2006

Field, geochemical, and geochronologic study of the inner Tuolumne Intrusive Series

Seth D. Burgess
San Jose State University

Follow this and additional works at: https://scholarworks.sjsu.edu/etd_theses

Recommended Citation

Burgess, Seth D., "Field, geochemical, and geochronologic study of the inner Tuolumne Intrusive Series" (2006). *Master's Theses*. 2871.
DOI: <https://doi.org/10.31979/etd.cepb-v5v3>
https://scholarworks.sjsu.edu/etd_theses/2871

This Thesis is brought to you for free and open access by the Master's Theses and Graduate Research at SJSU ScholarWorks. It has been accepted for inclusion in Master's Theses by an authorized administrator of SJSU ScholarWorks. For more information, please contact scholarworks@sjsu.edu.

FIELD, GEOCHEMICAL, AND GEOCHRONOLOGIC STUDY OF THE INNER
TUOLUMNE INTRUSIVE SERIES

A Thesis Presented to
The Faculty of the Department of Geology
San Jose State University

In Partial Fulfillment
of the Requirements for the Degree of
Master of Science

By
Seth D. Burgess

June 2006

UMI Number: 1436896

INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

UMI Microform 1436896

Copyright 2006 by ProQuest Information and Learning Company.

All rights reserved. This microform edition is protected against unauthorized copying under Title 17, United States Code.

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

© 2006

Seth D. Burgess

ALL RIGHTS RESERVED

APPROVED FOR THE DEPARTMENT OF GEOLOGY

Dr. Jonathan Miller

Dr. Robert Miller

Dr. Ellen Metzger

APPROVED FOR THE UNIVERSITY

04/18/06

ABSTRACT

FIELD, GEOCHEMICAL, AND GEOCHRONOLOGIC STUDY OF THE INNER TUOLUMNE INTRUSIVE SERIES

By Seth D. Burgess

Early work on the Tuolumne Intrusive Series suggested that chemical variations resulted from *in-situ* igneous differentiation processes operating on a single large magma body. In contrast, recent U/Pb geochronology indicating an 8 -10 m.y. age span requires multiple magma inputs. Geochronologic data reported here suggest that the voluminous interior of the Tuolumne was constructed in the last 1-2 m.y. of this time interval, allowing for interaction between pulses. Initial granitoid melts were derived by deep crustal melting in equilibrium with garnet, and have slightly different isotopic compositions from unit to unit. This precludes genesis of younger units by direct fractionation from older units. However, within each unit, field relations, isotopic similarity, modest major element variation, and trace element variability favor fractionation as the dominant within-unit differentiation process, whereas mixing is relatively limited within and/or between units.

ACKNOWLEDGEMENTS

This research was supported by National Science Foundation grant EAR-0074099. I would like to thank my committee for working so hard on this project and for their patience in seeing it to completion. Field assistance was provided by Jonathan Miller, Ante Mlinarevic, and Ron Karpowicz, who tirelessly lugged samples much larger than were actually needed in the end. I would also like to thank all the folks at UNC Chapel Hill, especially Dr. Drew Coleman, who put up with my rookie understanding of their wonderful lab. Dr. Tom Sisson at the USGS was also a great help in getting me more plagioclase microprobe data than I could ever hope to use.

TABLE OF CONTENTS

	Page
INTRODUCTION.....	1
GEOLOGIC SETTING.....	2
The Cretaceous Sierra Nevada Magmatic Arc	2
The Tuolumne Intrusive Series	4
Origin and Synthesis of the TIS: Current Models	4
OBJECTIVES AND STUDY AREA.....	9
Objective	9
Area and Sampling	9
METHODS	12
Sampling Strategy and Field Methods	12
Petrography	13
Geochemistry	13
Mineral Chemistry of Plagioclase and Potassium Feldspar	14
Geochronology	14
Whole Rock Isotopic Analysis	15
FIELD RELATIONSHIPS.....	17
Magmatic Fabrics	17
Cathedral Peak Granodiorite	17
Half Dome Granodiorite.....	17
Other Internal Structures and Heterogeneities	20
Schlieren	20

Ladder Dikes	24
Mingling Zones	24
Microgranitoid Enclaves	27
Potassium Feldspar Concentrations	28
Aplitic Dikes	30
Magmatic Faults	30
PETROGRAPHY	32
Equigranular Half Dome Granodiorite	32
Porphyritic Half Dome Granodiorite	33
Cathedral Peak Granodiorite	34
Compositional Outliers	39
FELDSPAR MINERAL CHEMISTRY	42
Plagioclase Mineral Chemistry	42
Potassium Feldspar Chemistry	48
GEOCHRONOLOGY	49
Zircon U/Pb Age Results	49
WHOLE ROCK GEOCHEMISTRY	52
Major Element Variation	52
Trends with Distance	55
Trace Element Variation	55
Trends with Distance	61
RARE EARTH ELEMENTS	64
Chondrite-Normalized Plots	64
Trends with Distance	67

ISOTOPIC DATA	70
Variation in Initial Strontium and Epsilon Nd with Silica and Longitude	70
$^{87}\text{Sr}/^{86}\text{Sr}_{(t)} - \epsilon\text{Nd}_{(t)}$ Co-variation	72
DISCUSSION.....	75
Geologic Constraints	75
Internal Contacts along the Mapped Transects	78
Partial Melting, Melt Source, and Geochemical Variability	83
Fractional Crystallization	87
Magma Hybridization	98
CONCLUSIONS	104
REFERENCES	107
APPENDIX 1: PLAGIOCLASE AND POTASSIUM FELDSPAR DATA	111
APPENDIX 2: GEOCHRONOLOGIC DATA	122
APPENDIX 3: MAJOR AND TRACE ELEMENT DATA	124
APPENDIX 4: ISOTOPE DATA	133
APPENDIX 5: THEORETICAL MODELS	135

LIST OF FIGURES

Figure	Page
1. Generalized Outline of Jura-Cretaceous Sierra Nevada Batholith	3
2. Simplified geology of the Tuolumne Intrusive Series	5
3. Magma hybridization and crystal fractionation	7
4. Sample locations across both transects from the Tenaya Lake area	10
5. Contoured stereonet plot of poles to foliations	18
6. Contoured stereonet plot of poles to foliations	19
7. Contoured stereonet plots showing poles to schlieren	21
8. Steeply dipping sub-planar schlieren within the Cathedral Peak Granodiorite	22
9. Generalized map of the study area showing attitudes of mafic schlieren with corresponding dip labels	23
10. Photograph of a ladder dike on a subhorizontal surface within the Cathedral Peak Granodiorite	25
11. Photo of an intrusive interaction zone on a subhorizontal surface within Cathedral Peak Granodiorite	26
12. Photograph of two attenuated enclaves	28
13. Photograph showing different scales of K-feldspar concentrations	29
14. Photograph of an aplite dike separating typical porphyritic Half Dome and a K-feldspar concentration	29
15. Photograph of a gently dipping magmatic fault offsetting a ladder dike	31
16. Photomicrograph of perthitic K-feldspar megacryst	35
17. Backscattered electron images of (A) zoned uranothorite crystal and (B) chalcopyrite within sphalerite	37
18. Photomicrograph of accessory allanite under plane light	38
19. Photomicrograph of possible primary igneous epidote crystals	38

20. Photomicrograph of mafic schlieren under plane light	40
21. Photomicrograph (crossed polars) of granophyric texture in an aplite dike	41
22. Microprobe data from BTL042B showing core-to-rim-zonation	43
23. Backscattered electron images of plagioclase grains from sample BTL028.....	44
24. Average molar anorthite variation with (A) silica and (B) longitude	45
25. Groups of rim and core anorthite concentrations for three plagioclase grains from the Cathedral Peak Granodiorite.	47
26. Microprobe data from a K-feldspar grain within BTL043	48
27. U/Pb concordia diagram for BTL045.....	50
28. U/Pb concordia diagram for BTL056.....	51
29. Major elements versus silica for all samples within the study area.....	53
30. Major elements versus silica concentration	54
31. Major elements versus longitude	56
32. Feldspar compatible elements versus silica.....	57
33. Mafic compatible elements versus silica for all samples	59
34. (A) Incompatible versus incompatible trace element. (B) Compatible versus incompatible trace element.....	60
35. Feldspar compatible trace elements versus longitude	62
36. Strongly incompatible trace elements (U, Th) and a compatible trace element (Sc) versus longitude.....	63
37. Chondrite normalized REE plots from the Cathedral Peak Granodiorite	65
38. Chondrite normalized REE plots of samples within the porphyritic and equigranular Half Dome Granodiorites	66
39. REE's versus longitude	68
40. Light to heavy REE ratios versus longitude	69
41. Initial strontium isotopes verses (A) silica concentration and (B) longitude	71

42. Neodymium variation with (A) silica concentration and (B) longitude	73
43. $^{87}\text{S}/^{86}\text{Sr}_{(i)}$ versus $\varepsilon\text{Nd}_{(i)}$ covariation	74
44. Strontium versus Sc and V for Tuolumne Series rocks	85
45. Aluminum oxide versus silica for Tuolumne Intrusive Series rocks	88
46. Strontium versus silica in granodioritic Tuolumne Intrusive Series samples.....	92
47. Chondrite normalized rare-earth element plot for geographically adjacent but compositionally dissimilar samples	94
48. Barium variation with silica in granodioritic Tuolumne Intrusive Series samples .	96
49. Major elements versus silica for samples from the chemical transects	100
50. Strontium versus silica for samples from the chemical transects	100
51. Epsilon Nd versus silica for Tuolumne Intrusive Series data superimposed on a two component mixing line	101

LIST OF TABLES

Table	Page
1. Feldspar composition determined by electron microprobe	112
2. Potassium feldspar compositions for a single grain from BTL043 as determined by electron microprobe	119
3. Potassium feldspar compositions for a single grain from BTL043 as determined by electron microprobe	120
4. Potassium feldspar compositions for a single grain from BTL042 as determined by electron microprobe	121
5. U/Pb zircon analytical data for BTL045 and BTL056	123
6. Normalized major element concentrations determined by X-ray fluorescence	125
7. Unnormalized trace elements determined by X-ray fluorescence	127
8. Trace element concentrations determined by ICP-MS.....	129
9. Isotope concentrations as determined by ICP-MS	134
10. Bulk compositions, partition coefficients (K-plag, K-amph...etc.) and calculated bulk distribution coefficients (bulk D) for various trace elements in various starting compositions	136
11. Trace element liquid concentrations for different starting compositions at different melt fractions.	137
12. Least squares mixing model using hornblende-biotite schlieren and plagioclase as the fractionating cumulate.	138
13. Least squares mixing model using hornblende and plagioclase as the fractionating cumulates.	139
14. Least squares mixing model using hornblende-biotite schlieren and K-feldspar as the fractionating cumulate.....	140
15 Least squares mixing model using a granodiorite as the parent and a granite as the daughter composition	141
16. Bulk compositions, partition coefficients (K-plag, K-amph...etc.) and calculated bulk distribution coefficients (bulk D) for Ba in an amphibolite with or without	

K-feldspar and in an eclogite. Also shown are Ba liquid concentrations for different melt fractions	142
--	-----

INTRODUCTION

Compositionally zoned igneous intrusions have direct bearing on continental crust construction and magma genesis processes, and also provide a natural laboratory for studying mature arc magma systems. Despite extensive research, many uncertainties remain in understanding composite magma systems, for example: 1. Are zoned intrusions an amalgamation of smaller plutons or a solidified single large chamber? 2. What processes operated to create the zonation? 3. Where did these processes occur (i.e., in the source region or at emplacement depth)? 4. On what time scales are zoned intrusions formed?

Zoned intrusions are commonly mafic at their outer margins and increasingly more felsic inward. Classically, zonation has been attributed to fractional crystallization, restite unmixing, or hybridization of compositionally variable magmas (e.g. Chappell and White, 1974; Bateman and Nokleberg, 1978; Bateman and Chappell, 1979; Walawender et al., 1990; Bateman, 1992; Reid et al., 1993). These processes are inferred to occur *in-situ* and operate on relatively large batches of magma. However, a recent study suggests that *in-situ* processes are relatively unimportant in the construction of zoned intrusions (Glazner et al., 2004), rather attributing compositional and chemical zonation to source-controlled phenomena.

This study concentrates on field, geochronologic, and geochemical data from a small portion of the Tuolumne Intrusive Series within the Sierra Nevada batholith in order to help understand the processes involved in the petrogenesis of this zoned intrusion.

GEOLOGIC SETTING

The Cretaceous Sierra Nevada Magmatic Arc

Subduction of the Farallon plate beneath the North American craton during the Mesozoic gave rise to a classic subduction zone, complete with trench, accretionary prism, forearc basin, and magmatic arc. Subsequent uplift and erosion of the arc exposed an approximately 600 km-long, northwest-southeast trending plutonic terrane (Bateman, 1992). This swath of plutonic rocks, deemed the Sierra Nevada batholith, is chiefly intermediate in composition but also contains subordinate felsic and mafic intrusions (Fig. 1).

The Sierra Nevada batholith is bounded on the east by Proterozoic and Paleozoic sedimentary rocks and on the west by allochthonous Paleozoic and Mesozoic metamorphosed sedimentary and volcanic rocks and plutonic parts of ophiolites (e.g., Bateman, 1992). Most of the batholith consists of Cretaceous plutons, which are progressively younger to the east. A less voluminous Triassic sequence lies east of the Cretaceous plutons, whereas Jurassic arc plutons are relatively common on either side (Stern et al., 1981). The plutons in the Sierra Nevada batholith are commonly elongate in a northwesterly orientation parallel to the long axis of the batholith. A major pulse of plutonism occurred along the Sierran crest during the Cretaceous, and includes the Sonora pluton, Tuolumne Intrusive Series, Mono Pass (John Muir) Intrusive Suite and the Mount Whitney Intrusive Suite (Stern et al., 1981, Kistler et al., 1986, Bateman, 1992, Coleman and Glazner, 1997) (Fig. 1). The extensive exposure and easy accessibility of the Tuolumne Intrusive Series make it an excellent candidate for field, geochemical, and isotopic investigation.

Figure 1. Generalized outline of Jura-Cretaceous Sierra Nevada batholith and major Upper Cretaceous intrusive suites. Labeled intrusive suites are compositionally zoned from blue mafic outer phases to red felsic inner phases. Lilac outer shading represents the extent of the entire batholith.

The Tuolumne Intrusive Series

The Tuolumne Intrusive Series is a 93.5-85.4 Ma felsic to intermediate pluton that trends roughly north-northwest to south-southeast and covers an area of approximately 1000-1200 km² in the eastern Sierra Nevada (Fig. 1). The units of the Tuolumne Intrusive Series are progressively younger inward (Stern et al., 1981; Kistler and Fleck, 1994; Fleck et al., 1996; Coleman and Glazner, 1997; Coleman et al., 2004). From outer to inner, these units are: Kuna Crest Granodiorite, Half Dome Granodiorite (equigranular and porphyritic), Cathedral Peak Granodiorite, and Johnson Granite porphyry (Bateman and Chappell, 1979) (Fig. 2). Collectively, the units of the Tuolumne Intrusive Series show a gradation from mafic-intermediate to felsic and generally a regular inward increase in SiO₂, Na₂O, and K₂O, and an inward decrease in Al₂O₃, CaO, FeO, and MgO (Bateman et al., 1988).

Origin and Synthesis of the TIS: Current Models

Bateman and Chappell (1979) originally suggested that the entire Tuolumne Intrusive Series was emplaced as one large intrusion that differentiated via fractional crystallization. Unit margins were believed to have formed by upward and outward surging of a melt-rich core. This hypothesis is supported by the elliptical map pattern, gradation from mafic outer to felsic inner units, and by inward younging of the units. Inner units cut preceding units in some areas, whereas in other areas contacts are gradational. Also lending support to the Bateman and Chappell (1979) model are relatively smooth major-element trends on Harker diagrams (Bateman and Eaton, 1967; Robinson, 1977; Bateman and Chappell, 1979).

Figure 2. Simplified geology of the Tuolumne Intrusive Series showing general outline of study area. Tenaya Lake is shown in blue as a reference location. Map is modified from Bateman (1992).

Systematic variation in initial $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ vs. SiO_2 within the Tuolumne Series was documented by Kistler et al. (1986), which resulted in a model employing magma mixing. In this model, mixing between low $^{87}\text{Sr}/^{86}\text{Sr}_i$, high $^{143}\text{Nd}/^{144}\text{Nd}$ mafic magmas and high $^{87}\text{Sr}/^{86}\text{Sr}_i$, low $^{143}\text{Nd}/^{144}\text{Nd}$ felsic melts resulted in magmas of intermediate composition, which were then modified by closed-system fractional crystallization.

Reid et al. (1993) also challenged the importance of fractional crystallization as a widespread differentiation process and favored a model of mixing between mafic and felsic end-members in the Tuolumne rocks for the following reasons: 1. Obvious cumulates (ladder “dikes” and mafic schlieren) constitute a minor fraction of the Tuolumne rocks. 2. The chemical compositions of the main Tuolumne units are not compatible with derivation by removal of these cumulates (Fig. 3). 3. Isotopic variation between major units and enclaves precludes closed system fractionation of a single parent magma.

All of these petrogenetic models assume one (or several large) shallow-level magma chamber(s), wherein differentiation or mixing can occur. Coleman et al. (2004) and Glazner et al. (2004) challenged this view of the Tuolumne Series based on U/Pb zircon geochronology that shows the series was emplaced over a period of 10 Ma (See also Kistler and Fleck, 1996). They concluded that extensive time spans make large batch, shallow-chamber differentiation impossible. As an alternative, Coleman et al. (2004) and Glazner et al. (2004) proposed that the Tuolumne Series was constructed episodically by small-volume inputs. In addition, they suggested that the chemical and isotopic variability observed within the series is the result of heterogeneity in the source and/or variations in melt fraction and residual mineralogy.

Figure 3. Magma hybridization and crystal fractionation trends for Tuolumne Series rocks. Long dashed line represents magma hybridization between two end members where the majority of Tuolumne rock compositions fall. Arrows represent fractionation vectors if mafic schlieren (J, T and L) are removed from the main trend magma. This figure demonstrates that magma hybridization between mafic and felsic end-members can create the majority of Tuolumne Series rocks plotted, whereas fractionation of schlieren from the assemblage is responsible for little of the main trend. Glen Aulin unit is analogous to Kuna Crest Granodiorite. Figure is from Reid et al. (1993).

Although end-member hypotheses have been developed for petrogenesis of the Tuolumne Intrusive Series, detailed chemical and isotopic data are still lacking in many areas of the suite, and challenges remain in correlating chemical, isotopic and field-based data sets. Additional challenges remain in quantitatively describing the size,

number, and location of pulses. In particular, in order to evaluate the hypothesis that the Tuolumne Suite was constructed in small increments, it is necessary to conduct studies at relatively small spatial scale and over a variety of temporal scales. Such work will help to constrain the relative roles of variations in partial melting source or melt fraction, magma mixing, and crystal fractionation in producing the observed chemical variation in the Tuolumne Intrusive Series.

OBJECTIVES AND STUDY AREA

Objective

Extensive exposure and easy accessibility have allowed researchers to study the Tuolumne Intrusive Series extensively, but many questions remain. These questions include the following. 1. Have internal magma-chamber differentiation processes such as fractional crystallization and magma hybridization operated and to what degree (e.g. over what spatial and/or compositional scale)? 2. At what scale do pulses and increments occur and how are they best delineated? 3. Did different pulses have the same source material(s)? 4. Are these different pulses of primary importance in explaining geochemical variability or is the variability primarily due to internal processes operating on magmas during or after emplacement? The objective of this study was to use detailed field observations, geochemistry, mineral chemistry, isotope geology, and geochronology to address some of these questions, to develop a model that best describes the petrogenesis of the Tuolumne Intrusive Series, and to assess how this might inform the debate about the evolution of the Series.

Area and Sampling

This study focused on a small portion of the suite, which includes the Cathedral Peak Granodiorite and equigranular and porphyritic Half Dome Granodiorites. Two field transects covered these Tuolumne units and crossed their contacts (Fig. 4). These transects provided a data set that documents within-unit and across-unit chemical and isotopic variation. Detailed field observations and descriptions were also made along and adjacent to these transects and focused on schlieren, enclaves, xenoliths,

Figure 4. Sample locations across both transects from the Tenaya Lake area. Each red diamond represents a field station and the location of one sample processed for geochemistry and/or isotopic analysis. Purple polygons delineate coherent zones of abundant schlieren. Green stars represent samples analyzed for U/Pb geochronology.

felsic sheets, dikes, mafic troughs, and magmatic foliation. Samples were collected along both transects and processed for petrographic, chemical, geochronologic, and isotopic analysis. Additional isotopic and chemical data sets already exist for the Tuolumne Intrusive Series units, and were also utilized in the study.

METHODS

Sampling Strategy and Field Methods

Two field transects stretch east-west from within the Cathedral Peak Granodiorite across the porphyritic Half Dome and into the equigranular Half Dome Granodiorite. The transects run roughly perpendicular to the contacts between units. One transect covers the northern portion of the study area and the other covers the southern portion (Fig. 4). Field observations such as steep magmatic foliation and steep unit contacts suggest that the sampling transects cross an upright section (as it was emplaced) of the inner Tuolumne Intrusive Series. For further explanation of this hypothesis refer to the Discussion chapter.

Samples were collected at approximately 500 m increments along each transect (Fig. 4). In cases where contacts were present or where significant rock heterogeneities were noted, additional samples were taken at closer spatial scale. In addition to sampling, foliation measurements and basic descriptive observational data were gathered at each station. In order to increase the density of structural data within the area, foliations were also gathered at more closely spaced intervals and on either side of the transects.

Petrography

Thin sections were made for each sample from the study area that was processed for geochemistry. Additional sections were prepared from schlieren layering, enclaves, aplitic dikes and xenoliths. This was done to gain a better understanding of the textural and compositional variation in the area. Analysis focused on primary igneous mineralogy, secondary alteration, grain-grain interaction, and accessory phase identification. Analysis also focused on crystallization relationships within and between different primary phases.

Geochemistry

A total of 39 samples were analyzed for whole-rock and trace-element geochemistry. For coarse-grained samples, including those with large K-feldspar crystals, an excess of 20 kg was crushed to ensure sample homogeneity. Each sample was processed through a series of jaws, decreasing the grain size and homogenizing the sample. Splits of each sample were then processed at the Washington State University GeoAnalytical Laboratory for whole-rock and trace element concentrations on a *Rigaku* automated X-ray fluorescence spectrometer (XRF) and for trace element concentrations on a *Hewlett-Packard* inductively coupled plasma mass spectrometer (ICP-MS). The reported values were checked for accuracy and precision using common elements analyzed by both XRF and ICP-MS (e.g., Ba, Sr, Zr). Repeat measurements were made on a separate split in two cases where abundances yielded values outside of typical interlab agreement at the Washington State University GeoAnalytical Lab. Upon reanalysis, agreement was within expected interlab variation (<5% difference). See:

<http://www.wsu.edu/~geology/Pages/Services/Geolab.html> for complete XRF and ICP-MS procedures.

Mineral Chemistry of Plagioclase and Potassium Feldspar

Plagioclase and K-feldspar compositions were obtained using a JEOL JXA-8800L electron microprobe at the United States Geological Survey in Menlo Park, CA. Operating conditions were 15 kV accelerating voltage and 10 nA beam current with a 2 micron beam diameter. Matrix effects were corrected for using CITZAF data reduction. Synthetic and natural standards were used, and included Tiburon Albite (Si, Na), Barite (Ba), ORIA (K), Anorthite 100 (Al, Ca) and RGSC (Mg).

Geochronology

Two samples of Cathedral Peak granodiorite were collected from either end of the northern sampling transect for U/Pb zircon geochronology (Fig. 4). After the bulk samples were processed, zircon crystals were separated from other minerals in the assemblage. Single zircon crystals were then manually picked in ethanol from bulk fractions and cleaned in HNO₃. All analyzed grains were abraded using standard air abrasion for over 72 hours. Zircons were then digested using 29M HF. Zircon weights were estimated using a video camera and scale, and were known to within 10%. Uranium and Pb were spiked with a mixed ²⁰⁵Pb-²³³U-²³⁶U tracer and separated using HCl chemistry, then loaded on to zone-refined rhenium filaments using clean H₃PO₄ and silica gel. All analysis was accomplished with a Micromass Sector 54 thermal ionization mass spectrometer at the University of North Carolina (UNC). Lead was analyzed using a single Daly collector, and analyses are corrected by 0.18 % /amu for mass

fractionation. After subtraction of blank Pb (<5 pg), common Pb corrections were unnecessary for most fractions. For fractions with total common Pb in excess of 5 pg, corrections were made using Stacey and Kramers (1975) initial Pb. Uranium was analyzed using a dynamic peak-hopping routine. Decay constants used were $^{238}\text{U} = 0.155125 \times 10^{-9} \text{ yr}^{-1}$, and $^{235}\text{U} = 0.98485 \times 10^{-9} \text{ yr}^{-1}$ (Steiger and Jäger, 1977).

Whole Rock Isotopic Analysis

Twenty samples were analyzed for Rb-Sr and Sm-Nd isotopes. Two hundred mg of whole rock powder from each sample were dissolved and spiked with mixed ^{150}Nd - ^{147}Sm and dissolved in a mixture of HF and HNO_3 in a sealed Teflon bomb at 220°C for 5-7 days. After conversion to chlorides, separation of Sm and Nd was accomplished using a two-column REE separation with RE-spec and LN-spec columns. Strontium was separated using Sr-spec column chemistry and HNO_3 . Neodymium was loaded on single Re filaments with dilute HCl and Sm was loaded on single-Ta filaments with H_3PO_4 . Strontium was loaded with H_3PO_4 and TaCl_5 emitter on a Re filament. All analyses were performed on a Micromass Sector-54 mass spectrometer at UNC. Neodymium was analyzed in dynamic multicollector mode as NdO using an oxygen bleed valve at 1V, and Sm was analyzed in static multicollector mode with $^{147}\text{Sm} = 200$ mV. Strontium was analyzed in dynamic multicollector mode with $^{88}\text{Sr} = 3\text{V}$. Neodymium data are normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. Strontium data are normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$. Replicate analysis of SRM-987 yielded $^{87}\text{Sr}/^{86}\text{Sr} = 0.710246 \pm 0.000010$ (2 standard errors, $n = 25$). Replicate analysis of J-Nd standard gave $^{143}\text{Nd}/^{144}\text{Nd} = 0.512099$ and data are referenced to this standard, which is in turn referenced to La Jolla Nd ($^{143}\text{Nd}/^{144}\text{Nd} = 0.511853$). Initial Sr ratios were calculated

using $\lambda^{87}\text{Rb} = 1.42 \times 10^{-11} \text{ yr}$, and using Rb and Sr concentrations measured by ICP-MS.

Epsilon Nd and $T_{(\text{DM})}$ were calculated using $^{143}\text{Nd}/^{144}\text{Nd}_{\text{CHUR}} = 0.512638$, $^{147}\text{Sm}/^{144}\text{Nd}_{\text{CHUR}}$

$= 0.1967$, and $\lambda^{147}\text{Sm} = 6.54 \times 10^{-12} \text{ yr}^{-1}$, as well as the depleted mantle model of

DePaolo (1981).

FIELD RELATIONSHIPS

Magmatic Fabrics

Cathedral Peak Granodiorite

Two magmatic foliations were recognized at most stations within the Cathedral Peak unit. Foliation is defined by aligned hornblende and biotite. Due to the relative paucity of amphiboles in the majority of the Cathedral Peak unit, the foliation is most commonly defined by biotite. One foliation strikes north-northeast, roughly parallel to major contacts and the other strikes west-northwest, discordant to major contacts (Bateman, 1992). The strike of the dominant foliation varies between stations, but dips are uniformly steep (average 77°). A contoured stereonet plot of poles to foliations shows clear maxima for both the north-northeast and west-northwest fabrics (Fig. 5). Mineral lineation was not recorded at the majority of stations due to weak intensity and lack of vertical outcrop face, but in the few cases where it could be observed, it was generally steeply plunging.

Half Dome Granodiorite

Two foliations were also observed within the Half Dome units (Paterson et al., 2003; Karpowicz, 2004; Zak and Paterson, 2005; Teruya, 2005) and are defined by aligned hornblende and biotite. The north-south, margin-sub-parallel foliation is dominant at most stations, but the less-intense east-west fabric is also widely observed. A contoured stereonet plot of poles to foliations for the porphyritic Half Dome Granodiorite displays maxima at both north-south and east-west orientations. Foliations from this unit dip 74° on average (Fig. 6A).

The foliation in the equigranular Half Dome unit also shows both north-south and east-west striking maxima and dips steeply (average 79°) (Fig 6B). In places, foliation cuts across igneous features such as enclaves and schlieren. In a few cases, foliation is deflected at enclave margins. Where both are clearly preserved, the east-west fabric cuts across the margin parallel fabric and is unaffected by presence of enclaves.

Figure 5. Contoured stereonet plot of poles to foliations within the Cathedral Peak Granodiorite. Contours are 4, 6 and 8%. $n = 66$

Figure 6. Contoured stereonet plots of poles to foliation. (A) Porphyritic Half Dome unit, $n = 96$ and (B) equigranular Half Dome unit, $n = 33$. Contours are 4, 6, and 8%.

Internal Structures and Heterogeneities

Schlieren

Schlieren are common, but heterogeneously distributed throughout the map area. Schlieren are defined by concentrations of biotite and hornblende, and commonly occur in sequences or sets that display sedimentary-like features such as size grading, “cross bedding,” and layer truncations. Subhedral to euhedral hornblende and biotite are commonly imbricated. In the Cathedral Peak unit, schlieren layers dominantly strike northwest (Fig. 7A). The average strike of schlieren within the entire study area is 157° (Fig. 7B) but varies up to 50° locally. Schlieren layering dips 60° on average, but varies within the area from nearly vertical to horizontal. The average strike of the major unit contacts is roughly 170° . Zones of schlieren varying from 5 to 40 m in width are observed near major unit contacts as mapped by Bateman et al. (1983), and occur nearly every place the contacts are exposed.

In the Cathedral Peak unit, schlieren are commonly associated with K-feldspar concentrations and generally form irregularly shaped boundaries around these features. K-feldspar crystals are commonly aligned parallel to layering, but are also discordant to the dominant orientation in the schlieren (see also discussion on p. 28). Some schlieren are wispy, folded and highly irregular in shape, and are only continuous over a few meters. Others are more planar, and laterally continuous for many tens of meters (Fig. 8).

Schlieren zones also occur well away from unit contacts. Within the Cathedral Peak Granodiorite, a semi-coherent zone of schlieren was documented. This zone strikes east-northeast and is continuous along strike for greater than a kilometer (Fig. 9).

Figure 7. Contoured stereonet plots showing poles to schlieren. (A) Schlieren layering within Cathedral Peak Granodiorite, $n = 50$. (B) Schlieren layering within the entire study area, $n = 125$. Contours are 4, 6 and 8%.

Figure 8. Steeply dipping sub-planar schlieren within the Cathedral Peak Granodiorite.

The across-strike extent of the entire schlieren-rich zone is approximately 2 km, and schlieren in individual outcrops range in thickness from 30 m to < 1 m. The zone is composed of both planar and irregular schlieren. Although not mapped in detail, several smaller isolated zones, together with the largest continuous outcrop, define a broad southwest dipping swath ($\sim 55^\circ$) (Fig. 9).

Figure 9. General map of the study area showing attitudes of mafic schlieren with corresponding dip labels. Purple shaded area represents zones of relatively continuous schlieren. Contacts are after Bateman (1992).

Ladder Dikes

Ladder dikes are common within the Cathedral Peak unit and are typically associated with schlieren-rich zones (Reid et al. 1993; Weinberg et al. 2001; Zak and Paterson, 2005). Ladder dikes are delineated by hornblende and biotite, which define sets of crescent-shaped, dark and light layers, forming stacks of concave-up curved layers (Reid et al. 1993). Most ladder dikes in the study area are in the Cathedral Peak unit, although a few occur within the equigranular and porphyritic Half Dome units. Ladder dikes within the Cathedral Peak Granodiorite are on average 2-3 m long (Fig. 10). Contacts with the host rock are sharp, although K-feldspar megacrysts from the host do span across contacts. Most of the ladder dikes are well within the Cathedral Peak Granodiorite.

Mingling Zones

In the northern transect, within the Cathedral Peak Granodiorite, two areas tens of square meters in outcrop area display intimate intrusive interaction. Both involve a more felsic, K-feldspar megacryst-poor granite that interacted with host granodiorite. Interaction boundaries range from sharp to diffuse, commonly displaying cusped/lobate geometries and “flame-like” structure. In a few cases, cm-scale veinlets of leucocratic melt intruded host granodiorite (Fig. 11). Interaction zones, like K-feldspar concentrations, may be marked by marginal schlieren. These schlieren form a discontinuous boundary between texturally variable felsic masses and are faint and irregular.

Figure 10. Photograph of a ladder dike on a subhorizontal surface within the Cathedral Peak Granodiorite showing finely graded layers and curved-layer truncations. Note K-feldspar megacrysts aligned roughly parallel to curved layers.

Figure 11. Photograph of an intrusive interaction zone on a subhorizontal surface in Cathedral Peak Granodiorite. Photo shows leucocratic sheets, schlieren-rich accumulations and megacryst-poor granodiorite.

The larger of the two zones, cropping out in the eastern edge of the area (near BTL043, see Fig. 4) near the Johnson Granite – Cathedral Peak Granodiorite contact, consists of three rock types, differentiated in the field by color index, mineralogy, and texture (Fig. 11). One rock type closely resembles Cathedral Peak Granodiorite, but has fewer K-feldspar megacrysts. The second rock type is leucocratic (color index (C.I.) ≤ 5), and contains subhedral quartz and plagioclase phenocrysts. This body is similar to the adjacent Johnson Granite Porphyry, but differs in that it contains K-feldspar megacrysts. Boundaries between this leucocratic material and the Cathedral Peak host range from sharp to diffuse. The third rock type contains abundant faint and discontinuous schlieren that are commonly folded into chaotic patterns. These three

rock types intermingle throughout the zone, displaying very complex geometric patterns and mutually cross-cutting intrusive relationships.

Microgranitoid Enclaves

Numerous studies indicate that microgranitoid enclaves are common in intermediate igneous intrusions (e.g., Vernon, 1984; Bateman, 1992; Barbarin, 2005). Within the studied area, enclaves are common, but represent much less than 1% of total outcrop in all three units, both away from and near internal contacts. Enclaves mimic the mineralogic assemblage of the host granodiorite, but contain a greater fraction of mafic minerals. Also common within enclaves are hornblende and plagioclase phenocrysts, ranging from 5 to 8 mm long.

Host rock-enclave interaction is limited, as the vast majority of boundaries are abrupt, although plagioclase and hornblende crystals span boundaries in places. Felsic rims of varying thickness (≤ 3 cm) surround enclaves locally. This feature has been documented in greater abundance elsewhere within the Tuolumne Series (Reid et al. 1983). Sparse solitary enclaves were observed, as were small swarms containing multiple enclaves (5-10) in close proximity. Enclaves in the swarms typically vary in aspect ratio, and commonly have their long axes oriented in different directions (Fig. 12).

Figure 12. Photograph of two attenuated enclaves (outlined) with their long axes oriented at nearly right angles to each other. Dotted lines show approximate trend of long axis for each enclave. The mineral foliation in this photo is oriented approximately 315/65.

Potassium Feldspar Concentrations

K-feldspar megacrysts up to 10 cm long are common in the Cathedral Peak unit.

In addition to being scattered throughout the unit as single crystals, K-feldspar megacrysts occur in dense concentrations of nearly 100% megacrysts. Individual megacrysts within a concentration are similar to isolated crystals in size, shape, and inclusions of biotite and hornblende along concentric growth rings. Within the study area, concentrations range from <10 cm in diameter to meter-scale, dike-like bodies (Fig. 13). Imbrication of K-feldspar megacrysts is common in the larger concentrations, which are found intruding the porphyritic Half Dome unit as irregularly shaped schlieren-bounded sheets. K-feldspar concentrations exhibit a wide variety of geometries, which can be roughly classified as tubes, troughs, irregularly shaped clusters, dikes, or small diapirs (Zak and Paterson, 2005) (Fig. 14).

Figure 13. Photographs showing different scales of K-feldspar concentrations within the Cathedral Peak Granodiorite. Note the normal modal abundance of K-feldspar megacrysts in the host granodiorite adjacent to concentrations in the photograph on the right.

Figure 14. Photograph of an aplite dike separating typical porphyritic Half Dome Granodiorite and a K-feldspar concentration.

A noteworthy feature of these K-feldspar concentrations is that the immediately adjacent host granodiorite does not show obvious depletion in K-feldspar (Fig. 13).

Aplitic Dikes

Late aplite dikes are common within the study area and range from 1 cm to 6 cm wide. Dikes crosscut nearly all features within the study area, and the majority have sharp contacts (Fig. 14); however, some dikes have irregularly shaped margins and, in a few cases, small dikes of aplite emanate from a larger dike and dissipate into host Granodiorite. Although dominantly "sugary" and homogeneous, some dikes, generally the larger ones, have pegmatitic cores composed of quartz, K-feldspar and plagioclase.

Magmatic Faults

Magmatic faults occur in several places within the Cathedral Peak unit. These faults commonly offset material of the same composition, making them difficult to observe, and so they may be more abundant than is apparent in the field. Faults offset other structures such as ladder dikes (Fig. 15). At two locations, the visible plane shows oblique normal-sinistral faulting. The extensional component is smaller than the strike-slip component in both cases. The small dilated area is healed by either K-feldspar-rich material, similar to that found in "pipes" and concentrations elsewhere in the Cathedral Peak unit, or aplite, much like that found in discrete dikes throughout the Tuolumne Intrusive Series.

Figure 15. Photograph of a gently dipping magmatic fault offsetting a ladder dike within Cathedral Peak Granodiorite. (A) Subhorizontal surface showing separation across the fault. (B) Cross section view of same feature on a steep surface.. Although difficult to see in this photo, there is K-feldspar concentration along the fault plane.

PETROGRAPHY

Petrography and detailed modal variation of all Tuolumne units in the study area have been well documented by Bateman and Chappell (1979), Bateman et al. (1988) and Bateman (1992); thus only brief descriptions are included here. Petrographic and field analysis for this study includes the Half Dome units, but is concentrated on the Cathedral Peak Granodiorite because this is where sampling for chemical analysis was focused.

Equigranular Half Dome Granodiorite

The equigranular Half Dome Granodiorite is composed of medium-to coarse-grained plagioclase, K-feldspar, quartz, biotite, and hornblende. Plagioclase is subhedral and ranges from unaltered to highly sericitized grains. Most grains show albite twins and some grains have oscillatory zoning. Many plagioclase grains are myrmekitic. Zircon crystals are common inclusions within plagioclase.

K-feldspar is primarily interstitial and has inclusions of all other minerals in the assemblage, of which plagioclase is the most frequent. K-feldspar (dominantly microcline) can be sizeable (up to 0.5 cm) and commonly shows perthitic exsolution and Carlsbad twinning. In most cases, perthitic exsolution is not pervasive throughout the crystal and is commonly segregated into smaller pockets within a larger grain of orthoclase or microcline. Quartz is typically interstitial and undeformed.

Hornblende is generally small (< 2 mm), subhedral to euhedral, and unaltered. Larger crystals are more highly deteriorated, and at least partially altered to oxides. Small biotite crystals and sphene wedges are commonly included within hornblende.

Biotite is commonly large (up to 5 mm), and partially altered to chlorite. Euhedral sphene is ubiquitous and the dominant accessory phase.

Porphyritic Half Dome Granodiorite

The porphyritic phase of the Half Dome unit is most readily distinguished from its equigranular counterpart by the presence of blocky K-feldspar phenocrysts. Two distinct populations of K-feldspar exist within the porphyritic Half Dome Granodiorite. The first is volumetrically less abundant and is composed entirely of cm-sized phenocrysts. These phenocrysts are commonly microcline, although orthoclase occurs throughout the unit. Both microcline and orthoclase exhibit pervasive perthitic exsolution and have inclusions of all other minerals within the assemblage. Plagioclase is the most common inclusion. The second population is interstitial and composed of both microcline and orthoclase. Overall, microcline is more common in the porphyritic Half Dome unit than in the equigranular unit.

Plagioclase grains are dominantly subhedral and are either fresh or highly sericitized. Fresh grains seldom have inclusions and have sharp boundaries with adjacent minerals. However, small zircon crystals are included within many less-fresh plagioclase grains. Some plagioclase grains are oscillatory zoned and have reacted to myrmekite along grain edges.

Quartz is less abundant than feldspar and is interstitial in most cases. Hornblende within the porphyritic phase forms as either large phenocrysts that are fractured and altered to oxides or small euhedral crystals, which are slightly degraded along cleavage planes. Biotite is commonly large and generally altered to chlorite. The dominant accessory within the porphyritic Half Dome unit is sphene, which is typically

seen in conjunction with accessory oxides. Both sphene and oxides are common inclusions within biotite and hornblende.

Cathedral Peak Granodiorite

K-feldspars are dominantly orthoclase with less abundant microcline. Similar to the porphyritic Half Dome unit, the K-feldspars can be divided into two separate categories. The first consists of megacrysts that volumetrically dominate many thin sections, even though only a portion of each grain is represented. These grains are multiple centimeters in diameter and enclose all other minerals in the assemblage. Plagioclase is the most abundant inclusion. Fine-grained inclusions of minerals such as biotite and plagioclase are commonly concentrated along growth surfaces within megacrysts, resulting in roughly concentric zones of inclusions from rim to core. These megacrysts have Carlsbad twins and are commonly exsolved to perthite (Fig. 16). The second population is dominantly interstitial and chiefly composed of orthoclase but includes minor microcline.

Plagioclase is volumetrically dominant and shows complex zoning and exhibits both oscillatory and concentric zoning. Grains are subhedral and range from fresh to highly altered (sericite) and fractured grains. Commonly, anhedral resorption surfaces can be seen truncating albite twins.

Mafic minerals are less abundant in the Cathedral Peak unit than in the Half Dome phases, and make up $\leq 10\%$ of the assemblage. Biotite is the dominant mafic phase and is found both as fresh grains and chloritized fragments. Euhedral sphene and oxide blebs are commonly included within biotite. Hornblende is sparse within the

Figure 16. Photomicrograph of perthitic K-feldspar megacryst from the Cathedral Peak Granodiorite (BTL 028) under crossed-polars. Both coarse and fine (micro) lamellae can be seen in this photomicrograph. Notice the albite twins within one of the coarse lamellae. Field of view is approximately 4x5 mm.

Cathedral Peak unit and is generally small (<1 mm) and euhedral. Sphene is the most common accessory phase and is dominantly euhedral. Oxides are found in small concentrations adjacent to, or in contact with, sphene crystals. Zircon is common inclusions within plagioclase and biotite.

Small inclusions of a variety of secondary phases were found within primary igneous minerals. Sphalerite and chalcopyrite are often found in association with magnetite (Fig. 17). Uranothorite was found in many samples as a subhedral igneous phase (Fig. 17). A few sections from the Cathedral Peak unit contained allanite, especially those with higher silica (Fig. 18). Another section contained an unusually

fresh epidote crystal that was euhedral and showed strong zonation and although this grain does not satisfy all criteria for magmatic origin (Zen and Hammarstrom, 1984) it is possibly a primary igneous phase (Fig. 19).

A

B

Figure 17. Backscattered electron images of (A) zoned uranothorite crystal. Green and red zones are the same phase and likely represent two stages of crystallization with different U/Th. Scale is $\sim 0.007 \text{ mm}^2$ (B) sphalerite (green and yellow) with included chalcopyrite (red zones). Adjacent black grains are magnetite. Scale for this image is $\sim 0.001 \text{ mm}^2$. Both crystals are from BTL 031A.

Figure 18. Photomicrograph of accessory allanite under plane light within a Cathedral Peak Granodiorite (BTL 043). Also visible in this section are a fresh biotite crystal (on left), showing small zircon inclusions and a biotite that is altered to chlorite (on right). Field of view is approximately 4x5 mm.

Figure 19. Photomicrograph of possible primary igneous epidote crystals under crossed polars within Cathedral Peak Granodiorite. Note the crystal showing penetration twins and concentric (igneous?) zoning. Field of view is approximately 4x5 mm.

Compositional Outliers

Samples that represented compositional outliers were examined in thin section in order to better understand compositional variation in the area. These samples include microgranitoid enclaves, mafic schlieren, and aplite dikes.

The enclaves are dominated by plagioclase, which is heavily sericitized and has reacted to myrmekite. Amphibole is the dominant mafic phase in enclaves, and biotite is slightly less abundant. Hornblende is acicular and bladed, presumably due to rapid undercooling of the enclave. Biotite is commonly small and fresh, but some grains are altered to chlorite. Accessory sphene is common and can be larger (up to 5 mm) than biotite and hornblende. Oxides compose a larger volume percentage of enclaves than average Cathedral Peak samples. Overall, enclaves are much finer-grained than average samples of Cathedral Peak Granodiorite.

Schlieren consist predominantly of plagioclase, which shows oscillatory zoning and has inclusions of hornblende, biotite, quartz, K-feldspar, sphene, oxides, and small euhedral zircon. In general, mafic minerals are volumetrically more abundant in schlieren (C.I. ~ 55), relative to other rock types, where typical color indices are ≤ 10 . Hornblende is generally small and subhedral, and commonly has inclusions of biotite, sphene, and oxides (Fig. 20). High sphene and oxide modal abundances also help to distinguish schlieren from other rocks in the Tuolumne Series.

Aplite dikes are distinctive and are nearly devoid of mafic minerals. Aplites are generally granophyric and contain abundant anhedral quartz (Fig. 21). Plagioclase is poorly zoned and is less altered in aplites than in any other sample collected. Veinlets of quartz are interspersed throughout one aplite section. Another aplite exhibits a strong bimodal grain size distribution, containing large phenocrysts of quartz and plagioclase

within a matrix of much smaller plagioclase and quartz. The only mafic mineral in aplites is biotite, which commonly occurs adjacent to sphene.

Figure 20. Photomicrograph of mafic schlieren (BTL 031A) under plane light showing abundance of hornblende, biotite, sphene and oxides. Note the euhedral form of the majority of sphene crystals. Field of view is approximately 4x5 mm.

Figure 21. Photomicrograph (crossed polars) of granophyric texture in an aplite dike from the Cathedral Peak Granodiorite (BTL 041). Field of view is approximately 4x5 mm.

Other felsic materials within the Cathedral Peak unit (e.g., those found in zones of interaction) have less biotite and hornblende than Cathedral Peak Granodiorite, but more than aplites. The mafic constituent is dominantly chloritized biotite, which has inclusions of sphene. These leucocratic samples also lack the granophyric texture of the aplites. In comparison to average Cathedral Peak Granodiorite, K-feldspar grains are smaller and commonly perthitic. Plagioclase is intermittently mantled by myrmekite. Accessory allanite was documented in two out of three leucocratic thin sections from the unit.

FELDSPAR MINERAL CHEMISTRY

Plagioclase Mineral Chemistry

A total of 44 plagioclase grains, representing 10 samples, were analyzed. These grains span the compositional range of the Cathedral Peak and “normal” porphyritic and equigranular Half Dome Granodiorites. Anorthite content among all samples ranges from An₄₈ (in mafic schlieren) to An₁. The highest non-schlieren An content (An₃₉) was from within the Cathedral Peak unit (Table 1, Appendix 1, pg. 112). The majority of plagioclase grains are normally zoned with respect to anorthite.

Calcium concentrations decrease from the core outwards in most grains, but in general, where detailed traverses were conducted, zonation shows a pattern where the interior of the grains (cores) have a relatively constant An content but are overgrown by rims showing approximately linear (i.e. monotonic) decrease in An content out to the very edge of the grain (Fig. 22). Abrupt shifts in composition may have been missed due to the relatively low number of points on most traverses. Zoning patterns observed optically and in backscattered electron images (e.g., Fig. 23 A,B) are in some cases more abrupt. Out of 43 plagioclase grains probed, only one instance of reverse zoning was documented. The average molar anorthite concentrations for plagioclase cores and rims decrease systematically with increasing silica (Fig. 24A).

Anorthite content in both rim and core positions also decreases with decreasing longitude (toward the interior of the Cathedral Peak unit) (Fig. 24B) (see also Bateman, 1992). Where several grains were analyzed from representative samples of outer and inner Cathedral Peak Granodiorite, plagioclase composition overlapped in the range of An₂₀₋₂₇.

Figure 22. Microprobe data from sample BTL042B (see Fig. 4) showing core-to-rim zonation of (A) An number and (B) Sr within plagioclase. Each line represents a different grain from the same polished section. Single analysis points for each grain are nearly equidistant from each other along the core to rim transect. 1 = "core" as observed in the thin section for all grains. Anorthite number is calculated as $\text{wt\% Ca} / (\text{Ca} + \text{Na} + \text{K})$.

A **B**

Figure 23. Backscattered electron images of plagioclase grains from sample BTL028 (refer to Figure 4). (A) Well-formed, unaltered grain lacking strong zonation. (B) Highly fractured and zoned grain. Field of view for both slides is approx. 2x2 mm. Zonation represents decreasing molar calcium (An #) from core to rim.

Figure 24. Average molar anorthite variation with (A) silica and (B) longitude. Plagioclase analysis from mafic schlieren and enclaves are omitted from plot (A).

Core compositions from these grains are relatively constant, showing approximately 6 mol% An variability for outer Cathedral Peak samples and approximately 4 mol% An variability for inner Cathedral Peak samples. Rim compositions are more variable (An_{2-30}) (Fig 25). The compositions of plagioclase analyzed from a mafic schlieren overlap with those from granodioritic Cathedral Peak samples. One core composition from the schlieren is more calcic than any from the granodiorite. Schlieren plagioclase grains have more variable core compositions than those from inner and outer Cathedral Peak samples (Fig 25). Strontium concentration shows zonation similar to An content, with more Sr-rich cores as compared to rims (Fig 22). Spikes and dips in Sr concentration are common within a single crystal, but are not consistent from grain to grain in most cases (Fig. 22).

Figure 25. Groups of rim and core anorthite concentrations for three plagioclase grains from the Cathedral Peak Granodiorite. In all cases, the lesser An number represents plagioclase rim composition and the greater value corresponds to plagioclase core composition.

Potassium Feldspar Chemistry

Three K-feldspar grains from two samples within the Cathedral Peak unit [BTL043 (2 grains) (Tables 2,3, Appendix 1, pg. 119, 120) and BTL042A (Table 4, Appendix 1, pg. 122)] were analyzed. Orthoclase compositions are consistent, and from core to rim, vary from a minimum of Or₈₃ to a maximum of Or₉₆. Although backscattered electron images of individual grains show faint concentric zonation, likely caused by Ba concentration variations (e.g., Kerrick, 1969), Or # shows no consistent zonation from core to rim. Rather, the grains typically display a sawtooth pattern (Fig. 26). Within entire samples and not specific to one grain, concentrations of BaO vary by a large amount (relative percentage) and mirror expected variations in Ba based on bulk composition (Table 6, Appendix 3, pg. 125). For example, BTL042A has K-feldspar with relatively low Ba and is among the most silica-rich samples in the data set.

Figure 26. Microprobe data from a K-feldspar grain within BTL043 showing orthoclase-number zonation from core to rim. Each line represents a separate crystal from the same polished section and single analyses are approximately equidistant from one another. Orthoclase number is calculated as $K_2O / (K_2O + CaO + Na_2O)$.

GEOCHRONOLOGY

Zircon U/Pb Age Results

Zircon U/Pb age data are presented in Table 5 (Appendix 2, pg. 123) and Figures 27 and 28. Two Cathedral Peak Granodiorite samples were chosen to represent the innermost and outermost geographic locations along the northern field transect. These locations represent the largest possible age gap along the transects, assuming progressive younging inward from the margins of the Tuolumne Series. Multiple single-grain fractions were analyzed from each of these two samples.

Both inner (BTL045) and outer (BTL056) samples have ages clustered about concordia. A weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of the four most concordant fractions from the outer sample (BTL056) is 87.3 ± 0.7 Ma. This age is indistinguishable (within error) from the inner sample, BTL045, which is 87.0 ± 0.7 Ma based on a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of the five most concordant fractions. Weighted means have MSWD substantially >1 , which means that the scatter is more than can be attributed to analytical scatter. Ages spread along concordia by up to, or even slightly greater than 1 Ma, suggesting that zircons are a heterogeneous population.

Given that all zircons were extensively abraded, the dispersion is most likely attributable to minor inheritance of slightly older grains. For sample BTL045, one grain shows appreciable inheritance. A discordia line through the cluster of grains close to concordia and this discordant grain gives an upper intercept age of 1.4 Ga. If the scatter in ages about concordia for these two samples is attributed to inheritance, then the minimum age from the array is likely the age that most closely approximates the final solidification of the sample.

Figure 27. U/Pb concordia diagram for BTL045. (A) Concordia diagram for all grains and associated discordia line, and (B) close up of five most concordant fractions.

WHOLE ROCK GEOCHEMISTRY

Major Element Variation

In addition to the 39 samples collected for this study, 18 samples of equigranular Half Dome Granodiorite collected by J.S. Miller during previous field work are included in the geochemistry data set (Table 6, Appendix 3, p. 125) (see Fig. 4 for locations). These 18 samples include 4 mafic rocks (schlieren and enclaves) and 5 very felsic rocks (leucocratic sheets and aplitic dikes). Excluding these mafic and felsic outliers, the rocks sampled along the two transects display a compositional range from 58 to 73 wt% silica. Including outliers, silica ranges from mafic schlieren with 48 wt% to an aplite dike with 78 wt%. The greatest major element scatter is observed at the low-silica range (Figs. 29, 30). These samples constitute a small fraction of the rocks seen across the field transect as a whole, but their compositions are important in evaluating the possible roles of mixing and fractionation within the suite. For this reason, these outliers are included in major element plots. (Figs. 29,30). With all samples plotted, alkalis (NaO, K₂O) generally show appreciable scatter versus silica (Fig. 29). With compositional outliers omitted, other major oxides are fairly well correlated with some scatter in the low to intermediate silica range, and inversely proportional to increasing silica (Fig. 30). The equigranular Half Dome unit shows the greatest major element scatter (Figs. 29,30). Porphyritic Half Dome rocks show little major element variation with varying silica content, which may reflect the relative similarity in silica content.

Figure 29. Major elements versus silica for all samples within the study area. Compositional outliers (mafic enclaves and schlieren and felsic dikes/layers) are delineated with "S" for schlieren and "E" for enclave or mafic dikes.

Figure 30. Major elements versus silica concentration. Compositional outliers such as mafic enclaves, schlieren and felsic dikes/layers are included here and not delineated because they are easily discernable from the main data cluster.

Trends With Distance

From the margin of the study area inward, major elements generally show linear trends (Bateman, 1992). Within the study area, silica increases inward while calcium decreases over the same interval (Fig. 31). Patterns for FeO, MgO, TiO₂, and Al₂O₃ are similar to CaO. Alkalis generally mimic silica and increase inward, but show appreciable scatter.

Trace Element Variation

Excluding mafic schlieren and enclaves, feldspar compatible trace elements (e.g. Rb, Sr, Ba) show differing trends with respect to silica (Tables 7, 8, Appendix 3, pg. 127, 129); (Fig 32). Strontium concentration is generally well correlated with silica for Cathedral Peak rocks, decreasing linearly with increasing silica. An interesting aspect of this correlation is that Cathedral Peak and equigranular Half Dome rocks appear to fall on distinct trends at low silica concentrations, such that Sr values are systematically lower for porphyritic and equigranular Half Dome rocks, the equigranular unit having the lowest Sr concentrations. Rubidium generally increases with increasing silica, but distinct trends for the different units are not apparent. Barium generally decreases with increasing silica, but Ba values for Half Dome rocks at low-silica are generally lower than Ba in Cathedral Peak rocks at the same silica content. Cathedral Peak Granodiorites form a generally steeper fanning array, and again, porphyritic Half Dome samples overlap data for equigranular Half Dome and Cathedral Peak samples at low silica. Outliers such as mafic schlieren and enclaves clearly lie off the main trend of Tuolumne Series data (Fig. 32).

Figure 31. Major elements versus longitude. Compositional outliers from the equigranular Half Dome Granodiorite have been omitted because they deviate greatly from the main trend. Outliers from Cathedral Peak are included, and are labeled where clearly deviant from the main trend. For transect locations refer to Figure 4.

Figure 32. Feldspar compatible elements versus silica. Adjacent plots show compositional outliers such as mafic schlieren and enclaves plotted next to "normal" Tuolumne Series rocks. "+" symbols are additional compositional outliers from the equigranular Half Dome unit collected by J.S. Miller.

Compatible elements (e.g., Sc, Y) show some correlation with silica, although there is a fair amount of scatter (Fig. 33). Scandium and Y decrease linearly with increasing silica. Zirconium shows scatter between units, but generally decreases with increasing silica for each discrete Tuolumne Series unit. Plotting two elements incompatible with nearly all phases in the assemblage (e.g., U, Th) against each other results in an overall positive correlation, but the data generally fan out from the origin (Fig. 34). Plotting incompatible versus compatible (e.g., Th, Sc) elements shows no clear trend (Fig. 34).

Figure 33. Mafic compatible elements versus silica for all samples. Compositional outliers from the equigranular Half Dome unit have been omitted. However, low silica schlieren from the Cathedral Peak unit are included in the adjacent plots and more clearly display enrichment in mafic compatible elements.

Figure 34. (A) Incompatible versus incompatible trace element. (B) Compatible versus incompatible trace element. Compositional outliers from equigranular Half Dome Granodiorite are included on adjacent plots.

Trends With Distance

Large-ion lithophiles show differing trends from the eastern side of the study area westward towards the center of the Tuolumne Series. Rubidium and Sr trends are subtle, with only a slight increase and decrease respectively (Fig. 35). These trends are most visible in the Cathedral Peak unit. Elemental concentrations vary considerably with longitude because many samples of variable compositions (both compositional outliers and granodioritic compositions) were collected in very close proximity. Outliers represent high-silica rocks (leucocratic sheets and aplite dikes), which are particularly abundant toward the interior of the Tuolumne Series, and mafic schlieren and enclave samples, which occur throughout. Barium values are scattered, but in general the range of Ba values increases in the Cathedral Peak Granodiorite if very high-silica rocks and schlieren are excluded (Fig. 35). Strongly incompatible elements (e.g., U, Th) show appreciable scatter and lack clear trends with longitude (Fig. 36). Compatible elements (e.g., Sc) are scattered about a main trend, but generally decrease inward despite appreciable scatter from mafic schlieren and enclave samples (Fig. 36).

Figure 35. Feldspar compatible trace elements versus longitude. Compositional outliers from the Cathedral Peak and equigranular Half Dome Granodiorites are included to demonstrate the compositional variation within these two units.

Figure 36. Strongly incompatible trace elements (U, Th) and a compatible trace element (Sc) versus longitude. Compositional outliers from both Cathedral Peak Granodiorite and equigranular Half Dome Granodiorite have been included to demonstrate compositional variation over short distances.

RARE EARTH ELEMENTS

Chondrite-Normalized Plots

Chondrite normalized rare earth element (REE) plots are separated based on unit and silica content because of the wide compositional variety of samples. From 67 to 73 wt% silica within the Cathedral Peak Granodiorite, REE patterns display a remarkable degree of similarity in overall shape. All samples show light rare earth element (LREE) enrichment (100-300 x chondrite), lack Eu anomalies and have relatively flat heavy rare earth elements (HREE's) (Fig. 37 A,B). In addition, these samples have a restricted total range of REE concentrations as displayed by the generally tight clustering of the patterns. Leucocratic samples from the Cathedral Peak unit (> 73 wt% silica) also lack Eu anomalies, but show more rare earth variability in comparison to granodioritic samples (Fig. 37C). One aplite dike is depleted in middle REE's relative to LREE's and HREE's, which is denoted by the deeply concave-up curvature of the REE pattern (Fig. 37A). An enclave from the Cathedral Peak unit shows a slightly negative Eu anomaly and like the granites and granodiorites, exhibits LREE enrichment. The two schlieren samples are characterized by overall REE enrichment reaching 800-1000 x chondrite for LREE's in the most mafic schlieren. Schlieren also display very slight negative Eu anomalies (Fig. 37D). The xenolith from this unit has the largest negative Eu anomaly (Fig 37D).

The porphyritic Half Dome unit, like the Cathedral Peak unit, has tightly packed groups of REE curves over 66-70 wt% SiO₂ (Fig. 38A). One sample in this data set shows a slight negative Eu anomaly and has higher overall total REE concentrations.

Figure 37. Chondrite normalized REE plots of samples within the Cathedral Peak Granodiorite.

Figure 38. Chondrite normalized REE plots of samples within the porphyritic and equigranular Half Dome Granodiorites.

This sample represents the lowest silica end-member of the porphyritic Half Dome Granodiorite data set. Average equigranular Half Dome Granodiorite exhibits much more variability in REE concentrations than do other major Tuolumne Series units (Fig. 38B).

Felsic rocks (> 72 wt% silica) show the most dramatic variations in REE concentrations and in profile shapes (Fig. 38D). LREE enrichment varies from just > 100x chondrite to > 500x chondrite. The two samples with the lowest total REE concentration have extreme depletions in middle REE's and, like the one leucocratic sheet from the Cathedral Peak unit, have values that display the characteristic concave up profile (Fig. 38D). The aplite dike with the greatest concentrations of total REE's has a slight negative Eu anomaly, whereas one of the other aplites with strong middle REE depletion actually displays a slight positive Eu anomaly (Fig 38D). Mafic schlieren from the equigranular Half Dome unit exhibit higher total REE concentrations with modest negative Eu anomalies. Enclaves, and a texturally similar mafic dike, show somewhat variable patterns with variable degrees of LREE enrichment and either absent or modest negative Eu anomalies (Fig 38C).

Trends With Distance

From the margins of the study area inward, Ce shows no clear trend, but Sm and Y are fairly well correlated with distance (although there is scatter in the main trend), decreasing uniformly over this same interval (Fig. 39). For the volumetrically dominant granodiorites and granites, Ce/Yb ratios show a systematic increase over this interval, indicating a general LREE enrichment toward the center of the Tuolumne Intrusive Series (Fig. 40) (see also Frey et al. 1978). Given that the LREE's (e.g., La, Ce) are

weakly correlated with distance, the systematic variation in Ce/Yb observed is controlled primarily by systematic changes in Yb.

Figure 39. REE's versus longitude. Compositional outliers from the equigranular Half Dome Granodiorite have been omitted.

ISOTOPIC DATA

Variation in Initial Strontium and Epsilon Neodymium with Silica and Longitude

For the twenty samples analyzed, initial Strontium ($^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$) ranges from 0.70614 – 0.70654, a total range of 4.0×10^{-4} (Table 9, Appendix 4, pg. 134). The end-member values of this range represent a leucocratic, megacryst-poor Cathedral Peak sample and a relatively low-silica Cathedral Peak sample, respectively. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ is not well correlated with silica over the total exhibited range (Fig. 41A). However, higher silica samples, which correspond to the inner portions of the field area, show slightly lower $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ values in comparison to lower silica samples (Fig. 41A). The variation in initial $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ (Fig. 41A,B) is outside analytical precision (typically ± 0.00002 , see methods section).

For high silica samples having large Rb/Sr ratios, the initial ratio is extraordinarily sensitive to the age correction. Initial ratios were calculated using Rb and Sr concentrations determined by ICP-MS and are considered precise to $\pm 5\%$. However, even this modest amount of variation in either Rb or Sr would change the calculated initial ratio for the highest silica samples by > 0.0005 . Thus, $^{87}\text{Sr}/^{86}\text{Sr}$ values for the highest silica sample (> 75 wt% silica) should be regarded as having a fairly large uncertainty. In general, the range of $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ from the study area is small in comparison to the range reported elsewhere for the entire Tuolumne Intrusive series (e.g., Kistler et al., 1986; Coleman and Glazner, 1997; Gray, 2003).

When segregated by unit, it is not possible to make a distinction between the Half Dome Granodiorite and the Cathedral Peak Granodiorite using $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$.

Figure 41. Initial strontium ($^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$) isotopes versus (A) silica concentration and (B) longitude.

The one low- silica schlieren sample from the Cathedral Peak unit has an $^{87}\text{Sr}/^{86}\text{Sr}_{(t)}$ value similar to the other granodiorite and granite samples (Fig. 41A).

Initial epsilon Nd ($\epsilon\text{Nd}_{(t)}$) values are mostly less than - 5 (one value at -4) and with a minimum of -6.85 (Fig. 42A,B). In the Cathedral Peak Granodiorite, $\epsilon\text{Nd}_{(t)}$ is not correlated (within error) with increasing silica (Fig. 42A). This is also reflected in non-variant $\epsilon\text{Nd}_{(t)}$ with respect to longitude (Fig. 42B). Epsilon Nd values from the Half Dome Granodiorite are also not correlated with silica or longitude along the transect (Fig. 42A, B). However, between the map units (as delineated by Bateman, 1992), there is generally a negative correlation with silica. The equigranular Half Dome is more positive than is the porphyritic phase of the unit. Only one Cathedral Peak sample overlaps with the porphyritic Half Dome Granodiorite, but this sample is within the contact zone of these two units (as mapped by Bateman, (1992) and in this study).

$^{87}\text{Sr}/^{86}\text{Sr}_{(t)}$ - $\epsilon\text{Nd}_{(t)}$ Co-variation

Plotting $^{87}\text{Sr}/^{86}\text{Sr}_{(t)}$ versus $\epsilon\text{Nd}_{(t)}$ reiterates that neither $^{87}\text{Sr}/^{86}\text{Sr}_{(t)}$ nor $\epsilon\text{Nd}_{(t)}$ show more limited variation along the transects (Fig. 43) compared to the Tuolumne Series as a whole (e.g., Kistler et al., 1986; Coleman and Glazner, 1997), which ranges from $^{87}\text{Sr}/^{86}\text{Sr}_{(t)} = 0.7057$; $\epsilon\text{Nd}_{(t)} = -3.2$ to $^{87}\text{Sr}/^{86}\text{Sr}_{(t)} = 0.7067$; $\epsilon\text{Nd}_{(t)} = -8.0$ (Kistler, et al. 1986). This is in general agreement with Bateman (1992), who showed that much of the observed spread in initial isotopic ratios occurs in the outer units of the Tuolumne Intrusive Series (e.g., Kuna Crest and equigranular Half Dome Granodiorites).

Figure 42. Neodymium (ϵ_{Nd}) variation with (A) silica concentration and (B) longitude. Errors are $\epsilon \pm 0.3$ epsilon units for all data points.

Figure 43. $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ versus $\epsilon_{\text{Nd}(t)}$ covariation for twenty Tuolumne Intrusive Series samples. Errors are $\epsilon \pm 0.3$ epsilon units for Nd all data points and $\pm 2 \times 10^{-5}$ for initial Sr data.

DISCUSSION

Scale is fundamental to understanding the petrogenetic development of the Tuolumne Intrusive Series. If the individual mapped units of the Tuolumne Series were constructed as a series of numerous, discrete magma inputs (e.g., Glazner et al., 2004), what is the geometry, frequency, and size of the inputs? What effect might new inputs have on the compositional characteristics and physical evolution of the resident (i.e. “chambered”) magma, if any, and how can field observations, geochronology, geochemistry, and isotopic analysis help delineate different inputs? Furthermore, at what scale do these different sets of data correspond with one another, and what might this say about the petrogenesis of the Tuolumne Intrusive Series? This question applies particularly in regards to the issue of whether a persistent magma chamber was present in the mid-crust during all or part of the intrusive history.

Geologic Constraints

The processes that are primarily responsible for the petrogenesis of the Tuolumne Series must ultimately be reconciled with the ages recorded by various geochronometers (e.g., U-Pb zircon, Ar-Ar in hornblende and biotite). In general, the efficacy of igneous differentiation processes such as magma hybridization and fractional crystallization that might occur in a mid-crustal magma chamber are limited by the rate of magma input relative to solidification rate. A short intrusion interval with a high volume of magma input would likely permit interaction between discrete magma pulses. This scenario would involve ample heat and mass for mixing between new and resident magmas and fractional crystallization, which requires solidification on a time scale that is

longer than that needed for processes that separate melt from crystals (e.g., crystal settling, boundary layer melt migration, and filter pressing). The other end of this spectrum (i.e. a long interval of construction with a slow rate of intrusion) would limit the possibility of extensive interaction.

Coleman et al. (2004) and Kistler and Fleck, (1994) showed that the entire Tuolumne Series was assembled over 8-10 Ma. Examination of their data shows that a significant fraction of this time applies to the outer units of the suite (Sentinel, Kuna Crest and equigranular Half Dome Granodiorites), including the oldest age (95.0 ± 1 My), which is from the Sentinel Granodiorite. The Sentinel Granodiorite is a controversial unit, as some researchers consider it to be genetically related to the rest of the Tuolumne Intrusive Series (Kistler and Fleck, 1994; Coleman et al., 2005; Glazner et al., 2005) while others (primarily based on map relations to the remaining Tuolumne Series units) do not (Bateman, 1992; Zak and Paterson, 2005). Among the individual mapped Tuolumne Intrusive Series units, the most convincing case for a long duration of construction comes from the equigranular Half Dome unit, which spans approximately 3 Ma (Coleman et al., 2004). The interior units of the suite (porphyritic Half Dome, Cathedral Peak and Johnson granite), which are the main focus of this study, and make up the largest volume of Tuolumne rocks, span a maximum of 3.3 Ma and a minimum of 0.8 Ma based on U-Pb ages of Coleman et al. (2004) and Kistler and Fleck (1994). Existing geochronologic constraints are more equivocal in terms of estimating the duration of construction, and the estimation of the intrusion rate is also hampered by the lack of data.

The two samples dated in this study were chosen from the inner and outer Cathedral Peak unit (Fig. 4). Over the 4 km of distance between the samples, no

significant difference in U-Pb zircon age can be discerned (Figs. 27,28). Both samples have zircons clustered about concordia, but also clearly show inheritance. This is most clearly seen in BTL045, which has a Proterozoic upper intercept for a discordia line fit through the data. If the scatter in ages about concordia for these two samples is attributed to inheritance of older grains, then the minimum age from the array is likely the most accurate. The weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages for the concordant zircons for both samples are also the same within error. The slightly older concordant grains within these samples are most easily interpreted as a recycling of zircons from previously emplaced magma pulses or older solidified units. The most important result of the zircon work on these two samples is that the solidification ages are indistinguishable at the level of resolution shown by the age data.

Possibly, it could be argued that over the geographic extent of the sampling transects, the Cathedral Peak Granodiorite is actually a sill intrusion, in which case no age difference would be expected between the two geochronology samples (i.e. two samples from the same sill). However, it is clear from steep contacts, (Fig. 5) that within the area covered by the sampling transects, the pulse or pulses that comprise the Cathedral Peak Granodiorite are vertically rather than horizontally oriented. This is supported by steep foliation throughout the area. Therefore, it is reasonable to conclude that the two samples represent approximately the oldest and youngest possible portions of the Cathedral Peak along the transects.

These data, along with those from previous work, suggest that although the entire Tuolumne Series was constructed over an 8-10 Ma time period, the volumetrically dominant inner units of the Series were constructed within the last 1-2 Ma of this period.

Internal Contacts Along the Mapped Transects

In the model of Bateman and Chappell (1979) and Bateman (1992), the mapped contacts in the Tuolumne Series are viewed as the result of the upward and outward surging of the more mobile melt-rich core of a large batch of inwardly solidifying magma. These contacts generally represent compositional/mineralogical changes within Tuolumne rocks, although they range from sharp to gradational over several tens to hundreds of meters. For example, the contact between the porphyritic Half Dome and Cathedral Peak units is fairly sharp (2 - 15 m) throughout the study area, and is demarcated by the clear presence of K-feldspar megacrysts (generally > 4-5 cm long diameter) in the Cathedral Peak unit and paucity in the porphyritic Half Dome unit. The most notably variable contact within the Tuolumne Series, and within the study area, occurs between the equigranular and porphyritic Half Dome Granodiorite. Along strike, this contact ranges from gradational over nearly a kilometer to "knife sharp." The reasons for the variation in the contact are unclear.

If the Tuolumne Series was constructed in small increments, it is possible that inputs of compositionally similar magma might cumulatively construct the Series, with relatively subtle and perhaps even unrecognizable contacts between increments. Compositionally variable inputs might produce gradational contacts, as is observed along parts of the contact between porphyritic and equigranular Half Dome Granodiorites. However, for this process to create compositionally gradational contacts, the increments would have to fortuitously show systematic variation in bulk chemical composition, and intrusion inputs must have occurred at a high enough rate to mitigate appreciable cooling and chilling of later increments against subsoildus granodiorite host rock.

As mentioned previously, the study area is constrained to the last 1-2 Ma of Tuolumne Intrusive Series emplacement, and U-Pb ages are indistinguishable along approximately 4 km of the northern field transect through the Cathedral Peak unit. Over this distance, and excluding the main contact mapped by Bateman and Chappell (1979) and Bateman (1992), a variety of contacts were visible, representing previously unrecognized internal boundaries within the Cathedral Peak Granodiorite. The types of contacts observed are not exclusive to the Cathedral Peak Granodiorite (e.g., Zak and Paterson, 2005), but my observations are focused primarily on this unit.

The first readily visible contact within the Cathedral Peak unit is that of schlieren layering juxtaposed against granodioritic host material. Schlieren presumably represent locations in the magma system where crystals have been segregated in some fashion from melt. Therefore, these features are possible cumulates within the Cathedral Peak unit (e.g., Reid, et al., 1993). The laterally continuous schlieren zone delineated within the study area is an example of large-scale (km) cumulates within the granodiorite (Figs 7,9). This zone is at a high angle to the sampling transects, so it is difficult to constrain its lateral dimension and overall contiguity. Nevertheless, the zone is continuous in the field for hundreds of meters and extends discontinuously along strike for over 1 km (Fig. 9). Thus, the zone is a large and previously unrecognized area within the Cathedral Peak unit where crystals were segregated from melt repeatedly, given that younger layered sets show truncations of older layers in this zone as they do elsewhere in the Tuolumne Series (Reid et al., 1993; Zak and Paterson, 2005).

The outcrop patterns of the layers, such as variability in dip, suggest widely varying rheology in the granodiorite during, and subsequent to formation of the schlieren layers. Straight, and relatively steep continuous layering like that seen in Figure 7 may

represent areas in the magma where fairly rigid (high crystallinity) “walls” existed and along which magma flow and segregation of crystals from melt could occur. However, it is not clear from the layers whether magma was primarily moving up (i.e. because of positive buoyancy) or down, perhaps as a high particle concentration flow (Bergantz, 2000). Nevertheless, the strong rheologic contrast could result in a fairly ordered sequence of schlieren, where each set of mineral layers perhaps represents a separate small-scale flow-segregation event. In contrast, areas where layering is poorly or subtly developed and geometries include layer truncations, folds, and mingling with host granodiorite may represent areas in the magma where either the rheologic contrast between schlieren and granodiorite was modest or wholesale collapse of a semi-rigid mush occurred. This may have occurred in conjunction with partial mixing of magmas with slightly different compositions, perhaps during intrusion or a new pulse of magma (e.g., Bergantz, 2000).

Monomineralic K-feldspar concentrations are most easily reconciled with having formed by accumulation of crystals in contact with host granodiorite. These contacts are commonly sharp and fairly linear. K-feldspar megacrysts concentrations can result from flow of megacryst-bearing melt that is “necked” down, effectively decreasing the diameter of the conduit through which the same volume of material is attempting to flow. This would in effect create a logjam of megacrysts, resulting in the outcrop scale concentrations (Weinberg et al., 2001; Zak and Paterson, 2005). In many cases, clusters of megacrysts are detached from adjacent larger bodies and segregated in host granodiorite. These clusters appear to have been detached from nearby source concentrations and stranded within host material. These features could either be a true late-stage brittle separation of a small portion of megacrysts from a larger mass into a

more melt-rich environment, or alternatively could represent smaller “logjams” resulting from flow within the magma, perhaps akin to glomerophyric clots in lava flows.

The second contact relationship observed within the Cathedral Peak unit is defined by small, meter scale zones of magma interaction where magmas of generally felsic compositions are in contact. Unlike mafic schlieren contacts, which separate crystal-cumulates from granodiorite, these contacts separate granodioritic to granitic rocks with subtle compositional differences, which are less obviously cumulates. Contacts range from gradational to abrupt and are generally highly irregular over a short distance (Fig. 11). The generally intricate and irregularly shaped contacts between different rock compositions in these areas are indicative of a partially molten state. These rocks may be the product of variable degrees of fractionation within a larger mass of granitic mush, which eventually juxtaposed the two compositions. The presence of abundant and highly disrupted wispy schlieren in one of these locations may indicate that even in these zones, fractionation of felsic melt from granite mush may have occurred. Alternatively, each distinct composition may represent separate inputs of new magma. Therefore, boundaries between different compositions would represent contacts between resident mush and a new low-crystallinity magma.

The third contact relationship readily visible within Cathedral Peak rocks is that of late aplitic dikes cutting surrounding granodiorite. These contacts are sharp and planar in most cases. This relationship suggests that the aplite was either a late addition to the pluton, and that the host material was near or below its solidus at the time of intrusion, or was a late evolved felsic melt extracted from the granodiorite when it was at near-solidus conditions. Chemical criteria (discussed later) suggest these felsic dikes are distinct

from the felsic masses discussed above, which have faint and irregular contacts with the host rock, indicating the presence of significant melt.

The three distinct contact-types within the study area likely indicate the presence of mush within the evolving magma system, the repeated separation of crystals from melt within this mush, and reworking, either by late inputs and/or internal processes (e.g., convection) that destabilized and mobilized the mush. It is unclear from any of these contact types whether they exclusively represent the contact between two discrete magma inputs or rather are the result of an *in-situ* process where melt and/or crystals were re-distributed within a dynamic system.

Partial Melting, Melt Source, and Geochemical Variability

In addition to the constraints that field data and geochronology provide for the processes of differentiation and modification of Tuolumne Series rocks, a successful petrogenetic model must also satisfy the major geochemical trends. For the interior of the Tuolumne Series, this model must satisfy (1) the limited range of isotopic values along the transects, (2) generally smooth major element variation with silica content and longitude, and (3) trace element trends that display appreciable scatter with longitude but somewhat more coherent, albeit variable variation with bulk silica. These trace element trends are especially apparent in transition metals and HREE's (e.g., Sc, Y, Yb), which are generally well correlated with silica whereas LIL's, LREE's, HFSE's and more incompatible elements show greater variability (e.g., Rb, Ce, Zr and Th).

Major element trends for samples in this study, and in previously studied samples throughout the Tuolumne Intrusive Series, are generally linear. Melting experiments on postulated source materials (Ratajeski et al., 2001; Sisson et al., 2005) generally show a linear variation in major element bulk composition over the range of SiO_2 (i.e. experimental melt fractions) pertinent to this study. Thus, the major element trends could potentially arise by mixing of magmas derived by variable degrees of partial melting of the source. However, such trends are non-unique and could also arise by fractionation (discussed in the next section). Trace element and isotopic trends are required to evaluate a partial melting and mixing model. In general, the trace element trends as discussed in the chapter on Results show variable degrees of coherency or scatter, so partial melting and mixing of melts must also be able to account for this feature of the data. The focus in this section is primarily to address likely melt sources.

Possible modification of Tuolumne magmas by subsequent processes (e.g., fractionation and/or mixing) after initial partial melting is discussed later.

The variations in trace elements that are likely to be sensitive to melt-source variability (e.g., Sc, V, Sr) provide powerful first order constraints on potential melt sources. Scandium and V are generally strongly compatible in mafic silicates (pyroxenes and amphiboles), whereas Sr is highly sensitive to the proportion of plagioclase in the source. Batch partial melting models were constructed using these trace elements and the results are shown in Fig. 44 as a series of batch melting curves (Tables 10,11, Appendix 5, pg. 136, 137). Partially melting any plagioclase-rich crustal rock will result in much lower Sr concentrations than are found in the majority of rocks in this study (Fig. 44) and more widely in the Tuolumne Intrusive Series because residual plagioclase will retain Sr in the solid. This observation therefore rules out partial melting of an amphibolite source (e.g., Ratajeski et al., 2001). The general lack of an Eu anomaly in granodiorite trace element patterns also suggests that melt sources contained relatively small amounts (if any) of plagioclase, assuming the REE contents of the granodiorites are little modified by processes occurring after partial melting. Trace element models with plagioclase-poor starting compositions, like those suggested by Ducea (2001, 2002), are better candidates for the main melt source(s) of Tuolumne Series rocks. Melting without abundant residual plagioclase shifts partial melting curves at all melt fractions toward higher Sr concentrations (Fig. 44). Taking starting compositions from Ducea (2002), partially melting a plagioclase-poor, garnet-bearing granulitic source results in a better fit to the Tuolumne data with respect to Sr than does melting an amphibolite, but still cannot account for the high V and Sc values.

Figure 44. Strontium versus Sc and V for Tuolumne Series rocks. Additional samples not collected on the chemical transects were collected by J.S. Miller during previous fieldwork. Chemical data for these samples is also found in Tables 2-4. Enclave compositions from the Half Dome and Cathedral Peak Granodiorites are excluded from the larger plots to better show data trends but have been included in inset plots to show compositional range. The aberrant low-Sr, high-Sc sample is BTL042B, which was collected from within the interaction zone and contains a higher schlieren component than normal granodioritic samples. Partial melting curves on all plots range from $f = 0.1$ to $f = 0.9$. ap = apatite, sph = sphene.

Melting in equilibrium with an eclogite source most closely fits Tuolumne Series rock compositions. With less than 10 % plagioclase in the starting assemblage, low percentage partial melts have high Sr and low V, matching the bulk of inner Tuolumne rocks; although Sc concentrations are still quite low in low degree partial melts, owing to the strongly compatible behavior of this element in both garnet and clinopyroxene.

The relatively limited initial $\epsilon\text{Nd}_{(t)}$, and $^{87}\text{Sr}/^{86}\text{Sr}_{(t)}$ values within the study area require that regardless of the actual melt protolith(s), the isotopic composition of the source(s) either (a) must have been fairly homogenous throughout the genesis of the inner Half Dome and Cathedral Peak Granodiorites, even though the modest variation observed is real; or (b) the process of magma genesis in the source, which possibly involved more than one isotopic reservoir, was capable of producing isotopically similar magma that then rose to higher crustal levels and solidified with little modification. The low initial $\epsilon\text{Nd}_{(t)}$ and high $^{87}\text{Sr}/^{86}\text{Sr}_{(t)}$ values of the inner Tuolumne Series rocks suggest partial melting of a source(s), which has/have had long-term LIL and LREE enrichment (Coleman and Glazner, 1997; Ratajeski et al., 2001)(Figs. 37,38).

It is not clear from the data presented here whether mixing of a relatively young asthenospheric mantle with older crustal rocks, or melting of a crustal source having the observed isotopic composition, produces the isotopic characteristics of the inner Tuolumne Series units. The isotopic variation that is observed in the porphyritic Half Dome Granodiorite was considered by Kistler and Fleck (1994) to result from mixing between equigranular Half Dome and Cathedral Peak magmas, but where, in terms of crustal level, this mixing might have occurred is uncertain (i.e., deep crustal source area versus shallow chamber). Hybridization processes that may have operated at depth and at the exposed level along the transect are both considered later in this discussion.

Fractional Crystallization

Major element trends are compatible with the removal of mafic silicates, plagioclase, and accessory minerals (i.e., sphene, Fe-Ti oxides and apatite) (Figs. 29,30). As discussed previously, cumulates rich in these components are widely present in the Cathedral Peak unit. However, as Reid et al. (1993) noted, removal of a typical schlieren cumulate assemblage from the granodioritic parent magma would result in compositions that fail to match Tuolumne Series rocks (see Fig. 3). Reid et al. (1993) did not consider plagioclase to be part of the cumulate assemblage in their model and presumed that the schlieren were representative of the likely cumulates. The mafic layers in the schlieren are predominantly hornblende and biotite with minor plagioclase and abundant Fe-Ti oxides and sphene. It is unclear from Reid et al.'s work exactly how they chose samples from the schlieren (i.e. single layer versus average of many layers, or whether they sampled primarily the mafic concentrations as opposed to the felsic portions of layers). Based on major element trends (Figs. 29, 30), any possible fractionating assemblage is also likely to include feldspars, particularly plagioclase (Fig. 45). Thus, several least squares mixing models using a mafic component as represented by hornblende-biotite schlieren with either K-feldspar or plagioclase as fractionating cumulates were constructed for representative Cathedral Peak rocks, in order to more rigorously examine possible chemical relationships between schlieren zones, Cathedral Peak Granodiorites, and more felsic Cathedral Peak rocks. Examples of this interaction would be the irregular felsic sheets in the "interaction" zones and felsic dikes-host granodiorite interaction (Tables 12-15, Appendix 5, pg 138-142). The least squares models involving schlieren would also probably apply to the Half Dome

Figure 45. Al_2O_3 versus SiO_2 for Tuolumne Intrusive Series rocks including schlieren and K-feldspar compositions from the Cathedral Peak Granodiorite and plagioclase compositions from the Half Dome and Cathedral Peak units. This figure is similar to Figure 3. As noted by Reid et al. (1993), the mafic schlieren layers, which are predominantly hornblende and biotite-rich, have Al_2O_3 -poor bulk compositions that are too low to be plausible cumulate extracts given the main rock trend. However, if fractionating minerals include sufficient plagioclase in addition to biotite and hornblende, then the main trend can be explained.

rocks studied here, inasmuch as there is no change in the schlieren mineral assemblage between these two units, although modal abundances vary significantly from one schlieren to another. The models used an average 71 wt% silica granodiorite as parent (an average Cathedral Peak rock) and an average 75 wt% leucogranodiorite/granite as daughter magma, which is similar to the more felsic sheets in Cathedral Peak Granodiorite. The best model fit (sum of squared residuals < 1.0) results from the fractionation of schlieren (average of BTL031A and B) in conjunction with plagioclase (average from granodiorites in microprobe analyses) (Table 12, Appendix 5, pg. 138). The resulting cumulate is an approximately 60 wt% SiO₂ rock, which is more mafic than the majority of sampled compositions, excluding the schlieren themselves and mafic enclaves (Fig. 44). The model cumulate rock has relatively high FeO and low MgO and is broadly dioritic/tonalitic with high Na₂O/K₂O, a geochemical trait not widely documented in Tuolumne Series rocks.

Models using representative hornblende from Dodge et al., 1968 and plagioclase rather than bulk schlieren + plagioclase, also produce acceptable fits (sum of squared residuals < 1.0). The cumulate has 59 wt.% SiO₂ and a somewhat lower FeO/MgO in comparison to models with schlieren, but also has high Na₂O/K₂O and is therefore broadly similar to the models using the schlieren and plagioclase and results in a dioritic/tonalitic model cumulate (Table 13, Appendix 5, pg. 139).

A fractionation model involving schlieren and K-feldspar yielded a poor model fit (sum of squared residuals >> 1.0), which is not surprising, given that K₂O generally increases with increasing SiO₂ (Table 14, Appendix 5, pg. 140).

Because 60 wt% SiO₂, low-K rocks are not widely observed in the Tuolumne Series, it seems unlikely that fractional crystallization involving just the schlieren (e.g.,

Reid et al., 1993; Fig. 44) or schlieren + feldspar or hornblende + feldspars can easily reproduce the range of rock types observed in Cathedral Peak or Half Dome Granodiorites.

An important assumption made by Reid et al. (1993), and by the models above, is that the schlieren are the most likely representative cumulates, but they may also be "red herrings" in that they may not relate directly to main Tuolumne Series rocks. Abundant field evidence suggests that schlieren are indeed mineral accumulations that formed in the presence of melt. However, the questions of their exact origin and the location of the resultant liquid remain.

Simple bulk-segregation of mafic granodiorite from granite to produce more evolved granite and leucogranite is possible given the linearity of the major element data for rocks in the range of 66 wt% SiO₂ and higher. To assess the feasibility of this, a least squares mixing model was also constructed using a 72 wt% silica granodiorite as a parent, a 75 wt% silica granite as the daughter composition and a 69 wt% granodiorite as the "cumulate" (Table 15, Appendix 5, pg. 141). This model also produces a good fit (sum of squared residuals < 1.0). However, it is not a robust model in that it is possible to produce multiple "un-mixing" (i.e., linear subtraction) models for multiple sets of samples that have good fits. This model is also mathematically identical to a restite unmixing or a "magma mixing" (i.e., linear addition) model, even though conceptually the models are all very different.

Evidence for or against fractionation as an important process must therefore come from examination of other data, including trace elements, isotopes, and mineral chemistry.

Trace element trends show a significant amount of scatter both with SiO_2 and longitude as already observed, but the patterns are generally consistent with fractional crystallization. Like most of the major elements, trace elements that are generally compatible in hornblende and biotite show smoothly decreasing trends with silica. Yttrium is compatible with hornblende and Sc with biotite, and as these minerals crystallize from the magma the concentrations of Sc and Y in the residual melt should decrease accordingly (Fig. 33).

Within the data set, feldspar-compatible elements (Sr and Ba), some high field strength elements (e.g., Zr) and the generally strongly incompatible elements (e.g., Th, U) typically show the greatest scatter, both with longitude and with bulk silica (Figs. 32-35). Such scatter may be attributable to: (1) mixing of multiple inputs of magma where trace element composition is controlled by variations in partial melt source and/or degree of partial melting; (2) modest differential redistribution of melt and crystals within mush; or (3) both processes operating simultaneously during solidification of the inner Tuolumne Series.

Importantly, although these groups of elements show the greatest scatter, they are nevertheless correlated with silica in a broad sense. For example, Sr versus SiO_2 shows a fairly good negative correlation over a broad range of SiO_2 , suggesting a systematic crystal-chemical control (e.g., plagioclase abundance) on Sr variation in the inner Tuolumne Series (Figs. 32, 46). This is best illustrated by considering the trend within the Cathedral Peak unit, which covers the broadest silica range. It is important to note, however, that the Cathedral Peak data form a coherent trend that is separate from both porphyritic and equigranular Half Dome trends, and these more exterior units have Sr concentrations that plot below where Sr concentrations would plot on an extrapolation

Figure 46. Strontium versus silica in granodioritic Tuolumne Intrusive Series samples. An average plagioclase composition is connected to average low and high silica compositions by mixing lines with tick marks indicating 10% increments.

to lower silica (Fig. 46). This rules out fractionation of these Half Dome units to produce the Cathedral Peak Granodiorite because on average, excluding schlieren and felsic sheets in Half Dome, Half Dome rocks have slightly higher modal plagioclase (Bateman, 1992) and should therefore have higher Sr if the units form a common magma lineage.

Rare earth element patterns are also consistent with fractionation processes within the interior of the Tuolumne Series. Mafic samples (i.e., < 67 wt% SiO₂) show greater scatter with respect to one another and all show negative Eu anomalies, which would be attributable to fractionation of plagioclase (Fig. 37). However, these anomalies are relatively small. Modest Eu anomalies in Tuolumne Series rocks suggest that plagioclase crystallization is not of paramount importance in producing the REE patterns. Small Eu anomalies do perhaps suggest that Tuolumne Series magmas were strongly oxidized (high fO_2), which would tend to favor Eu³⁺ rather than Eu²⁺. The persistence and relatively high abundance of sphene throughout most of the compositional range is consistent with high fO_2 .

Chondrite-normalized rare earth element curves from the Cathedral Peak unit, which range from 67-75 wt% SiO₂, are very similar in shape and concentration (Fig. 37). For these rocks, it is likely that the overall relative depletion of middle and heavy REE's is due to the fractionation of hornblende (Frey et al., 1978). The most leucocratic samples (i.e., >75 wt% SiO₂) have distinctly greater depletion of middle REE's, which is chiefly attributed to the removal of sphene and allanite.

Evolved samples from the interaction zone likely represent localized fractionated melts extracted from more average granodioritic Cathedral Peak magmas (Fig. 47). Removal of mafic silicates + accessory minerals can also generally explain the observed REE depletions in these samples. This particular zone is especially instructive because felsic magmas of variable composition are mingled or partially mixed (discussed below), but the magmas were derived by variable fractionation from a common parent, as might be expected in mushy magma.

Figure 47. Chondrite normalized rare-earth element plot for geographically adjacent but compositionally dissimilar samples. Arrows represent fractionation of megacryst poor Cathedral Peak granodioritic to more evolved leucogranite.

Fractionation of magma, melt extraction from mushy cumulates, and redistribution and internal mixing of mush and melts could also explain the scatter seen in the Ba data. At a fixed silica concentration (e.g., 71 wt%), a wide range of Ba concentrations (approximately 200-900 ppm) are observed (Fig. 32). Barium concentrations in K-feldspar (Table 6, Appendix 2, pg. 123) are variable but range up to an order of magnitude larger than those in the majority of Tuolumne Intrusive Series samples and K-feldspars typically have 64-65 wt% silica. Therefore, slight variations in the amount of K-feldspar in each sample can produce a wide range of Ba concentrations

(Fig. 48), but the change in SiO_2 resulting from a few percent of accumulated K-feldspar would be negligible. Additionally, achieving this large range of Ba scatter by randomly batch melting an amphibolite or eclogite source and then mixing those pulses together is unlikely. Barium concentrations produced from 0 to 25% partial melt of an amphibolite or eclogite spans only 20 ppm (Table 16, Appendix 5, pg. 142).

Some minor scatter in Sr data may also be attributable to slight variations in the proportion of plagioclase from sample to sample. Plagioclase analyses (Table 1, Appendix 1, pg. 112) show Sr concentrations of 2x that of Tuolumne Series granodiorites. Although not as pronounced as the effects of K-feldspar accumulation on Ba content, modest accumulation of plagioclase in an either low or high silica sample would shift the composition of that sample toward the low silica, high Sr end-member (Fig 46). Rubidium, which is incompatible in plagioclase, generally increases toward the interior of the Cathedral Peak unit as the proportion of plagioclase decreases and the proportion of biotite (in which Rb is compatible) increases slightly (Fig. 32).

Figure 48. Barium variation with silica in granodioritic Tuolumne Intrusive Series samples. An average K-feldspar composition is connected to average low and high silica compositions by mixing lines with tick marks representing 10% increments. Note that the y-axis is highly compressed with regard to the Tuolumne Series data because of the very high Ba content of the K-feldspar. Thus, very small variations (< 5 modal percent of K-feldspar) in a given sample could produce variations in Ba of several hundred to as much as 1000 ppm. This variation would produce a negligible shift in bulk composition, although it is noteworthy that of the major elements, the alkalis (K_2O and Na_2O) show the greatest scatter and are generally poorly correlated with SiO_2 (Fig. 29).

The invariance of $^{87}Sr/^{86}Sr_{(t)}$ and $\epsilon Nd_{(t)}$ for the Cathedral Peak unit can be classically interpreted as the result of a closed-system fractionation process (e.g., Bateman 1992) (Figs. 41,42,43). Over the entire silica range observed within Cathedral Peak Granodiorite (48-77 wt%) $\epsilon Nd_{(t)}$ values overlap substantially within error. As mentioned in Results, the $^{87}Sr/^{86}Sr_{(t)}$ values are more sensitive to age correction and the

Rb/Sr system is generally more open to sub-solidus modification than is the Sm/Nd system. Alternatively, as mentioned earlier, the uniform isotopic compositions of Cathedral Peak rocks could be due to isotopic homogeneity of the source. Samples from the Half Dome Granodiorite, particularly equigranular Half Dome, and samples from the Cathedral Peak Granodiorite that overlap in SiO_2 have distinct isotopic compositions (Figs. 41,42 and Table 9, Appendix 4, pg. 134), with Cathedral Peak samples having lower $\epsilon\text{Nd}_{(t)}$. This precludes deriving Cathedral Peak magmas from fractionation of Half Dome magmas, which is consistent with arguments made earlier from trace element data, particularly Sr. Thus, if fractionation is an important process in producing the chemical variation in Tuolumne Series magmas, it could only be responsible for inter-unit variation, perhaps operating dominantly on smaller aliquots of magma with identical isotopic compositions. Therefore, one must postulate that between intrusion of the Half Dome and Cathedral Peak Granodiorites the magma source shifted. Some porphyritic Half Dome Granodiorite samples overlap both equigranular Half Dome and Cathedral Peak Granodiorites as discussed more in the next section. Additionally, the isotopic data show that schlieren from the Cathedral Peak unit are a product of crystal accumulation processes operating on magmas having Cathedral Peak-like isotopic compositions, as their isotopic signatures do not differ greatly from those of granodioritic Cathedral Peak samples.

Magma Hybridization

A number of previous studies have favored *in-situ* mixing of granitic magmas with mafic to intermediate magmas having compositions represented by either hypothetical basaltic parents (e.g., Kistler et al., 1986) or enclave magmas (e.g., Reid et al., 1983; 1993; cf. Fig. 3) to produce the Tuolumne Intrusive Series. Kistler and Fleck (1994) also used field, geochemical and isotopic data to argue that the porphyritic Half Dome Granodiorite was produced by mixing of outer Cathedral Peak Granodiorite with the equigranular Half Dome Granodiorite.

The fundamental components of a hybridizing magma system are the mafic and felsic end-members and the intermediate products of their mixing. Within the interior of the Tuolumne Series, two rock types can potentially be the low-silica end-member: schlieren and enclaves. Schlieren, which are relatively abundant in the field, are low-silica, but cannot represent the mixing end-member because they are not magma compositions, but rather are cumulate rocks formed by the segregation of mafic minerals from the bulk magma. Enclaves are a much more likely candidate, as they represent more mafic (andesitic in this case) magma dispersed throughout the granodioritic host.

Considering just the Cathedral Peak Granodiorite, mixing involving andesitic enclaves as one end member (e.g., Reid et al., 1993) is considered unlikely for the following reasons. (1). Microgranular mafic/intermediate enclaves are sparse within in the Cathedral Peak Granodiorite, typically comprising < 1% of the total outcrop, usually as solitary enclaves. (2). Sparks and Marshall (1986) and Frost and Mahood (1987) have argued that hybrids more felsic than 63 wt.% SiO₂ cannot be produced easily by ordinary magma mixing of mafic and silicic magmas because of thermal and rheological factors. This compositional limit might be circumvented if andesitic enclave magma was

hydrous, as seems likely, (Sisson et al., 1996) and/or underwent fractionation deeper in the magma chamber to produce melts which mixed with granite magma to make the main granodiorite magmas (Bateman, 1995; Weibe, 1996). However, a large compositional gap (~ 9 wt% SiO_2) exists between andesitic enclave compositions and the most mafic Cathedral Peak compositions (Fig 49). No possible hybrid magmas with < 68 wt% SiO_2 are present in the Cathedral Peak unit, although equigranular and porphyritic Half Dome rocks span much of this compositional gap. (3). Trace elements from the enclave (e.g., Sr, Fig. 50) generally preclude binary magma mixing for producing Cathedral Peak rocks because they are collinear with the granitoids.

It may be possible to mix enclave magma with felsic Cathedral Peak Granodiorite to produce magmas having the compositions of the Half Dome Granodiorite rocks, because these rocks plot at positions generally between the enclaves and the low silica (i.e., outer) Cathedral Peak magmas (Fig. 50). As mentioned previously, the porphyritic Half Dome also spans some of the compositional range between the enclave magmas and Cathedral Peak magmas. However, mafic enclaves have ϵNd_t that are distinctly lower than Half Dome samples, and are identical within error to Cathedral Peak rocks (Fig. 51). Thus, mixing of enclave and Cathedral Peak magmas cannot produce the granodioritic Half Dome rocks. It is therefore reasonable to conclude that enclave magmas were not involved, except perhaps locally, in mixing with felsic melts to produce intermediate rocks in the study area. The possibility of mixing between outer Cathedral Peak magma and innermost equigranular Half Dome magmas (rather than enclave magmas) to produce porphyritic Half Dome magmas must also be considered (cf., Kistler and Fleck, 1994).

Figure 49. Major elements versus silica for samples from the chemical transects showing Cathedral Peak enclave and schlieren samples at the low-silica end of the dominant chemical trend.

Figure 50. Strontium versus silica for samples from the chemical transects. Schlieren and enclave samples have been marked to demonstrate their low Sr concentrations relative to granodioritic samples. An amphibolite xenolith and a sample from the interaction zone within the Cathedral Peak unit have also been denoted.

Figure 51. Epsilon Nd versus silica for Tuolumne Intrusive Series data superimposed upon a two component mixing line. Colored fields delineate the general chemical trends of the major Tuolumne Series units. Khde = equigranular Half Dome Granodiorite, Khdp = porphyritic Half Dome Granodiorite, Kcp = Cathedral Peak Granodiorite, Kkc = Kuna Crest/Glen Aulin Granodiorite, Kjgp = Johnson Granite Porphyry. Data compiled from Kistler et al, (1986); Gray, (2003), and this study.

This mixing might be tenable given the data presented here, at least generally.

Trace element data for porphyritic Half Dome Granodiorite scatter, but generally fall between Cathedral Peak and equigranular Half Dome rocks. Thus, although pure binary mixing is precluded, repeated mixing of magmas of Cathedral Peak composition with magmas of equigranular Half Dome composition in this part of the magma system cannot be ruled out, and would be expected to produce modest scatter in the trace element data (e.g., Gray, 2003).

In addition, there is overlap between the $\epsilon\text{Nd}_{(t)}$ of the porphyritic Half Dome unit and the equigranular Half Dome and Cathedral Peak units adjacent to it on either side (Fig. 51). However, the ~ 3 Ma age difference (Coleman et al., 2004 and this study) between these two units makes hybridization thermally unlikely. Additionally, as mentioned previously, the consistently abrupt contact (within the study) between the porphyritic Half Dome and Cathedral Peak units suggests that hybridization between these two units is improbable. However, these abrupt contacts could also reflect a rheological contrast between intruding Cathedral Peak magmas. Neither case can be favored without more detailed geochronologic data across the contact.

A final aspect to consider is the degree and scale to which mixing in the Tuolumne Series occurred between relatively felsic melts (> 71 wt% SiO_2), as is seen within the inner Cathedral Peak interaction zone. The high-silica rocks in this zone show evidence of mingling between sheets and irregular masses and schlieren cumulate. As argued previously, trace element data (particularly REE patterns) argue against this, at least in this locale. On the scale of the chemical transects, the importance of repeated mixing between felsic magmas of slightly different composition is harder to evaluate. If schlieren, despite being cumulates, are perhaps associated with new magma inputs, possibly as flow-segregated crystals, then their rhythmic repeated development would suggest repeated injection of new magma into crystal-rich(?) magma or mush. This process would be capable of producing scatter, particularly among incompatible trace elements and perhaps feldspar-compatible elements. Such a scenario involves components of both fractionation and mixing of materials with a range of possible crystallinities.

If widespread hybridization were active within the unit, complex zoning and reverse zoning of plagioclase might be expected as chemically distinct magmas interacted. No mottled cores, resorption, or reaction coronas were observed, nor were multiple examples of reversely zoned plagioclase. Additionally, within a single sample, the An # is relatively restricted (Fig. 24. Table 1, Appendix 1, pg. 112).

CONCLUSIONS

The major conclusions supported by this research are the following:

1. Uranium-Lead zircon geochronology from this study and from previous work suggests that although the entire Tuolumne Series was constructed over an 8-10 Ma time period, the volumetrically dominant inner units of the Series were constructed within the last 1-2 Ma of this interval. These age constraints allow for magma interaction during the construction of the inner portion of the Tuolumne Series. This hypothesis is supported by field evidence of distinct contact types in the study area that likely indicate the presence of mush within the evolving magma system and the repeated separation of crystals from melt within this mush and reworking of this mush, either by late inputs and/or internal processes (e.g., transient convection) that destabilized and mobilized the mush.
2. Trace element data (particularly Sr) are incompatible with generating initial Tuolumne granitoid magmas by partial melting in equilibrium with plagioclase. Therefore, melting in equilibrium with an eclogitic source most closely fits Tuolumne compositions. Additionally, the relatively limited initial $\epsilon\text{Nd}_{(t)}$ and $^{87}\text{Sr}/^{86}\text{Sr}_{(t)}$ values within the study area require that regardless of the actual melt protolith(s), the isotopic composition of the source(s) either (a) must have been fairly homogenous throughout the genesis of the inner Half Dome and Cathedral Peak Granodiorites; or (b) the process of magma genesis in the source, possibly involving more than one isotopic reservoir, was capable of producing isotopically similar magma that then

- rose to higher crustal levels and solidified with little modification (e.g., by assimilation) of isotopic composition.
3. Samples from the Half Dome Granodiorite, particularly equigranular Half Dome, and from the Cathedral Peak Granodiorite that overlap in SiO_2 have distinct isotopic compositions (Figs. 41,42 and Table 9, Appendix 4, pg. 134), and Cathedral Peak samples have lower $\epsilon\text{Nd}_{(t)}$. This precludes deriving Cathedral Peak magmas from fractionation of Half Dome magmas, which is consistent with arguments from trace element data, particularly Sr. Thus, if fractionation is an important process in producing the chemical variation in Tuolumne Series magmas, it could only be responsible for inter-unit variation, perhaps operating dominantly on smaller aliquots of magma with identical isotopic compositions.
 4. Within each unit, notably the Cathedral Peak Granodiorite, modest major element variation and more complex scatter in trace elements, particularly the feldspar compatible elements, is consistent with crystal fractionation. Random mixing between different granitic partial melts is less likely to produce these trends due to the lack of a volumetrically significant hybridization end-member with < 68 wt% SiO_2 . Additionally, REE patterns within the Cathedral Peak unit, especially the depletion in middle REE's, are attributed to the fractionation of hornblende in granodioritic samples and sphene and allanite in more leucocratic samples, rather than complex hybridization of melts of similar composition.
 5. Pure binary mixing between outer Cathedral Peak magma rather than enclave magmas, and innermost equigranular Half Dome magmas to produce porphyritic Half

Dome magmas (cf., Kistler and Fleck, 1994) is precluded because of the scatter in trace elements. Repeated mixing of magmas of Cathedral Peak composition with magmas of equigranular Half Dome composition in this part of the magma system cannot be ruled out, and is consistent with overlap in $\epsilon\text{Nd}_{(t)}$ values between these two units and would be expected to produce modest scatter in the trace element data (e.g., Gray, 2003). The contact within the study area between the porphyritic Half Dome and Cathedral Peak units is consistently mappable and is gradational over 2 to 30m, which suggests that hybridization between these two units is limited. However, these contacts could also reflect a rheological contrast between intruding Cathedral Peak magmas and the already partially crystallized Half Dome porphyritic magmas.

REFERENCES

- Barbarin, B., 2005, Mafic magmatic enclaves and mafic rocks associated with some granitoids of the central Sierra Nevada batholith, California: nature, origin and relations with the hosts: *Lithos*, v. 80, p. 155-177.
- Bateman, P. C., and Chappell, B.W., 1979, Crystallization, fractionation, and solidification of the Tuolumne intrusive Series, Yosemite National Park, California: *Geological Society of America Bulletin*, v. 90, p. 465-482.
- Bateman, P. C., and Nokelberg, W.J., 1978, Solidification of the Mount Givens Granodiorite, Sierra Nevada, California: *Journal of Geology*, v. 86, p. 563 – 579.
- Bateman, P.C., Kistler, W.R., Peck, D.L., and Busacca, A.J., 1988, Tuolumne Meadows quadrangle, California – Analytic data: *United States Geological Survey Bulletin* 1819, 43 p.
- Bateman, P. C., and Eaton, J.P., 1967, Sierra Nevada batholith: *Science*, v. 158, p. 338-341.
- Bateman, P. C., 1992, Plutonism in the Central Part of the Sierra Nevada Batholith, California: *United States Geological Survey Professional Paper* 1483, 186 p.
- Bateman, P. C., 1995, The interplay between crystallization, replenishment and hybridization in large felsic magma chambers: *Earth Science Reviews*, v. 39, p. 91-106.
- Bergantz, G.W., 2000, On the dynamics of magma mixing by reintrusion: Implications for pluton assembly processes: *Journal of Structural Geology*, v. 22, p. 1297-1309.
- Chappell, B.W., and White, A.J.R., 1974, Two contrasting granite types: *Pacific Geology*, v. 8, p. 173-174.
- Coleman, D.S., and Glazner, A.F., 1997, The Sierra Crest magmatic event: rapid formation of juvenile crust during the Late Cretaceous in California: *International Geology Review*, v. 39, p. 768-787.
- Coleman, D.S., Gray, W., and Glazner, A.F., 2004, Rethinking the emplacement and evolution of zoned plutons: Geochronologic evidence for incremental assembly of the Tuolumne Intrusive Suite, California: *Geology*, v. 32, p. 433-436.
- Chen, J.H., and Moore, J.G., 1982, Uranium-lead isotopic ages from the Sierra Nevada Batholith, California: *Journal of Geophysical Research*, v. 87, p. 4761-4784.
- Ducea, D.N., 2001, The California arc: Thick granitic batholiths, eclogitic residues, lithospheric-scale thrusting and magmatic flare-ups: *GSA Today*, Nov. p. 4-10.

- Ducea, D.N., 2002, Constraints on the bulk composition and root foundering rates of continental arcs: A California arc perspective: *Journal of Geophysical Research*, v. 107, p. 15-1 - 15-13.
- Dodge, F.C.W., Papike, J.J., and Mays, R.E., 1968, Hornblendes from granitic rocks of Central Sierra Nevada Batholith, California: *Journal of Petrology*, v. 9, part 3, p. 378-410.
- Eugster, O., Tera, F., Burnet, D.S., and Wasserberg, G.J., 1970, The isotopic composition of gadolinium and neutron capture effects in some meteorites: *Journal of Geophysics Research*, v. 75, p. 2753-2768.
- Fleck, R.J., Kistler, R.W., and Wooden, J.L., 1996, Geochronologic complexities related to multiple emplacement history of the Tuolumne Intrusive Suite, Yosemite National Park, California [abs.]: *Geological Society of America Abstracts with Program*, v. 28, p. 65 – 66.
- Frey, F.A., Chappell, B.W., and Roy, S.D., 1978, Fractionation of rare-earth elements in the Tuolumne Intrusive Series, Sierra Nevada Batholith, California: *Geology*, v. 6, p. 239-242
- Frost, T.P., and Mahood G.A., 1987, Field, chemical, and physical constraints on mafic-felsic interaction in the Lamarck Granodiorite, Sierra Nevada, California: *Geologic Society of America Bulletin*, v. 99, p. 272-291.
- Gray, W., 2003, Chemical and Thermal evolution of the Late Cretaceous Tuolumne Intrusive Suite, Yosemite National Park, California, [Ph.D. Dissertation]: Chapel Hill, University of North Carolina, 202.
- Glazner, A.F., Bartley, J.M., Coleman, D.S., Gray, W., Taylor, R.Z., 2004, Are plutons assembled over millions of years by amalgamation from small magma chambers?: *GSA Today*; v. 14; no. 4/5 p. 4-10
- Karpowicz, R.A., 2004, Structure and emplacement of the southern margin of the Tuolumne Intrusive Suite: [Master's Thesis] San Jose, CA, San Jose State University, 73p.
- Kerrick, D.M., 1969, K-feldspar megacrysts from a porphyritic quartz monzonite central Sierra Nevada, California: *The American Mineralogist*, v. 54, p. 839-847.
- Kistler, R.W., Chappell, B.W., Peck, D.L., and Bateman, P.C. 1986, Isotopic variation in the Tuolumne Intrusive Suite, central Sierra Nevada, California: *Contributions to Mineralogy and Petrology*, v. 94, p. 205-220.
- Kistler, R.W., Fleck, R.J., 1994, Field guide for a transect of the central Sierra Nevada, California: *Geochronology and isotope geology: United States Geological Society open file report* 94-267.

- Reid, J.B., Evans, O.C., and Fates, D.G., 1983, magma mixing in granitic rocks of the central Sierra Nevada, California: *Earth and Planetary Science Letters*, v. 66, p. 243-261.
- Reid, J.B., Murray, D.P., Hermes, O.D., and Steig, E.J., 1993, Fractional crystallization in granites of the Sierra Nevada: How important is it? : *Geology*, v. 21, p. 587-590.
- Robinson, C.A., 1977, Differentiation of the Tuolumne intrusive series, Yosemite National Park, California: *Geological Society of America Abstracts with Programs*, v. 9, p. 487-488.
- Rollinson, H.R., 1993, *Using geochemical data: evaluation presentation, interpretation*: Longman Scientific and Technical, United Kingdom, 352 p.
- Sparks, R.S.J. and Marshall, L.A., 1986, Thermal and mechanical constraints on mixing between mafic and silicic magmas: *Journal of Volcanology and Geothermal Research*, v. 29, p. 99-124.
- Stacey, J.S., and Kramers, J.D., 1975, Approximation of terrestrial lead isotope evolution by a two-stage mode: *Earth and Planetary Science Letters*, v. 26, 207-221.
- Steiger, R.H., and Jager, E., 1977, Subcommittee on geochronology: convention on the use of decay constants in geo- and cosmo-chronology: *Earth and Planetary Science Letters*, v. 36, p. 359-362.
- Stern, T.W., Bateman, P.C., Morgan, B.A., Newell, M.F., and Peck, D.L., 1981, Isotopic U-Pb ages of zircon from the granitoids of the central Sierra Nevada, California: *U.S. Geological Survey Professional Paper 1185*, 17p.
- Teruya, L., 2005, *Magmatic fabric relationships at two contacts in the Tuolumne Intrusive Suite*: [Master's Thesis] San Jose, CA, San Jose State University, 92p.
- Walawender, M.J., Gastil, R.G., Clickenbeard, J.P., McCormick, W.V., Eastman, R.S., Wernicke, R. S., Wardlaw, M. S., Gunn, S. H., and Smith, B.M., 1990, Origin and evolution of the zoned La Posta-Type plutons, eastern Peninsular Ranges batholith, southern and Baja California: in *The Geology of North America, The nature and origin of Cordilleran magmatism*, editor, Anderson J.L., *Memoir 174*, p. 1-18.
- Wiebe, R.A., 1996, Mafic-silicic layered intrusions: the role of basaltic injections in the magmatic process and evolution in silicic magma chambers: *Transactions of the Royal Society of Edinburgh: Earth Sciences*, v. 87, p. 233-242.
- Wiebe, R.A., and Collins, W.J., 1998, Depositional features and stratigraphic sections in granitic plutons: implications for the emplacement and crystallization of granitic magma: *Journal of Structural Geology*: v. 20, p. 1273-1289.

- Weinberg, R.F., Sian, A.N., and Pessoa, R.R., 2001, Magma flow within the Tavares pluton, northeastern Brazil: Compositional and thermal convection: *Geologic Society of America Bulletin*, v. 113, p. 508-520.
- Vernon, R.H., 1991, Microgranitoid enclaves in granites - globules of hybrid magma quenched in a plutonic environment: *Nature*, v. 309, p. 438-439.
- Zak, K., and Paterson, S.R., 2005, Characteristics of internal contacts in the Tuolumne Batholith, central Sierra Nevada, California (USA): Implications for episodic emplacement and physical processes in a continental arc magma chamber: *Geologic Society of America Bulletin*, v. 117, p. 1242-1255.
- Zen, E-an, and Hammarstrom, J.M., 1984, Magmatic Epidote and its petrologic significance: *Geology*, v. 12, p. 515-518.

APPENDIX 1:
PLAGIOCLASE AND POTASSIUM FELDSPAR DATA

Table 1. Feldspar composition determined by electron microprobe. All values are in weight% oxide.

Sample Grain	1		2		3		4		1		2	
	BTL 42A	BTL 42A	BTL 42A	BTL 42A	BTL 42A	BTL 42A	BTL 42A	BTL 42A	BTL 42B	BTL 42B	BTL 42B	BTL 42B
Run	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim
SiO ₂	62.14	65.17	62.05	69.05	62.45	68.52	64.57	65.64	61.33	63.49	61.92	61.95
Al ₂ O ₃	23.87	22.13	23.45	19.74	23.95	20.32	22.66	22.41	24.48	19.80	23.74	23.50
FeO	0.14	0.14	0.17	0.05	0.17	0.09	0.16	0.15	0.17	0.17	0.16	0.14
MgO	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.01
CaO	5.17	2.76	4.89	0.27	5.07	0.40	3.33	2.72	5.88	0.70	5.32	5.10
Na ₂ O	8.41	10.14	8.83	11.60	8.74	11.52	9.71	9.87	8.08	9.99	8.26	8.79
K ₂ O	0.42	0.18	0.30	0.13	0.27	0.16	0.18	0.20	0.28	0.14	0.36	0.24
SrO	0.20	0.08	0.21	0.05	0.20	0.02	0.08	0.06	0.28	0.09	0.20	0.17
BaO	0.00	0.00	0.02	0.01	0.01	0.00	0.00	0.05	0.04	0.04	0.04	0.03
Total	100.36	100.59	99.93	100.88	100.87	101.02	100.69	101.10	100.53	94.43	99.99	99.92
Si	2.75	2.86	2.76	2.99	2.75	2.97	2.83	2.86	2.72	2.94	2.75	2.76
Al	1.25	1.14	1.23	1.01	1.24	1.04	1.17	1.15	1.28	1.08	1.24	1.23
Fe	0.01	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.25	0.13	0.23	0.01	0.24	0.02	0.16	0.13	0.28	0.03	0.25	0.24
Na	0.72	0.86	0.76	0.97	0.75	0.97	0.83	0.83	0.69	0.90	0.71	0.76
K	0.02	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.02	0.01	0.02	0.01
Sr	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.00
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	5.00	5.01	5.01	5.00	5.01	5.00	5.00	4.99	5.00	4.97	4.99	5.01
An num	0.25	0.13	0.23	0.01	0.24	0.02	0.16	0.13	0.28	0.04	0.26	0.24

Table 1 continued. All values are in weight% oxide.

Sample	3		4		1		2		3		4	
	BTL 42B	BTL 42B	BTL 42B	BTL 42B	BTL 43	BTL 43	BTL 43	BTL 43	BTL 43	BTL 43	BTL 43	BTL 43
Grain	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim
Run												
SiO ₂	61.42	66.66	61.86	67.34	61.29	64.62	60.86	64.37	62.08	67.49	61.28	62.87
Al ₂ O ₃	23.78	21.83	23.71	20.41	24.00	22.38	24.18	22.01	23.53	19.81	23.67	23.05
FeO	0.18	0.05	0.20	0.04	0.18	0.12	0.22	0.12	0.18	0.07	0.16	0.17
MgO	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.01
CaO	5.11	2.41	5.05	0.83	5.48	3.31	5.65	3.10	4.98	0.61	5.15	4.04
Na ₂ O	8.37	10.48	8.48	11.16	8.44	9.83	7.76	9.86	8.79	11.49	8.37	9.27
K ₂ O	0.42	0.10	0.29	0.16	0.30	0.24	0.52	0.17	0.33	0.14	0.39	0.31
SrO	0.24	0.18	0.19	0.04	0.19	0.08	0.22	0.06	0.16	0.05	0.20	0.10
BaO	0.03	0.00	0.04	0.05	0.04	0.00	0.00	0.06	0.01	0.00	0.02	0.00
Total	99.53	101.70	99.82	100.03	99.92	100.58	99.42	99.75	100.05	99.66	99.25	99.82
Si	2.74	2.88	2.75	2.95	2.73	2.84	2.72	2.85	2.76	2.97	2.75	2.79
Al	1.25	1.11	1.24	1.05	1.26	1.16	1.28	1.15	1.23	1.03	1.25	1.21
Fe	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.01
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.24	0.11	0.24	0.04	0.26	0.16	0.27	0.15	0.24	0.03	0.25	0.19
Na	0.72	0.88	0.73	0.95	0.73	0.84	0.67	0.85	0.76	0.98	0.73	0.80
K	0.02	0.01	0.02	0.01	0.02	0.01	0.03	0.01	0.02	0.01	0.02	0.02
Sr	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	5.00	5.00	5.00	5.00	5.01	5.01	4.99	5.01	5.01	5.01	5.00	5.01
An num	0.25	0.11	0.24	0.04	0.26	0.15	0.28	0.15	0.23	0.03	0.25	0.19

Table 1 continued. All values are in weight% oxide.

Sample	1		2		3		4		5		1	
	BTL 65	Rim	BTL 65	Core	BTL 65	Core	BTL 65	Rim	BTL 65	Core	BTL 65	Rim
Grain	BTL 65	BTL 65	BTL 65	BTL 65	BTL 65	BTL 65	BTL 65	BTL 65	BTL 65	BTL 65	BTL 65	BTL 75
Run	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim
SiO ₂	60.70	63.34	60.05	61.70	59.90	64.72	60.55	63.02	59.75	63.20	59.05	63.07
Al ₂ O ₃	24.61	22.60	24.99	23.79	24.93	22.16	24.69	23.10	25.00	22.51	25.09	22.61
FeO	0.12	0.08	0.15	0.10	0.18	0.05	0.17	0.14	0.15	0.16	0.19	0.10
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01
CaO	6.23	3.98	6.81	5.32	6.66	3.12	6.29	4.50	6.88	3.82	6.98	3.98
Na ₂ O	7.94	9.38	7.74	8.25	7.48	9.56	7.92	8.92	7.35	9.07	7.42	9.12
K ₂ O	0.27	0.21	0.24	0.20	0.24	0.17	0.19	0.25	0.31	0.29	0.24	0.19
SrO	0.21	0.10	0.24	0.15	0.26	0.10	0.20	0.11	0.16	0.09	0.19	0.14
BaO	0.09	0.00	0.04	0.06	0.00	0.00	0.09	0.00	0.05	0.00	0.00	0.03
Total	100.15	99.69	100.27	99.57	99.65	99.88	100.08	100.06	99.64	99.14	99.17	99.24
Si	2.70	2.81	2.68	2.75	2.68	2.85	2.70	2.79	2.68	2.82	2.66	2.81
Al	1.29	1.18	1.31	1.25	1.32	1.15	1.30	1.21	1.32	1.18	1.33	1.19
Fe	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.30	0.19	0.33	0.25	0.32	0.15	0.30	0.21	0.33	0.18	0.34	0.19
Na	0.69	0.81	0.67	0.71	0.65	0.82	0.68	0.77	0.64	0.78	0.65	0.79
K	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01
Sr	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.00
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	5.00	5.01	5.01	4.99	4.99	4.98	5.00	5.00	4.99	4.99	5.00	5.00
An num	0.30	0.19	0.32	0.26	0.33	0.15	0.30	0.21	0.33	0.19	0.34	0.19

Table 1 continued. All values are in weight% oxide.

Sample	2		3		4		5		1		2	
Grain	BTL 75	BTL 75	BTL 75	BTL 75	BTL 75	BTL 75	BTL 75	BTL 75	BTL 28	BTL 28	BTL 28	BTL 28
Run	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim
SiO ₂	58.57	60.60	59.77	59.90	58.79	63.51	59.55	61.30	61.65	61.31	62.05	66.20
Al ₂ O ₃	25.57	24.53	25.02	25.08	25.71	22.78	24.94	24.23	24.19	23.56	24.14	21.32
FeO	0.21	0.10	0.14	0.09	0.14	0.12	0.20	0.05	0.18	0.22	0.19	0.00
MgO	0.01	0.00	0.01	0.00	0.02	0.00	0.00	0.00	0.01	0.01	0.00	0.01
CaO	7.49	5.97	6.55	6.76	7.38	4.01	6.58	5.73	5.36	5.06	5.32	2.15
Na ₂ O	7.05	8.05	7.63	7.61	7.29	9.39	7.60	8.34	8.40	8.27	8.56	10.78
K ₂ O	0.29	0.19	0.31	0.19	0.19	0.23	0.25	0.19	0.66	0.57	0.42	0.16
SrO	0.22	0.12	0.15	0.15	0.17	0.09	0.20	0.09	0.21	0.23	0.17	0.13
BaO	0.04	0.00	0.06	0.06	0.00	0.01	0.09	0.00	0.00	0.04	0.00	0.00
Total	99.44	99.55	99.63	99.83	99.68	100.12	99.40	99.92	100.68	99.24	100.84	100.74
Si	2.64	2.71	2.68	2.68	2.64	2.81	2.68	2.73	2.73	2.75	2.74	2.89
Al	1.36	1.29	1.32	1.32	1.36	1.19	1.32	1.27	1.26	1.25	1.26	1.10
Fe	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.36	0.29	0.31	0.32	0.35	0.19	0.32	0.27	0.25	0.24	0.25	0.10
Na	0.62	0.70	0.66	0.66	0.63	0.80	0.66	0.72	0.72	0.72	0.73	0.91
K	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.04	0.03	0.02	0.01
Sr	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	5.00	5.00	5.00	5.00	5.01	5.01	5.00	5.00	5.02	5.00	5.01	5.02
An num	0.36	0.29	0.32	0.33	0.35	0.19	0.32	0.27	0.25	0.24	0.25	0.10

Table 1 continued. All values are in weight% oxide.

Sample Grain Run	1		2		3		4		1		2	
	BTL 27	Rim	BTL 27	Core	BTL 27	Rim	BTL 27	Core	BTL 31A	Rim	BTL 31A	Core
SiO ₂	61.86	68.92	62.23	65.43	59.98	65.21	59.06	64.16	61.00	67.98	55.46	64.90
Al ₂ O ₃	23.62	19.43	23.60	21.82	25.31	22.26	25.56	22.39	23.83	20.31	27.77	21.89
FeO	0.19	0.08	0.17	0.12	0.10	0.10	0.12	0.12	0.13	0.04	0.11	0.13
MgO	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
CaO	5.00	0.13	5.11	2.70	6.87	3.01	7.31	3.58	5.73	0.81	9.91	3.03
Na ₂ O	8.67	11.69	8.69	10.21	7.68	10.03	7.22	9.43	8.09	11.63	5.91	10.09
K ₂ O	0.46	0.15	0.36	0.19	0.16	0.12	0.21	0.32	0.15	0.12	0.13	0.13
SrO	0.23	0.04	0.21	0.08	0.25	0.09	0.28	0.06	0.18	0.10	0.37	0.09
BaO	0.09	0.03	0.00	0.00	0.09	0.10	0.00	0.00	0.00	0.01	0.02	0.03
Total	100.11	100.46	100.38	100.55	100.44	100.91	99.78	100.07	99.11	101.01	99.68	100.28
Si	2.75	3.00	2.76	2.87	2.67	2.85	2.65	2.83	2.74	2.95	2.51	2.86
Al	1.24	1.00	1.23	1.13	1.33	1.15	1.35	1.17	1.26	1.04	1.48	1.14
Fe	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.24	0.01	0.24	0.13	0.33	0.14	0.35	0.17	0.28	0.04	0.48	0.14
Na	0.75	0.99	0.75	0.87	0.66	0.85	0.63	0.81	0.70	0.98	0.52	0.86
K	0.03	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01
Sr	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.00
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	5.02	5.00	5.01	5.01	5.00	5.00	5.00	5.00	4.99	5.02	5.01	5.01
An num	0.24	0.01	0.24	0.13	0.33	0.14	0.35	0.17	0.28	0.04	0.48	0.14

Table 1 continued. All values are in weight% oxide.

Sample	BTL 31A	BTL 31A	BTL 31A	BTL 18	BTL 18	BTL 18	BTL 18	BTL 18	BTL 18	BTL 18	BTL 18
Grain	3	3	4	1	2	3	4	3	4	3	4
Run	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Rim
SiO ₂	61.79	63.71	59.42	63.69	65.40	68.12	62.70	64.37	63.44	63.57	63.51
Al ₂ O ₃	24.20	23.12	25.37	23.47	21.87	19.37	23.27	22.40	22.74	22.33	22.50
FeO	0.11	0.14	0.16	0.22	0.01	0.00	0.18	0.18	0.18	0.18	0.09
MgO	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00
CaO	5.32	4.18	7.16	4.44	2.57	0.20	4.67	3.52	4.00	3.51	3.73
Na ₂ O	8.45	9.34	7.37	9.35	10.41	11.86	9.30	9.86	9.39	9.66	9.69
K ₂ O	0.21	0.24	0.16	0.20	0.09	0.06	0.22	0.08	0.39	0.19	0.10
SrO	0.22	0.06	0.19	0.05	0.14	0.05	0.10	0.10	0.11	0.08	0.12
BaO	0.00	0.04	0.05	0.04	0.00	0.03	0.00	0.00	0.04	0.00	0.03
Total	100.30	100.82	99.88	101.47	100.51	99.68	100.44	100.51	100.28	99.52	99.77
Si	2.74	2.80	2.66	2.78	2.87	2.99	2.77	2.83	2.80	2.82	2.82
Al	1.26	1.20	1.34	1.21	1.13	1.00	1.21	1.16	1.18	1.17	1.18
Fe	0.00	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.25	0.20	0.34	0.21	0.12	0.01	0.22	0.17	0.19	0.17	0.18
Na	0.73	0.80	0.64	0.79	0.89	1.01	0.80	0.84	0.80	0.83	0.83
K	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.02	0.01	0.01
Sr	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	5.00	5.01	5.00	5.01	5.01	5.02	5.03	5.01	5.02	5.01	5.02
An num	0.25	0.20	0.35	0.21	0.12	0.01	0.21	0.16	0.19	0.17	0.17

Table 1 continued. All values are in weight% oxide.

Sample	BTL 28		BTL 28		BTL 28		BTL 59		BTL 59		BTL 59		BTL 59		BTL 59	
Grain	3		4		1		2		3		4					
Run	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim
SiO ₂	61.90	64.03	57.47	68.66	61.25	61.89	59.59	60.39	60.35	62.88	58.97	62.97				
Al ₂ O ₃	24.02	22.86	26.34	19.86	24.14	23.46	24.74	24.56	24.36	23.48	25.32	22.80				
FeO	0.19	0.15	0.13	0.06	0.18	0.14	0.16	0.13	0.20	0.18	0.14	0.13				
MgO	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00				
CaO	5.30	3.68	8.43	0.19	5.68	4.86	6.48	6.12	6.27	4.86	7.09	4.09				
Na ₂ O	8.55	9.76	6.95	11.77	7.89	8.69	7.66	7.58	7.77	8.83	7.20	9.02				
K ₂ O	0.27	0.23	0.15	0.18	0.47	0.20	0.44	0.35	0.38	0.16	0.23	0.20				
SrO	0.18	0.07	0.33	0.06	0.23	0.13	0.23	0.20	0.22	0.09	0.23	0.12				
BaO	0.04	0.04	0.00	0.02	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.03				
Total	100.47	100.81	99.80	100.81	99.84	99.39	99.30	99.35	99.54	100.48	99.18	99.35				
Si	2.74	2.81	2.59	2.98	2.73	2.76	2.68	2.71	2.70	2.77	2.66	2.80				
Al	1.25	1.18	1.40	1.02	1.27	1.23	1.31	1.30	1.29	1.22	1.34	1.20				
Fe	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00				
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
Ca	0.25	0.17	0.41	0.01	0.27	0.23	0.31	0.29	0.30	0.23	0.34	0.19				
Na	0.73	0.83	0.61	0.99	0.68	0.75	0.67	0.66	0.67	0.75	0.63	0.78				
K	0.02	0.01	0.01	0.01	0.03	0.01	0.03	0.02	0.02	0.01	0.01	0.01				
Sr	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.00	0.01	0.00				
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
Total	5.01	5.02	5.02	5.01	4.99	5.00	5.01	4.99	5.00	5.00	4.99	4.99				
An num	0.25	0.17	0.40	0.01	0.28	0.23	0.31	0.30	0.30	0.23	0.35	0.20				

Table 2. Potassium feldspar compositions for a single grain from BTL043 as determined by electron microprobe. All values are in weight % oxide unless otherwise specified.

Analysis	1	2	3	4	5	6	7	8	9	10	11	12
Core												
Na ₂ O	1.23	0.60	0.50	1.12	0.91	0.89	1.06	1.10	0.93	0.83	1.01	0.54
Sr	0.09	0.09	0.07	0.03	0.12	0.09	0.08	0.07	0.08	0.09	0.06	0.07
Sr (ppm)	786.40	735.66	600.37	228.31	972.43	794.85	642.65	608.82	668.02	727.21	532.72	591.91
SiO ₂	63.56	64.98	64.78	64.63	64.77	64.53	64.44	64.74	64.70	64.78	64.83	64.80
FeO	0.23	0.03	0.01	0.07	0.10	0.11	0.10	0.07	0.09	0.10	0.08	0.06
CaO	1.09	0.01	0.00	0.04	0.03	0.03	0.05	0.04	0.02	0.00	0.00	0.03
MgO	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00
Al ₂ O ₃	18.00	18.12	18.44	18.07	18.25	18.17	18.28	18.43	18.22	18.33	18.43	18.24
K ₂ O	13.71	14.75	15.05	14.92	14.93	15.10	14.88	14.89	15.36	15.93	15.18	15.66
BaO	0.03	0.05	0.05	0.01	0.00	0.01	0.00	0.13	0.00	0.03	0.00	0.03
Total	97.95	98.63	98.90	98.89	99.11	98.93	98.88	99.47	99.42	100.09	99.60	99.43
Or num	0.86	0.96	0.97	0.93	0.94	0.94	0.93	0.93	0.94	0.95	0.94	0.96
Rim												
Na ₂ O	1.05	0.68	1.31	0.98	1.11	1.18	1.33	0.92	1.12	0.91	1.10	0.38
Sr	0.08	0.07	0.07	0.07	0.05	0.06	0.05	0.08	0.07	0.07	0.04	0.09
Sr (ppm)	634.19	591.91	591.91	617.28	414.34	498.90	405.88	642.65	549.63	591.91	321.32	786.40
SiO ₂	64.96	64.45	65.01	64.98	64.81	64.37	64.85	65.02	64.53	64.94	64.99	64.46
FeO	0.08	0.11	0.08	0.07	0.07	0.06	0.10	0.09	0.07	0.13	0.08	0.07
CaO	0.04	0.04	0.04	0.01	0.04	0.03	0.00	0.01	0.00	0.00	0.00	0.00
MgO	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al ₂ O ₃	18.15	18.22	18.61	18.31	18.09	18.37	18.34	18.32	18.34	18.37	18.30	18.09
K ₂ O	15.16	15.52	14.78	14.74	15.08	15.03	14.96	15.28	14.97	15.59	14.85	15.52
BaO	0.05	0.00	0.00	0.00	0.05	0.08	0.00	0.01	0.01	0.00	0.00	0.04
Total	99.56	99.08	99.89	99.17	99.29	99.17	99.62	99.73	99.11	100.01	99.37	98.65
Or num	0.93	0.96	0.92	0.94	0.93	0.93	0.92	0.94	0.93	0.95	0.93	0.98

Table 3. Potassium feldspar compositions for a single grain from BTL043 as determined by electron microprobe. All values are in weight % oxide unless otherwise specified.

Analysis	Core →											
	1	2	3	4	5	6	7	8	9	10	11	12
Na ₂ O	0.71	0.94	0.70	0.57	0.74	1.08	0.75	0.98	0.94	0.84	0.89	0.95
SrO	0.08	0.07	0.06	0.09	0.10	0.05	0.06	0.09	0.08	0.10	0.11	0.07
Sr (ppm)	701.84	608.82	490.44	727.21	845.59	448.16	490.44	744.12	651.10	879.41	887.87	608.82
SiO ₂	64.63	64.91	64.60	64.59	64.69	64.81	64.75	64.58	64.61	64.91	64.60	64.59
FeO	0.06	0.07	0.10	0.09	0.08	0.07	0.07	0.06	0.08	0.11	0.06	0.08
CaO	0.00	0.00	0.00	0.00	0.03	0.03	0.03	0.03	0.06	0.03	0.06	0.00
MgO	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00
Al ₂ O ₃	18.18	18.39	18.31	18.54	18.22	18.21	18.32	18.44	18.21	18.19	18.28	18.22
K ₂ O	15.72	15.24	15.62	16.10	15.43	15.32	15.45	15.41	15.17	15.31	15.25	15.22
BaO	0.04	0.03	0.00	0.01	0.03	0.00	0.06	0.04	0.07	0.08	0.06	0.07
Total	99.43	99.65	99.40	99.98	99.30	99.58	99.49	99.62	99.22	99.57	99.30	99.21
Or num	0.96	0.94	0.96	0.97	0.95	0.93	0.95	0.94	0.94	0.95	0.94	0.94

Analysis	Rim →		
	1	2	3
Na ₂ O	0.98	1.01	1.16
SrO	0.09	0.13	0.10
Sr (ppm)	744.12	1073.90	862.50
SiO ₂	65.04	65.25	65.34
FeO	0.09	0.10	0.08
CaO	0.02	0.00	0.01
MgO	0.00	0.00	0.00
Al ₂ O ₃	18.29	18.50	18.21
K ₂ O	15.28	9.91	0.93
BaO	0.16	0.07	0.03
Total	99.93	94.97	85.86
Or num	0.94	0.91	0.44

Table 4. Potassium feldspar compositions for a single grain from BTL042 as determined by electron microprobe. All values are in weight % oxide unless otherwise specified.

Analysis	1	2	3	4	5	6	7	8	9	10	11	12
	Core											
Na ₂ O	0.91	1.06	1.15	1.37	1.43	1.20	1.00	1.39	1.23	1.00	0.57	1.19
SrO	0.14	0.22	0.13	0.18	0.18	0.13	0.15	0.20	0.17	0.18	0.18	0.20
Sr (ppm)	1175.37	1843.39	1116.18	1488.24	1547.43	1090.81	1293.75	1699.64	1445.96	1538.97	1479.78	1648.90
SiO ₂	64.51	64.63	64.09	64.06	64.06	64.41	64.25	64.55	64.74	59.28	63.63	64.38
FeO	0.10	0.12	0.08	0.07	0.10	0.11	0.07	0.09	0.12	0.11	0.05	0.01
CaO	0.00	0.00	0.00	0.01	0.03	0.00	0.00	0.05	0.02	0.01	0.00	0.01
MgO	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00
Al ₂ O ₃	18.71	18.97	18.66	18.89	18.72	18.58	18.53	18.77	18.63	17.62	18.56	18.74
K ₂ O	14.94	14.78	14.76	14.71	14.51	14.97	14.98	14.44	14.74	14.30	15.30	14.62
BaO	0.87	1.40	1.13	1.19	1.03	0.77	1.07	0.94	1.06	1.15	1.11	1.03
Total	100.18	101.18	100.01	100.47	100.05	100.18	100.06	100.43	100.70	93.65	99.40	100.17
Or num	0.94	0.93	0.93	0.91	0.91	0.93	0.94	0.91	0.92	0.93	0.96	0.92

Analysis	13	14	15	16
	Rim			
Na ₂ O	1.04	0.95	1.94	1.25
SrO	0.18	0.16	0.03	0.01
Sr (ppm)	1479.78	1319.12	228.31	67.65
SiO ₂	63.95	64.48	63.66	63.96
FeO	0.00	0.09	0.07	0.08
CaO	0.00	0.01	0.05	0.06
MgO	0.01	0.00	0.01	0.01
Al ₂ O ₃	18.72	18.59	18.51	18.93
K ₂ O	14.97	14.83	14.09	14.41
BaO	1.02	1.17	1.14	1.27
Total	99.88	100.28	99.49	99.98
Or num	0.94	0.94	0.88	0.92

APPENDIX 2:
GEOCHRONOLOGIC DATA

Table 5. U/Pb zircon analytical data for BTL045 and BTL056.

BTL045																
Errors 2-sigma																
Concentrations																
Fractions	Weight* (mg)	U (ppm)	Pb** (ppm)	206 Pb ^y (ppm)	208 Pb ^p (ppm)	206 Pb ^p (ppm)	238 U (ppm)	% err	207 Pb (ppm)	235 U (ppm)	% err	207 Pb (ppm)	235 U (ppm)			
Age (Ma)																
common																
corr. Pb																
coef. (pg)																
206 Pb 207 Pb 235 U 206 Pb 207 Pb 235 U 206 Pb 207 Pb 235 U 206 Pb 207 Pb 235 U 206 Pb 207 Pb 235 U																
_8z	0.0050	1067.61	18.49	810.16	0.107	0.01654	0.51	0.12684	0.60	0.05560	0.30	105.8	121.3	436.5	0.864	7.1
_3z	0.0050	900.99	12.81	808.94	0.122	0.01370	0.72	0.09046	0.89	0.04790	0.50	87.7	87.9	94.2	0.827	5.0
_4z	0.0050	1074.62	15.50	727.69	0.124	0.01365	0.60	0.08984	0.67	0.04772	0.29	87.4	87.4	85.5	0.902	6.6
_1z	0.0050	1040.71	14.13	1432.12	0.112	0.01357	0.63	0.08941	0.83	0.04777	0.51	86.9	87.0	88.1	0.788	3.2
_5z	0.0030	2108.64	29.93	861.51	0.122	0.01356	0.51	0.08900	0.56	0.04759	0.20	86.8	86.6	79.2	0.931	6.5
_6z	0.0030	1357.71	21.09	343.15	0.131	0.01344	0.79	0.08884	1.06	0.04794	0.67	86.1	86.4	96.3	0.772	10.7

BTL056																
Errors 2-sigma																
Concentrations																
Fractions	Weight* (mg)	U (ppm)	Pb** (ppm)	206 Pb ^y (ppm)	208 Pb ^p (ppm)	206 Pb ^p (ppm)	238 U (ppm)	% err	207 Pb (ppm)	235 U (ppm)	% err	207 Pb (ppm)	235 U (ppm)			
Age (Ma)																
common																
corr. Pb																
coef. (pg)																
206 Pb 207 Pb 235 U 206 Pb 207 Pb 235 U 206 Pb 207 Pb 235 U 206 Pb 207 Pb 235 U 206 Pb 207 Pb 235 U																
_6z	0.0050	485.89	7.41	334.60	0.119	0.01367	1.30	0.09073	1.54	0.04814	0.80	87.5	88.2	106.0	0.855	6.7
_7z	0.0050	1224.30	17.82	891.26	0.143	0.01371	0.53	0.09048	0.69	0.04785	0.41	87.8	88.0	91.8	0.799	6.1
_3z	0.0050	1208.57	17.04	1163.60	0.135	0.01360	0.54	0.08976	0.61	0.04788	0.28	87.1	87.3	93.3	0.893	4.6
_1z	0.0050	1041.11	14.13	1432.12	0.112	0.01357	0.63	0.08938	0.83	0.04777	0.51	86.9	86.9	88.1	0.788	3.2
8z	0.0060	1016.56	16.07	1112.50	0.086	0.01577	0.47	0.10518	0.51	0.04836	0.21	100.9	101.5	117.2	0.913	5.6

*estimated, **radiogenic Pb, ^ymeasured ratio corrected for fractionation only, ^pcorrected for fractionation, spike, blank, and initial common Pb.

*estimated, **radiogenic Pb, ^ymeasured ratio corrected for fractionation only, ^pcorrected for fractionation, spike, blank, and initial common Pb.

APPENDIX 3:
MAJOR AND TRACE ELEMENT DATA

Table 6. Normalized major element concentrations determined by X-ray fluorescence

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	Weight % oxide				CaO	Na ₂ O	K ₂ O	P ₂ O ₅
					MnO	MgO						
BTL 9	70.85	0.349	15.31	2.06	0.054	0.60			2.41	4.23	4.00	0.141
BTL 10	70.46	0.446	15.15	2.66	0.066	0.75			2.96	4.36	2.97	0.190
BTL 18	60.29	0.845	17.72	5.86	0.171	2.09			4.49	5.42	2.69	0.406
BTL 25	70.92	0.345	15.41	2.06	0.053	0.62			2.44	4.26	3.75	0.133
BTL 27	74.88	0.198	13.85	1.21	0.030	0.32			1.74	3.68	4.02	0.079
BTL 28	70.97	0.351	15.24	2.16	0.055	0.66			2.52	4.15	3.75	0.143
BTL 30	70.42	0.390	15.48	2.35	0.051	0.69			2.95	4.41	3.11	0.162
BTL 31A	48.30	2.815	9.91	20.86	0.378	2.15			4.05	2.42	2.91	0.500
BTL 31B	62.53	1.185	14.79	7.68	0.170	2.22			3.39	3.75	3.87	0.404
BTL 36	69.52	0.432	15.72	2.56	0.055	0.73			2.91	4.32	3.59	0.183
BTL 37	70.39	0.410	15.31	2.40	0.055	0.74			2.74	4.21	3.58	0.166
BTL 39	67.89	0.332	15.61	2.58	0.100	1.64			1.20	3.21	7.34	0.109
BTL 41	77.62	0.062	12.69	0.44	0.017	0.05			0.69	3.80	4.63	0.011
BTL 42A	76.78	0.179	12.55	0.93	0.025	0.20			1.10	2.96	5.22	0.058
BTL 42B	71.09	0.380	14.97	2.53	0.073	0.71			2.17	4.44	3.51	0.127
BTL 43	73.58	0.234	14.47	1.32	0.036	0.38			2.00	4.08	3.83	0.077
BTL 46	71.77	0.327	15.02	1.90	0.051	0.52			2.30	4.31	3.69	0.120
BTL 48	70.97	0.362	15.17	1.94	0.059	0.60			2.47	4.31	3.97	0.142
BTL 55	69.76	0.499	15.27	2.96	0.066	0.82			3.03	4.24	3.15	0.193
BTL 56	70.85	0.415	15.00	2.56	0.060	0.77			3.06	4.24	2.86	0.171
BTL 58	69.98	0.445	15.45	2.62	0.059	0.80			3.04	4.32	3.10	0.182
BTL 59	68.72	0.428	16.05	2.60	0.055	0.88			3.05	4.03	4.02	0.166
BTL 68	69.83	0.415	15.51	2.49	0.055	0.71			2.85	4.19	3.79	0.165
BTL 69	70.32	0.435	15.31	2.51	0.057	0.75			2.89	4.32	3.24	0.174
BTL 79	67.657	0.533	16.196	3.142	0.065	0.954			3.441	4.197	3.602	0.213
BTL 81	68.936	0.475	15.755	2.809	0.066	0.806			3.107	4.272	3.576	0.198
BTL 82	70.140	0.469	15.102	2.709	0.058	0.726			2.984	4.035	3.583	0.195

Table 6 continued.

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	Weight % oxide					CaO	Na ₂ O	K ₂ O	P ₂ O ₅
					MnO	MgO							
BTL 61A	69.56	0.475	15.18	2.79	0.052	0.88	3.06	3.72	4.11	0.176			
BTL 62	68.28	0.543	15.83	3.06	0.059	1.02	3.38	4.09	3.54	0.193			
BTL 64	68.87	0.466	15.61	2.88	0.061	1.02	3.14	4.09	3.69	0.172			
BTL 65	67.75	0.504	16.12	2.99	0.061	1.09	3.40	4.14	3.76	0.180			
BTL 76	67.006	0.539	16.051	3.481	0.065	1.317	3.767	3.814	3.763	0.197			
BTL 77	66.645	0.636	15.799	3.963	0.077	1.463	4.003	3.838	3.349	0.228			
BTL 85	68.751	0.557	15.134	3.436	0.067	1.136	3.615	3.828	3.275	0.200			
BTL 73	66.249	0.610	16.069	4.193	0.076	1.450	4.229	3.921	2.968	0.235			
BTL 74	67.020	0.580	15.710	3.732	0.085	1.475	3.659	3.819	3.718	0.202			
BTL 75	66.640	0.642	15.562	4.063	0.086	1.490	3.930	3.851	3.513	0.222			
MIL 1-2A	62.869	1.305	12.938	8.906	0.193	3.245	3.032	2.941	4.235	0.337			
MIL 1-2B	75.697	0.192	13.381	1.388	0.027	0.352	2.160	4.189	2.552	0.061			
MIL 1-2C	69.233	0.436	15.506	2.744	0.072	1.138	3.182	3.816	3.736	0.138			
MIL 1-2D	59.422	1.005	16.907	6.390	0.172	3.605	6.576	3.827	1.802	0.294			
MIL 1-2F	76.162	0.059	13.472	0.533	0.010	0.230	1.109	3.568	4.837	0.021			
MIL 1-2J	70.753	0.291	15.498	1.899	0.041	0.734	2.927	3.761	3.983	0.114			
MIL 1-3D	56.741	1.072	17.501	6.881	0.188	3.683	6.683	4.831	2.013	0.408			
MIL 1-3E	58.293	1.769	13.249	10.339	0.253	4.730	3.768	2.573	4.609	0.417			
MIL 1-3F	69.238	0.319	16.181	2.244	0.047	0.935	3.075	4.050	3.809	0.102			
MIL 1-3G	77.095	0.058	12.990	0.417	0.006	0.100	0.717	3.653	4.957	0.007			
MIL 1-8A	60.791	1.545	12.570	9.704	0.196	3.938	4.493	2.878	3.453	0.433			
MIL 1-8B	74.887	0.140	13.670	1.167	0.026	0.421	1.712	3.395	4.526	0.056			
MIL 1-8C	72.373	0.241	14.712	1.804	0.049	0.674	2.242	3.711	4.113	0.080			
MIL 1-9C	48.835	1.612	14.336	12.590	0.410	9.202	7.066	2.542	3.274	0.133			
MIL 1-9F	54.331	0.956	18.871	7.988	0.176	3.913	7.021	4.798	1.609	0.336			
MIL 1-10A	75.828	0.139	13.320	0.986	0.030	0.342	1.398	3.441	4.467	0.048			

Table 7. Unnormalized trace elements determined by X-ray fluorescence.

Sample	Ni	Cr	Sc	V	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn	Pb	La	Ce	Th	Nd
									ppm									
BTL9	0.81	0.28	3.12	35.80	849.8	149.0	612	121.4	7.0	7.0	19.0	5.3	59.5	17.8	31.7	46.3	16.8	17.9
BTL10	0.83	0.57	3.74	45.63	557.4	120.3	649	155.3	9.3	8.2	20.8	4.3	63.8	16.3	34.3	66.2	15.1	23.4
BTL18	3.34	1.73	12.80	103.83	269.5	178.7	546	206.5	14.2	16.9	28.8	41.8	145.0	19.1	54.3	106.1	30.5	38.4
BTL25	3.54	22.71	3.28	35.21	879.4	142.0	599	119.0	6.9	6.8	20.7	5.0	57.0	19.6	30.5	46.1	16.9	16.2
BTL27	1.21	0.18	2.06	21.05	296.5	161.5	415	75.3	5.8	5.9	20.1	5.4	33.7	21.6	19.2	32.1	23.1	7.9
BTL28	0.78	0.00	3.76	37.76	597.1	146.8	608	119.9	8.1	6.7	21.9	6.3	58.9	18.4	33.0	50.6	14.2	14.2
BTL30	3.82	0.00	3.55	39.87	608.9	113.6	684	132.0	8.0	8.3	21.9	4.4	56.7	15.5	32.0	57.8	12.3	19.9
BTL31A	0.54	11.39	14.36	422.77	245.8	147.6	235	1400.7	61.2	51.1	29.9	8.7	383.0	9.8	216.7	436.3	105.5	183.5
BTL31B	1.96	4.25	9.34	131.29	451.4	192.0	487	416.7	21.4	19.7	26.6	3.4	173.2	15.2	92.2	153.5	58.9	53.8
BTL36	0.68	0.00	3.78	42.24	945.2	115.2	697	147.6	9.1	8.1	21.5	4.6	59.4	15.4	53.6	69.9	41.0	22.0
BTL37	2.33	1.98	3.65	42.08	787.0	142.0	634	130.1	7.5	6.5	19.5	3.4	62.4	18.3	29.1	53.7	16.9	20.8
BTL39	3.95	48.05	6.62	33.79	1124.0	392.3	434	132.3	6.3	4.3	15.7	46.5	101.7	33.8	31.5	43.6	13.7	11.6
BTL41	4.04	1.70	0.91	5.89	10.2	231.9	49	51.4	2.4	4.6	20.0	3.7	14.5	32.3	19.3	14.6	25.6	0.0
BTL42A	4.73	0.89	2.47	15.05	746.5	209.7	316	71.6	5.3	5.8	16.8	4.2	22.8	25.4	23.3	27.7	16.0	8.9
BTL42B	3.22	1.65	4.70	38.31	165.8	185.9	413	156.9	7.7	8.3	23.9	4.4	74.4	21.1	35.8	47.3	27.0	16.4
BTL43	4.26	1.51	1.68	22.96	606.5	137.4	487	81.7	4.9	4.9	20.3	3.6	38.1	19.3	21.8	34.9	16.2	13.0
BTL46	3.31	0.00	2.46	31.87	518.6	166.5	545	121.6	7.2	8.0	21.0	5.0	52.7	19.6	30.7	49.6	18.9	16.9
BTL48	2.54	1.06	4.21	31.46	748.6	135.0	559	125.9	7.1	7.1	21.2	4.2	48.9	18.9	32.5	53.8	18.4	20.0
BTL55	3.76	2.57	3.82	50.21	572.5	131.3	608	165.2	10.2	9.2	21.3	4.7	63.5	19.0	35.4	66.8	17.0	26.7
BTL56	2.54	0.00	3.58	43.21	409.9	127.6	625	136.5	8.7	8.2	20.7	3.7	62.7	15.6	39.6	57.1	20.9	18.5
BTL58	4.28	1.95	4.01	44.23	608.7	126.0	632	140.9	7.8	6.6	22.1	6.0	62.3	17.2	33.1	59.2	17.8	23.9
BTL59	5.32	23.72	4.10	45.38	1181.8	125.5	681	121.4	7.3	6.1	19.4	5.6	54.1	18.2	28.1	39.9	14.2	15.4
BTL68	6.04	0.00	4.24	40.46	992.9	135.6	683	137.9	8.7	8.9	20.4	6.2	58.6	17.8	35.2	49.7	18.2	20.2
BTL69	3.60	3.34	2.91	44.40	631.3	133.7	630	142.5	8.4	8.2	21.5	4.2	57.6	16.6	36.4	60.3	18.5	21.5
BTL79	2.13	0.00	4.18	54.46	1168.3	121.3	758	159.3	11.1	9.6	19.5	3.2	65.1	16.7	41.0	67.1	17.0	28.7
BTL81	3.22	0.00	4.51	50.00	776.9	137.9	671	156.1	10.4	10.5	22.9	6.9	63.4	16.2	33.1	67.6	26.8	24.1
BTL82	2.20	0.00	4.35	47.19	871.6	126.8	648	154.0	10.5	9.5	20.1	6.2	56.6	17.6	36.6	63.9	14.9	28.4
BTL61A	1.86	0.52	4.28	52.90	841.1	112.1	609	127.8	9.2	8.3	17.6	5.8	54.1	16.4	28.3	43.5	9.0	20.6
BTL62	4.88	22.56	4.60	58.18	929.8	109.7	661	135.5	9.9	8.3	19.7	6.9	59.3	16.2	39.7	66.2	19.2	25.2

Table 7 continued.

Sample	Ni	Cr	Sc	V	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn	Pb	La	Ce	Th	Nd
									ppm									
BTL64	4.70	0.95	4.18	54.71	709.3	148.2	599.8	123.9	8.4	7.6	20.0	5.6	66.8	19.7	26.5	49.4	16.3	18.8
BTL65	5.09	0.14	4.50	58.15	1008.0	132.8	692.1	126.0	8.6	7.2	21.5	7.8	66.0	17.2	26.0	48.1	18.5	20.4
BTL76	4.62	1.69	5.38	70.34	1006.8	116.4	675.0	131.3	9.4	7.5	19.5	7.3	64.8	17.8	27.8	45.9	15.8	20.2
BTL77	5.05	3.00	6.46	77.67	924.9	123.8	630.4	150.3	13.4	10.3	19.8	8.1	68.1	17.3	34.7	62.9	17.2	24.1
BTL85	3.47	2.08	5.11	68.86	638.1	98.9	567.5	150.0	11.7	9.7	19.1	2.1	58.4	12.7	32.2	58.2	37.6	22.3
BTL73	2.54	1.17	6.42	79.97	810.2	104.4	604.1	163.7	13.9	10.0	18.6	7.1	67.0	14.3	29.9	65.5	21.9	28.1
BTL74	2.31	1.61	6.28	73.08	1060.9	146.6	619.7	134.8	10.4	8.7	19.8	7.4	75.0	16.0	34.8	53.6	17.7	21.7
BTL75	3.68	2.59	6.36	79.17	895.5	137.0	593.4	155.1	13.5	10.8	18.6	7.5	68.4	15.9	32.9	61.2	18.9	24.9
MIL 1-2A	7.0	18.0	14.0	152.0	453.0	197.0	192.0	243.0	23.0	21.4	21.0	16.0	166.0	15.0	65.0	104.0	55.0	NA
MIL 1-2B	4.0	0.0	3.0	25.0	123.0	86.0	207.0	61.0	5.0	6.4	15.0	7.0	26.0	19.0	22.0	53.0	32.0	NA
MIL 1-2C	4.0	3.0	7.0	40.0	703.0	142.0	457.0	102.0	9.0	9.8	18.0	8.0	57.0	18.0	37.0	50.0	22.0	NA
MIL 1-2D	9.0	18.0	9.0	141.0	625.0	114.0	685.0	162.0	14.0	9.3	22.0	38.0	118.0	14.0	38.0	60.0	11.0	NA
MIL 1-2F	3.0	0.0	0.0	6.0	128.0	168.0	111.0	72.0	2.0	4.2	16.0	9.0	11.0	26.0	27.0	15.0	34.0	NA
MIL 1-2J	5.0	4.0	3.0	32.0	747.0	133.0	460.0	75.0	7.0	8.0	18.0	9.0	36.0	18.0	27.0	17.0	17.0	NA
MIL 1-3D	17.0	43.0	16.0	153.0	274.0	100.0	502.0	145.0	15.0	12.1	23.0	13.0	125.0	16.0	33.0	73.0	12.0	NA
MIL 1-3E	11.0	13.0	15.0	186.0	564.0	281.0	250.0	290.0	28.0	28.3	27.0	16.0	208.0	11.0	77.0	130.0	47.0	NA
MIL 1-3F	7.0	0.0	4.0	41.0	445.0	127.0	476.0	78.0	5.0	5.8	18.0	10.0	43.0	17.0	10.0	37.0	21.0	NA
MIL 1-3G	3.0	0.0	3.0	6.0	47.0	173.0	38.0	54.0	1.0	5.6	18.0	9.0	8.0	29.0	5.0	19.0	29.0	NA
MIL 1-8A	9.0	14.0	13.0	197.0	478.0	170.0	254.0	295.0	39.0	31.0	22.0	17.0	148.0	14.0	83.0	148.0	51.0	NA
MIL 1-8B	7.0	2.0	0.0	10.0	459.0	164.0	283.0	60.0	4.0	5.1	15.0	11.0	22.0	23.0	19.0	9.0	28.0	NA
MIL 1-8C	5.0	0.0	5.0	27.0	540.0	163.0	344.0	77.0	4.0	7.2	17.0	7.0	44.0	21.0	37.0	29.0	28.0	NA
MIL 1-9C	45.0	77.0	54.0	270.0	181.0	288.0	189.0	86.0	20.0	15.4	22.0	37.0	242.0	10.0	18.0	42.0	3.0	NA
MIL 1-9F	8.0	13.0	14.0	149.0	160.0	103.0	464.0	136.0	20.0	12.4	23.0	16.0	119.0	12.0	31.0	55.0	5.0	NA
MIL 1-10A	7.0	0.0	0.0	19.0	207.0	175.0	194.0	57.0	4.0	6.3	13.0	7.0	26.0	26.0	26.0	33.0	27.0	NA

Table 8 continued. All values are in ppm.

	BTL 42B	BTL 43	BTL 46	BTL 48	BTL 55	BTL 56	BTL 58	BTL 59	BTL 68	BTL 69	BTL 79	BTL 81	BTL 82	BTL 61A
La	38.23	22.39	31.49	33.99	38.61	37.24	34.37	27.00	30.04	36.12	48.23	29.01	30.81	23.53
Ce	54.22	33.60	47.39	51.59	64.33	58.75	55.10	43.53	49.15	56.17	79.32	47.28	51.11	41.74
Pr	5.02	3.26	4.69	5.06	6.68	6.01	5.66	4.51	5.07	5.65	8.41	4.90	5.24	4.49
Nd	17.30	11.56	16.49	18.07	24.34	21.55	20.41	16.37	18.40	20.50	30.82	17.87	19.22	16.56
Sm	2.77	1.92	2.73	3.02	4.19	3.79	3.57	2.96	3.27	3.52	5.40	3.10	3.38	3.07
Eu	0.66	0.50	0.66	0.74	1.00	0.93	0.89	0.78	0.83	0.85	1.30	0.79	0.85	0.81
Gd	1.88	1.26	1.79	2.03	2.88	2.58	2.44	2.05	2.15	2.39	3.88	2.11	2.32	2.14
Tb	0.24	0.16	0.23	0.26	0.38	0.32	0.31	0.27	0.28	0.30	0.48	0.27	0.30	0.28
Dy	1.23	0.85	1.15	1.30	1.94	1.69	1.66	1.39	1.46	1.53	2.50	1.39	1.52	1.43
Ho	0.23	0.15	0.21	0.24	0.34	0.31	0.30	0.25	0.27	0.28	0.45	0.25	0.27	0.26
Er	0.61	0.41	0.56	0.62	0.89	0.80	0.75	0.63	0.68	0.71	1.14	0.63	0.72	0.67
Tm	0.09	0.06	0.08	0.09	0.13	0.12	0.11	0.09	0.10	0.10	0.16	0.09	0.10	0.10
Yb	0.65	0.40	0.55	0.59	0.84	0.77	0.72	0.58	0.63	0.65	0.99	0.61	0.64	0.59
Lu	0.12	0.07	0.10	0.10	0.14	0.13	0.12	0.10	0.11	0.11	0.16	0.10	0.11	0.09
Ba	160	601	507	727	565	386	604	1164	991	607	1096	798	936	872
Th	26.29	16.36	23.07	18.30	16.89	27.22	16.50	12.86	14.91	16.59	19.67	15.79	13.55	8.17
Nb	10.22	5.58	7.52	8.81	10.55	9.32	9.02	6.81	7.80	9.01	11.40	7.47	7.80	6.32
Y	6.88	4.44	6.22	6.99	10.08	9.10	8.49	7.19	7.51	8.06	12.70	7.25	7.96	7.35
Hf	4.93	2.53	3.70	3.76	4.77	4.43	4.02	3.34	3.72	4.03	4.39	3.14	3.15	3.27
Ta	1.89	1.52	0.58	1.66	2.19	0.73	2.03	1.48	0.64	1.77	0.92	0.57	0.63	0.51
U	8.81	4.89	6.20	5.20	4.52	8.20	4.15	3.25	5.21	4.87	6.94	4.98	3.68	2.33
Pb	20.99	18.58	20.60	18.69	16.72	16.19	16.43	16.64	17.60	17.09	16.13	16.91	16.96	16.33
Rb	176.2	128.5	156.0	127.3	127.1	125.0	121.2	119.6	128.1	125.2	114.5	130.8	126.2	112.9
Cs	6.05	3.16	5.08	3.40	5.21	9.02	4.28	5.32	4.63	5.07	5.86	6.13	5.28	3.87
Sr	414	482	509	554	618	606	640	687	667	622	732	662	636	608
Sc	5.0	1.8	2.9	3.3	4.4	3.7	3.8	3.8	3.6	4.5	5.1	3.4	3.5	3.8
Zr	148	78	112	121	157	145	132	115	121	133	142	100	100	112

Table 8 continued. All values are in ppm.

	MIL 1-2J	MIL 1-3D	MIL 1-3E	MIL 1-3F	MIL 1-3G	MIL 1-8A	MIL 1-8B	MIL 1-8C	MIL 1-9C	MIL 1-9F	MIL 1-10A
La	16.83	45.83	70.29	25.27	12.33	24.73	96.74	16.88	16.61	28.66	17.30
Ce	29.63	79.97	132.56	37.90	10.27	34.13	162.42	20.76	38.90	60.34	21.53
Pr	3.04	8.51	14.32	3.75	0.56	3.17	16.79	1.70	4.70	7.06	1.85
Nd	10.96	33.58	54.26	13.57	1.25	10.83	62.60	5.58	19.14	27.55	6.07
Sm	2.06	6.52	10.61	2.47	0.17	1.96	12.18	0.95	4.39	5.86	1.02
Eu	0.59	1.71	2.09	0.66	0.05	0.49	2.23	0.31	0.85	1.19	0.27
Gd	1.53	4.98	8.09	1.92	0.13	1.39	9.25	0.66	3.95	4.81	0.75
Tb	0.21	0.67	1.11	0.27	0.02	0.20	1.31	0.10	0.61	0.72	0.11
Dy	1.11	3.51	6.12	1.41	0.12	1.05	7.07	0.53	3.49	4.07	0.62
Ho	0.22	0.61	1.08	0.27	0.03	0.20	1.27	0.09	0.67	0.75	0.11
Er	0.58	1.54	2.83	0.66	0.10	0.53	3.29	0.26	1.80	2.00	0.31
Tm	0.08	0.21	0.39	0.10	0.02	0.08	0.47	0.04	0.27	0.28	0.05
Yb	0.55	1.29	2.56	0.64	0.23	0.57	3.04	0.29	1.75	1.75	0.37
Lu	0.09	0.21	0.41	0.10	0.06	0.10	0.48	0.06	0.31	0.28	0.07
Ba	730	267	557	411	49	556	511	453	176	164	227
Th	16.03	13.58	47.51	27.35	30.76	25.98	54.89	25.90	3.92	8.00	26.17
Nb	5.69	11.79	27.87	6.59	3.48	6.75	28.42	3.68	13.69	11.51	4.91
Y	6.24	17.02	30.57	7.34	1.14	6.12	37.93	3.10	20.03	21.26	3.53
Hf	2.29	4.13	8.59	2.51	3.37	2.68	8.37	2.06	3.02	3.83	2.51
Ta	0.53	0.76	2.28	0.60	0.28	0.63	2.79	0.34	0.53	0.86	0.48
U	8.17	7.54	13.78	8.37	21.41	6.68	14.27	10.43	2.45	3.92	9.15
Pb	20.56	15.94	13.19	20.85	32.77	24.91	14.85	26.15	7.21	12.15	27.35
Rb	124.8	97.3	270.3	120.3	162.5	158.0	172.1	156.4	282.2	102.1	163.8
Cs	3.76	4.90	14.57	3.95	7.14	4.51	7.84	5.60	28.93	6.86	4.04
Sr	463	500	249	424	38	330	254	284	189	448	200
Sc	3.2	14.8	16.4	3.4	1.0	2.8	20.0	1.4	52.7	17.3	1.8
Zr	64	142	278	74	61	74	281	57	86	131	58

APPENDIX 4:
ISOTOPE DATA

Table 9. Isotope data.

Sample	Sm (ppm)	Nd (ppm)	Sm/Nd weight ratio	$^{147}\text{Sm}/^{144}\text{Nd}$ ratio	measured $^{143}\text{Nd}/^{144}\text{Nd}$	2 sigma error on measured $^{143}\text{Nd}/^{144}\text{Nd}$	initial $^{143}\text{Nd}/^{144}\text{Nd}$ T = 88 Ma	epsilon Nd at time T	$^{87}\text{Sr}/^{86}\text{Sr}$ measured	Calculated Initial $^{87}\text{Sr}/^{86}\text{Sr}$
BTL 028	2.96	19.84	0.09	0.149	0.51224	0.00009	0.51219	-6.53	0.70728	0.706401
BTL030	3.146	20.4	0.0932	0.1542	0.512249	0.000008	0.512195	-6.43	0.70705	0.706452
BTL031B	8.762	57.68	0.0918	0.1519	0.512241	0.000008	0.512189	-6.56	0.70779	0.706362
BTL 037	3.77	24.76	0.092	0.1523	0.512257	0.000009	0.512204	-6.25	0.70726	0.706445
BTL042A	1.762	11.76	0.0908	0.1502	0.512259	0.000007	0.512206	-6.21	0.70855	0.706143
BTL042B	2.412	16.59	0.0879	0.1454	0.51224	0.000008	0.512189	-6.54	0.70791	0.706276
BTL043	1.916	12.89	0.0898	0.1486	0.512249	0.000008	0.512198	-6.38	0.70704	0.706366
BTL048	0.691	19.87	0.021	0.0347	0.511816	0.000007	0.511804	-6.17	0.70731	0.706437
BTL055	3.448	22.13	0.0942	0.1558	0.512268	0.000008	0.512214	-6.07	0.70723	0.70645
BTL058	4.407	27.72	0.0961	0.159	0.512262	0.000009	0.512207	-6.20	0.70718	0.706462
BTL059	3.522	22.27	0.0956	0.1582	0.512301	0.000008	0.512246	-5.44	0.70699	0.706324
BTL061A	3.239	20.21	0.0969	0.1603	0.5123	0.000006	0.512245	-5.47	0.70713	0.70646
BTL064	2.957	18.67	0.0957	0.1584	0.512289	0.000008	0.512234	-5.68	0.70732	0.706427
BTL065	3.089	28.83	0.0723	0.1196	0.512289	0.000013	0.512247	-5.42	0.70715	0.706452
BTL069	3.331	21.52	0.0936	0.1548	0.512271	0.000006	0.512217	-6.00	0.7072	0.706426
BTL073	3.48	20.08	0.1048	0.1733	0.512336	0.000009	0.512276	-4.86	0.70695	0.70632
BTL076	3.928	23.16	0.1025	0.1696	0.512315	0.00001	0.512256	-5.25	0.70697	0.706351
BTL079	4.505	27.76	0.0981	0.1623	0.51223	0.00001	0.512174	-6.85	0.70712	0.706545
BTL081	3.551	22.71	0.0945	0.1564	0.512262	0.000006	0.51208	-6.18	0.70722	0.70648
BTL085	3.092	19.36	0.0965	0.1597	0.512284	0.00001	0.512228	-5.78	0.70716	0.706528

Rb, Sr concentrations determined by ICP-MS and given in Table 8.

Errors on ϵNd are ± 0.3 epsilon units for all samples.

Errors on initial Sr are 2×10^{-5} for all samples.

APPENDIX 5:
THEORETICAL MODELS

Table 10. Bulk compositions, partition coefficients (K_plag, K-amph...etc.) and calculated bulk distribution coefficients (bulk D) for various trace elements in various starting compositions. All mineral/melt partition coefficients are from Rollinson (1993).

Element	Composition	K	plag	%plag	K	amph	%amph	K	mag	%mag	ilm	K	bio	%bio	K	qtz	%qtz	K	sph	%sph
Ce	Amphibolite	0.26	0.6	0.044	0.330	3	0.02	0.3	0	0.014	0.03	15	0.01							
Yb	Amphibolite	0.07	0.6	6	0.33	1	0.02	0.4	0	0.017	0.02	0	0.02							
Sr	Amphibolite	3	0.61	0.022	0.330	0.01	0.02	0.3	0	0	0.02	2	0.01							
	Granulite	3	0.15	0.022	0.050	0.01	0	0.3	0.05	0	0	2	0							
	Eclogite	3	0.1	0.022	0.000	0.01	0	0.3	0	0	0	2	0							
Sc	Amphibolite	0.05	0.6	25	0.33	2	0.02	14	0	0.012	0.02	50	0.02							
	Granulite	0.05	0.15	25	0.05	2	0	14	0.05	0.012	0	50	0							
	Eclogite	0.05	0.1	25	0	2	0	14	0	0.012	0	50	0							
V	Amphibolite	0.01	0.6	30	0.33	30	0.02	14	0	0.012	0.02	50	0.02							
	Granulite	0.01	0.15	30	0.05	30	0	14	0.05	0.012	0	50	0							
	Eclogite	0.01	0.1	30	0	30	0	14	0	0.012	0	50	0							

Element	Composition	K_ap	%ap	K_gt	%Gt	K_cpx	%Cpx	K_opx	%Opx	Bulk D
Ce	Amphibolite	35	0.01							0.731
Yb	Amphibolite	24	0.01							2.282
Sr	Amphibolite	2.2	0.01	0.015						1.879
	Granulite	2.2	0	0.015	0.3	0.516	0.45			0.703
	Eclogite	2.2	0	0.015	0.35	0.516	0.5	0.009	0.05	0.564
Sc	Amphibolite	50	0.01							9.821
	Granulite	50	0	16	0.3	53	0.45			30.61
	Eclogite	50	0	16	0.35	53	0.5	18	0.05	33.01
V	Amphibolite	50	0.01							12.01
	Granulite	50	0	8	0.3	1.1	0.45			15.6
	Eclogite	50	0	8	0.35	1.1	0.5	0.6	0.05	4.886

Note: Bulk D calculated as $(K_{\text{plag}} \times \% \text{plag}) + (K_{\text{amph}} \times \% \text{amph}) \dots \text{etc.}$

Table 11. Trace element liquid concentrations for different starting compositions and melt fractions.

Melt Fraction	Amphibolite		Amphibolite		Eclogite		Granulite		Eclogite		Granulite		Amphibolite		Eclogite		Granulite		Eclogite	
	C_L	Ce	C_L	Yb	C_L	Sc	C_L	Sr	C_L	Sr	C_L	V	C_L	Sr	C_L	V	C_L	V	C_L	V
0.1	52.8		0.8		2.8		0.9		0.8		636.2		260.1		767.3		20.6		15.9	
0.2	51.0		0.9		3.1		1.0		0.9		611.4		273.5		715.9		22.9		17.7	
0.3	49.3		0.9		3.5		1.2		1.1		588.4		288.4		670.9		25.8		20.1	
0.4	47.7		1.0		4.0		1.3		1.2		567.1		305.0		631.2		29.6		23.1	
0.5	46.2		1.1		4.6		1.6		1.5		547.3		323.7		596.0		34.6		27.1	
0.6	44.8		1.2		5.5		1.9		1.8		528.9		344.7		564.5		41.6		32.9	
0.7	43.5		1.3		6.9		2.5		2.4		511.6		368.7		536.2		52.3		41.8	
0.8	42.3		1.4		9.0		3.6		3.4		495.4		396.3		510.6		70.3		57.4	
0.9	41.1		1.6		13.3		6.3		6.0		480.3		428.3		487.3		107.1		91.5	

Note: Liquid concentrations (C_L) were calculated using a batch partial melting model in the form $C_L = C_o / (D + f(1 - D))$ where C_o is the concentration in the melt source, D is the bulk distribution coefficient (Table 9) and f is the melt fraction.

Table 12. Least squares mixing model using hornblende-biotite schlieren and plagioclase as the fractionating cumulate.

	average fractionate	average parent	average cumulate (BTL031A)	average plagioclase*	predicted daughter	observed daughter	residuals "r"	residuals ²	observed cumulate
SiO ₂	75	71	56.82	62.34	75.124	75	0.124	0.015	60.28
TiO ₂	0.21	0.37	2.10	0.00	0.255	0.212	0.043	0.002	0.78
Al ₂ O ₃	13.66	15.07	12.72	23.45	13.953	13.665	0.289	0.083	19.46
FeO	1.21	2.23	14.74	0.10	1.268	1.212	0.056	0.003	5.55
MgO	0.27	0.68	2.22	0.00	0.649	0.265	0.384	0.148	0.82
CaO	1.54	2.60	3.93	4.87	2.062	1.541	0.521	0.272	4.52
Na ₂ O	3.78	4.16	3.19	8.93	3.426	3.780	-0.354	0.125	6.79
K ₂ O	4.25	3.65	3.52	0.13	4.376	4.250	0.127	0.016	1.40
P ₂ O ₅	0.08	0.15	0.47	0.00	0.138	0.076	0.063	0.004	0.17
Σ of r² = 0.66									

* average plagioclase compositions were calculated from microprobe analysis in Table 1.

Table 13. Least squares mixing model using hornblende and plagioclase as the fractionating cumulates.

	average fractionate	average parent	hornblende*	average plagioclase**	predicted daughter	observed daughter	residuals "r"	residuals ²	observed cumulate
SiO ₂	75	71	47.49	62.34	75.09	75.00	0.09	0.01	58.61
TiO ₂	0.21	0.37	1.21	0.00	0.40	0.21	0.18	0.03	0.30
Al ₂ O ₃	13.66	15.07	7.07	23.45	14.18	13.66	0.51	0.26	19.34
FeO	1.21	2.23	15.08	0.10	1.84	1.21	0.63	0.40	3.86
MgO	0.27	0.68	13.06	0.00	0.03	0.27	-0.24	0.06	3.28
CaO	1.54	2.60	11.92	4.87	1.61	1.54	0.06	0.00	6.64
Na ₂ O	3.78	4.16	0.75	8.93	3.52	3.78	-0.26	0.07	6.88
K ₂ O	4.25	3.65	0.49	0.13	4.58	4.25	0.33	0.11	0.22
P ₂ O ₅	0.08	0.15	0.00	0.00	0.18	0.08	0.11	0.01	0.00
$\Sigma \text{ of } r^2 = 0.95$									

* average hornblende composition from Dodge, et al. (1968).

** average plagioclase compositions were calculated from microprobe analysis in Table 1.

Table 14. Least squares mixing model using hornblende-biotite schlieren and K-feldspar as the fractionating cumulate.

	average fractionate	average parent	average cumulate (BTL031A)	average K- feldspar*	predicted daughter	observed daughter	residuals "r"	residuals ²	observed cumulate
SiO ₂	75	71	56.82	64.70	75.23	75.00	0.23	0.05	37.78
TiO ₂	0.21	0.37	2.10	0.00	0.31	0.21	0.10	0.01	7.18
Al ₂ O ₃	13.66	15.07	12.72	18.27	16.07	13.66	2.41	5.79	-0.69
FeO	1.21	2.23	14.74	0.09	1.78	1.21	0.57	0.32	50.13
MgO	0.27	0.68	2.22	0.00	0.64	0.27	0.37	0.14	7.57
CaO	1.54	2.60	3.93	0.06	2.61	1.54	1.07	1.15	13.27
Na ₂ O	3.78	4.16	3.19	0.95	4.33	3.78	0.55	0.30	8.61
K ₂ O	4.25	3.65	3.52	15.08	4.19	4.25	-0.06	0.00	-24.37
P ₂ O ₅	0.08	0.15	0.47	0.00	0.14	0.08	0.06	0.00	1.60
Σ of r² = 7.76									

* average plagioclase compositions were calculated from microprobe analysis in Table 1.

Table 16. Bulk compositions, partition coefficients (K_plag, K_amph....etc.) and calculated bulk distribution coefficients (Bulk D) for Ba in an amphibolite and eclogite with or without K-feldspar. Also shown are Ba liquid concentrations for different melt fractions.

Element	Composition	K plag	% plag	K amphib	% amphib	K K-spar	% K-spar	K bio	% bio	K qtz	% qtz	Bulk D
Ba	K-feldspar present	0.33	0.55	0.044	0.3	6	0	10	0.1	0.022	0.05	1.196
Ba	No K-feldspar	0.33	0.55	0.044	0.3	6	0.01	10	0.1	0.022	0.04	1.256
Ba	Eclogite	0.33	0.1	0.044	0	6	0	10	0	0.022	0	
		K gt	%Gt	K Cpx	%Cpx	K Opx	%Opx					
Eclogite		0.017	0.35	0.131	0.5	0.003	0.05					
												1.58

1.58

Melt Fraction	K-feldspar present		No K-feldspar	
	C		Ba	
0	238.9	250.9	190.1	
0.1	243.9	255.1	197.4	
0.15	246.5	257.2	205.2	
0.2	249.1	259.4	213.6	
0.25	251.7	261.6	222.8	