48	21.27	5.268	24.37 ± 0.73	
3.50	6.11	0.04	4.92	0.11	0.005	0.000	9.04	16.41	14.56	5.125	23.71 ± 0.69	
4.00	7.04	0.05	7.02	0.17	0.008	0.000	12.91	26.02	16.65	5.235	24.22 ± 1.15	
4.50	9.58	0.09	8.46	0.36	0.018	0.001	15.58	47.83	5.62	5.026	23.26 ± 3.53	
5.20	20.51	0.38	11.57	0.56	0.055	0.003	21.36	75.07	2.46	5.155	23.85 ± 7.44	
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Ca/K	%40Ar atm	f39Ar	40Ar*/39ArK	1σ	
Total/Average	7.469	0.021	3.270	0.040	0.0064	0.0001			100.00	5.150	0.046	
J = 0.0025755 ± 0.0000129												
Volume 39ArK =			0.088	Integrated Date =		23.83 ± 0.42	Ma					
(2s, including J-error of 1%)				MSWD = 0.41, probability=0.84			Includes 79.3% of the 39Ar		steps 3 through 8			
Inverse isochron (correlation age) results, plateau steps: Model 1 Solution (+95%-conf.) on 8 points												
Initial 40Ar/36Ar = 270 ± 39			MSWD = 3.0		Probability = 0.006		Age = 24.4 ± 1.3 Ma					

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Laser	Isotope Ratios 11CN-6 WR										(sample/mineral)	
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Ca/K	%40Ar atm	f39Ar	40Ar*/39ArK	Age	2σ
2.30	24.67	0.50	6.98	0.75	0.078	0.010	12.84	91.09	2.97	2.209	10.66 ± 29.70	
2.60	5.18	0.13	15.90	0.37	0.013	0.001	29.46	47.58	10.35	2.748	13.25 ± 3.77	
2.90	3.21	0.12	16.13	0.46	0.006	0.001	29.88	15.43	11.97	2.745	13.24 ± 2.19	
3.50	3.99	0.06	13.19	0.42	0.008	0.001	24.38	32.65	29.62	2.711	13.08 ± 2.06	
4.00	8.82	0.07	11.02	0.21	0.024	0.001	20.34	68.65	29.97	2.787	13.44 ± 1.80	
4.50	11.81	0.11	9.62	0.18	0.034	0.001	17.74	78.43	15.12	2.566	12.38 ± 2.89	
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Ca/K	%40Ar atm	f39Ar	40Ar*/39ArK	1σ	
Total/Average	6.234	0.037	11.343	0.119	0.0156	0.0003			100.00	2.727	0.107	
J = 0.0026774 ± 0.0000134				Volume 39ArK = 0.039		Integrated Date = 13.16 ± 1.03		Ma		Includes 100% of the 39Ar		
Plateau age = 13.2 ± 1.0 Ma				(2s, including J-error of 1%)		MSWD = 0.087, probability=0.994				steps 1 through 6		
Inverse isochron (correlation age) results, plateau steps: Model 1 Solution (±95%-conf.) on 6 points												
Initial 40Ar/36Ar =293 ± 19				MSWD = 0.094		Probability = 0.98		Age = 13.3 ± 1.6 Ma				

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Laser	Isotope Ratios 11CN-5a WR (sample/mineral)											
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Cu/K	%40Ar atm	f39Ar	40Ar*/39ArK	Age	2σ
2.30	87.96	2.14	3.70	0.37	0.202	0.018	6.79	67.47	1.41	28.684	132.94 ± 46.10	
2.60	4.08	0.04	11.51	0.63	0.012	0.001	21.26	62.10	8.78	1.561	7.49 ± 4.05	
3.00	1.78	0.01	16.59	0.48	0.005	0.000	30.75	3.82	12.27	1.734	8.32 ± 1.40	
3.50	1.66	0.01	13.80	0.29	0.004	0.000	25.53	3.60	24.60	1.612	7.73 ± 1.08	
4.00	2.43	0.02	10.90	0.21	0.006	0.000	20.11	34.25	19.65	1.609	7.72 ± 1.29	
4.50	3.58	0.03	9.57	0.23	0.009	0.000	17.64	51.30	16.36	1.753	8.41 ± 0.97	
5.50	4.66	0.08	9.63	0.25	0.012	0.000	17.76	60.40	12.81	1.860	8.92 ± 1.24	
6.50	8.22	0.12	10.41	0.57	0.027	0.001	19.20	87.53	4.12	1.032	4.96 ± 3.38	
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Cu/K	%40Ar atm	f39Ar	40Ar*/39ArK	1σ	
Total/Average	2.093	0.008	10.425	0.107	0.0076	0.0002		100.00		1.698	0.053	
J = 0.0026595 ± 0.0000133 Volume 39ArK = 0.040 Integrated Date = 8.15 ± 0.51 Ma Plateau age = 8.21 ± 0.53 Ma (2σ, including J-error of 1%) MSWD = 0.60, probability=0.70 Inverse isochron (correlation age) results, plateau steps: Model 1 Solution (±65%-conf.) on 7 points Age = 8.12 ± 0.70 Ma Initial 40Ar/36Ar = 296 ± 23 MSWD = 1.3 Probability = 0.25 Includes 94.5% of the 39Ar steps 2 through 7												

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Laser	Isotope Ratios 11CN-4 FFR											
	(sample/mineral)											
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Cu/K	%40Ar atm	f39Ar	40Ar*/39ArK	Age	2σ
2.30	6.04	0.05	2.12	0.09	0.018	0.001	3.89	86.59	20.66	0.811	3.94 ± 1.82	
2.60	1.66	0.04	4.35	0.14	0.003	0.000	7.99	29.78	31.73	1.171	5.69 ± 1.14	
2.90	1.39	0.04	8.49	0.17	0.003	0.000	15.64	14.71	31.96	1.363	6.62 ± 0.72	
3.20	1.67	0.10	15.76	0.51	0.005	0.000	29.18	9.14	13.70	1.532	7.44 ± 1.63	
6.00	13.89	0.70	60.58	1.91	0.057	0.003	115.92	85.53	1.94	2.099	10.18 ± 10.92	
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Cu/K	%40Ar atm	f39Ar	40Ar*/39ArK	1σ	
Total/Average	2.699	0.026	3.987	0.067	0.0044	0.0002			100.00	1.291	0.056	
J = 0.0026897 ± 0.0000134 Volume 39Ar/K = 0.038 Integrated Date = 6.27 ± 0.54 Ma Includes 79.3% of the 39Ar steps 2 through 5												
Plateau age = 6.49 ± 0.57 Ma (2σ, including J-error of 1%) MSWD = 1.3, probability=0.27												
Inverse isochron (correlation age) results, plateau steps: Model 1 Solution (+95%-conf.) on 5 points Age = 6.5 ± 1.3 Ma												
Initial 40Ar/36Ar = 272 ± 48 MSWD = 2.3 Probability = 0.08												
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Laser	Isotope Ratios										Age	2σ
	11CN4WR	(sample/mineral)										
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Ca/K	%40Ar atm	f39Ar	40Ar*/39ArK		
2.30	41.48	0.38	2.46	0.07	0.138	0.003	4.51	98.11	1.17	0.784		3.81 ± 8.83
2.60	7.88	0.06	2.58	0.05	0.024	0.001	4.74	86.29	12.50	1.083		5.26 ± 1.55
2.90	2.06	0.01	3.75	0.08	0.004	0.000	6.89	39.83	13.16	1.241		6.03 ± 0.75
3.20	1.46	0.01	5.89	0.11	0.002	0.000	10.83	7.45	22.13	1.354		6.57 ± 0.23
3.50	1.47	0.01	8.35	0.27	0.003	0.000	15.39	5.96	19.69	1.395		6.77 ± 0.34
3.90	1.74	0.01	12.91	0.28	0.004	0.000	23.87	2.23	15.66	1.713		8.31 ± 0.51
4.40	1.98	0.01	17.50	0.35	0.005	0.000	32.44	3.66	7.45	1.930		9.36 ± 0.86
5.20	3.55	0.03	25.47	0.57	0.010	0.000	47.51	25.75	4.63	2.683		13.00 ± 1.52
5.60	3.88	0.05	29.40	0.72	0.011	0.000	54.99	21.80	2.93	3.101		15.02 ± 1.52
6.20	2.97	0.07	27.17	1.00	0.010	0.003	50.73	25.59	0.69	2.250		10.91 ± 8.12

Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Ca/K	%40Ar atm	f39Ar	40Ar*/39ArK	1σ
Total/Average	1.821	0.005	3.643	0.035	0.0029	0.0000			100.00	1.454	0.017

$J = 0.0026897 \pm 0.0000134$ Volume $^{39}\text{Ar}/\text{K} = 0.205$ Integrated Date = 7.06 ± 0.17 Ma
 Plateau age = 6.60 ± 0.20 Ma (2σ, including J-error of 1%) MSWD = 1.7, probability=0.18 Includes 55% of the ^{39}Ar steps 3 through 5
 Inverse isochron (correlation age) results, plateau steps: Model 1 Solution (±95%-conf.) on 6 points Age = 6.60 ± 0.18 Ma
 Initial $^{40}\text{Ar}/^{36}\text{Ar} = 287.0 \pm 9.2$ MSWD = 1.19 Probability = 0.0

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Laser	Isotope Ratios 11CN-2 sanidine											
	(sample/mineral)											
Power(%)	40Ar/39Ar	1σ	37Ar/39Ar	1σ	36Ar/39Ar	1σ	Ca/K	%40Ar atm	f39Ar	40Ar*/39ArK	Age	2σ
2.30	8.46	0.07	1.89	0.09	0.023	0.001	3.47	78.15	9.79	1.851	8.69 ± 2.50	
2.60	3.75	0.03	3.74	0.13	0.005	0.000	6.87	34.25	17.61	2.469	11.59 ± 1.04	
2.90	3.39	0.02	5.89	0.14	0.005	0.000	10.84	27.61	22.37	2.462	11.56 ± 0.62	
3.20	3.46	0.02	10.16	0.26	0.006	0.000	18.74	26.44	18.48	2.567	12.04 ± 0.96	
3.70	5.49	0.03	12.00	0.32	0.013	0.000	22.16	51.11	19.69	2.707	12.70 ± 1.22	
4.20	8.17	0.06	16.49	0.29	0.024	0.001	30.55	70.23	8.20	2.461	11.55 ± 1.80	
5.00	12.49	0.16	15.91	0.41	0.038	0.002	29.47	78.83	3.86	2.673	12.54 ± 4.16	

Power(%)	40Ar/39Ar	1 σ	37Ar/39Ar	1 σ	36Ar/39Ar	1 σ	Ca/K	%40Ar atm	f39Ar	40Ar*/39ArK	1 σ
Total/Average	4.192	0.012	4.621	0.059	0.0076	0.0001		100.00		2.497	0.044

$J = 0.0026034 \pm 0.0000130$ Volume 39ArK = 0.069 Integrated Date = 11.72 $\pm$ 0.41 Ma
 Plateau age = 11.80 $\pm$ 0.44 Ma (2 σ , including J-error of 1%) MSWD = 0.69, probability=0.63 Includes 90.2% of the 39Ar steps 2 through 7
 Inverse isochron (correlation age) results, plateau steps: Model 1 Solution (+95%-conf.) on 7 points Age = 11.8 $\pm$ 1.0 Ma
 Initial 40Ar/36Ar = 292 $\pm$ 27 MSWD = 1.9 Probability = 0.099

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