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Fractionation, recharge, and hybridization in a shallow, bimodal magma reservoir

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FRACTIONATION, RECHARGE, AND HYBRIDIZATION IN A SHALLOW,
BIMODAL MAGMA RESERVOIR

A Thesis

Presented to

The Faculty of the Department of Geology

San Jose State University

In Partial Fulfillment

Of the Requirements for the Degree

Master of Sciences

by

Shelly Melissa Ericksen

May 2006

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ABSTRACT

FRACTIONATION, RECHARGE, AND HYBRIDIZATION IN A SHALLOW, BIMODAL MAGMA RESERVOIR

by Shelly M. Ericksen

The 15.7 Ma Aztec Wash pluton, emplaced at a depth of 4–7 km, preserves a record of bimodal (mafic-felsic) magma fractionation, recharge, and hybridization. This study examines a mafic lobe at structurally deep levels in the pluton. Within the lobe, mafic and felsic magmas form gently dipping sequences (10–20 m thick) composed of mafic sheets (0.5–4 m thick) with felsic interlayers (2 cm–2 m thick). The mafic sheets and felsic interlayers show chemical and textural evidence for increasing chemical and mechanical hybridization with structural height. Previous work has shown that both open and closed system processes operated within the active magma chamber. The new isotopic data in this study place important constraints upon these processes, and show that generation of the observed lithologies involved single- or multi-stage events of mafic magma fractionation, mafic recharge, and hybridization of mafic and felsic magmas and their cumulates.

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TABLE OF CONTENTS

	Page
INTRODUCTION	1
REGIONAL GEOLOGIC SETTING	3
THE AZTEC WASH PLUTON	5
PURPOSE AND OBJECTIVES	8
MAPPING AND FIELD RELATIONSHIPS.....	10
Highly Coherent Sheeted Sequences	16
Coherent Sheeted Sequences	19
Incoherent Sheeted Sequences	27
Pipes in Sheeted Sequences	29
Mafic Enclaves.....	32
Intermediate and Felsic Enclaves.....	35
Isolated Mafic–Ultramafic Pods	35
“Clasts” of Intermediate Rock	36
ANALYTICAL METHODS	38
Petrography	38
Major and Trace Element Geochemistry	38
Isotope Geochemistry	39
RESULTS	42
Petrography	42
Mafic–Ultramafic Units of the Heterogeneous Zone.....	42

Mafic Units of the Heterogeneous Zone	42
Intermediate Units of the Heterogeneous Zone	45
Monzodiorites–Quartz Monzodiorites	45
Coarse-Grained Monzonites–Quartz Monzonites.....	46
Coarse-Grained Quartz Monzonite Pipes	51
Heterogeneous Quartz Monzonites.....	51
Felsic Units of the Heterogeneous Zone and Granite Zone	53
Major and Trace Element Geochemistry	57
Mafic–Ultramafic Units of the Heterogeneous Zone.....	57
Mafic Units of the Heterogeneous Zone	69
Intermediate Units of the Heterogeneous Zone	69
Felsic Units of the Heterogeneous Zone and Granite Zone	71
Whole-Rock Isotope Geochemistry	75
$^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ vs. SiO_2 and ϵ_{Nd} vs. SiO_2	75
ϵ_{Nd} vs. $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$	78
$^{206}\text{Pb}/^{204}\text{Pb}$ vs. SiO_2	79
$^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$	80
$^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$	80
DISCUSSION	81
Mafic Input Magmas.....	83
Felsic Input Magmas.....	83
Felsic Magma Evolution in the Heterogeneous Zone.....	86

Felsic Magma Evolution in the Granite Zone.....	88
Isotopic Constraints on Felsic Units of the Heterogeneous Zone and Granite Zone	89
Heterogeneous Zone Cumulate Contamination.....	91
Silicic Melt Migration.....	93
Fractionated Mafic Melt Migration	95
Felsic Pipe Formation in the Heterogeneous Zone	96
Fractionation of Mafic Magma	97
Hybridization in the Heterogeneous Zone	98
Mechanical Hybridization in Breccia Zones.....	106
Construction of a Mafic Lobe	107
CONCLUSIONS.....	111
REFERENCES CITED.....	113

LIST OF FIGURES

Figure		Page
1.	Geologic Map Showing Location of the Aztec Wash Pluton	4
2.	Simplified Map of the Aztec Wash Pluton	6
3.	Map Detailing Units of the Granite Zone	11
4.	Map Showing Heterogeneous Zone and Granite Zone	12
5.	Schematic Representation of Map Area	15
6.	Highly Coherent Sheeted Sequences	17
7.	Detail of Mafic-Felsic Sheeted Sequence	18
8.	Mafic Pillows	20
9.	Fine-Grained Mafic Sheet Tip	21
10.	Hornblende Gabbro Sheet	23
11.	Seams and Pockets of Felsic Material	24
12.	Hornblende-Defined Schlieren	25
13.	Coarse-Grained Monzonite Hand Sample	26
14.	Pipes Protruding Through Gabbro	30
15.	Poorly-Formed Pipes	31
16.	Pipes Interconnected with Silicic Veins	33
17.	Mafic Enclave	34
18.	Fine-Grained Clasts in Granite	37
19.	Olivine Gabbro	45
20.	Coarse-Grained Monzodiorite	48

21. Subhedral Plagioclase in Monzodiorite	48
22. Hornblende Crystals and Granophyre in Monzodiorite.....	49
23. Rapakivi K-Feldspars in Monzonite	50
24. Kinked Biotite in Quartz Monzonite.....	52
25. Quartz Monzonite Variants.....	54
26. Plagioclase Phenocryst in Quartz Monzonite	55
27. Major Elements Versus SiO ₂	64
28. Trace Elements Versus SiO ₂	66
29. Ba, Rb, and Zr vs. Sr, and Zr vs. Ba	68
30. Rare Earth Element Profiles for Mafic–Ultramafic and Mafic Samples	70
31. Rare Earth Element Profiles for Intermediate Samples	72
32. Rare Earth Element Profiles for Late Dikes and GZ Enclaves.....	72
33. Rare Earth Element Profiles for Felsic Samples.....	73
34. ⁸⁷ Sr/ ⁸⁶ Sr _(i) , ε _{Nd} , and ²⁰⁶ Pb/ ²⁰⁴ Pb vs. SiO ₂ ; ε _{Nd} vs. ⁸⁷ Sr/ ⁸⁶ Sr _(i) ; ²⁰⁷ Pb/ ²⁰⁴ Pb vs. ²⁰⁶ Pb/ ²⁰⁴ Pb and ²⁰⁸ Pb/ ²⁰⁴ Pb vs. ²⁰⁶ Pb/ ²⁰⁴ Pb.....	76
35. HZ and GZ Samples Plotted with Mantle and Crustal Source Compositions ..	84
36. ε _{Nd} vs. SiO ₂ and ⁸⁷ Sr/ ⁸⁶ Sr _(i) vs. SiO ₂ for Samples in the HZ and GZ.....	90
37. HZ Cumulate Contamination by Silicic Melt Migration	94
38. Ba vs. Sr Including Fractional Crystallization Model for Mafic Magma.....	101
39. Mixing Scenarios for Hybrid Rocks	102
40. Gradational Sequence Depicting Hybridization of Mafic Material.....	105
41. Cartoon Depicting Formation of GZ and HZ	108

LIST OF TABLES

Table	Page
1. Modes and Textural Variability of Heterogeneous Zone (HZ) and Granite Zone (GZ) Units.....	43
2. Analytical Data for Heterogeneous Zone (HZ) Units.....	58
3. Analytical Data for Granite Zone (GZ) Units.....	62

INTRODUCTION

The physical and temporal evolution of open system continental magma reservoirs is still incompletely understood. To reflect the recent advances made in the conceptual views of magma chambers and reservoirs (e.g., Reid, 2003), this study defines a magma chamber as the liquid portion only of a larger magma reservoir (Reid, 2003). A magma reservoir is composed of two regimes: liquid and mush (Reid, 2003). The liquid regime behaves mechanically as a liquid, and may contain up to 25–40% crystals (Reid, 2003). The mush regime is effectively rigid, with 50–75% crystals (Reid, 2003). Evidence for open system evolution is best preserved in the deepest levels of magma reservoirs (e.g., Bateman, 1995), where inputs of new, usually mafic, magma have been shown to physically and chemically interact with more evolved intermediate to felsic magmas, typically along the magma reservoir floor (Wiebe, 1994; Wiebe et al., 2002). At higher levels in silicic magma reservoirs, the record of open system processes is often erased during subsequent evolution. The way in which these higher levels are linked to deeper processes involving the injection of mafic magmas into the reservoir can be obscure, and continuous pluton exposure in the field is commonly lacking.

How, then, is a silicic magma reservoir constructed, and how is reservoir evolution influenced by deep-level processes? To what extent do fresh inputs of magma interact with existing materials within the reservoir? Do hybrid magmas form primarily beneath (i.e., at deep source levels) or within an existing magma reservoir? What physical and chemical processes lead to hybridization between compositionally disparate

magmas, and is hybridization a single- or multi-stage event? A way to better understand these issues is through the examination of magma systems in areas where geologic structures have exposed, but not dramatically dismembered, plutons from the deepest levels to the shallowest (sub-volcanic) levels. With its excellent exposure and well-preserved stratigraphic record of pluton construction, the Miocene Aztec Wash pluton, located in the extended Colorado River Trough of southern Nevada and northwestern Arizona, is an ideal subject for such an examination.

REGIONAL GEOLOGIC SETTING

The 15.7 Ma Aztec Wash pluton is located in the Eldorado Mountains, in the northwestern corner of the Colorado River extensional corridor (CREC) (Fig. 1). The CREC is located in the Basin and Range province south of Las Vegas, Nevada and is a north-trending, 50–100 km-long extensional zone through which the Colorado River flows. Rapid east-west extension in the region began approximately 15.6–15.8 Ma and ended between 10–14 Ma (Faulds, 1993; Gans et al., 1994; Faulds et al., 2001).

Although east-west extension accompanied emplacement of the Aztec Wash pluton, the majority of tilting and extension in the northern Eldorado Mountains occurred after emplacement (Falkner et al., 1995). The major exposure of the pluton is tilted to the east-northeast and is located near or within an accommodation zone that separates an east-tilted block in the northern Eldorado Mountains from a west-tilted block in the southern Eldorado Mountains (Patrick and Miller, 1997; Harper et al., 2003).

The basement of the Eldorado Mountains is the Mojave terrane, which consists of Early to Middle Proterozoic rocks with a Late Archaean contribution seen in Nd model ages and zircons (Bennett and DePaulo, 1987; Wooden and Miller, 1990). Mesozoic granitoids are also present (Falkner et al., 1995; Patrick and Miller, 1997). The Aztec Wash pluton intrudes the Cretaceous Ireteba granite to the south and southeast (D'Andrea-Kapp et al., 2002), Proterozoic gneiss to the north and northeast, and the middle Miocene Nelson pluton and early Miocene sedimentary and volcanic rocks to the north (Fig. 1) (Falkner et al., 1995; Miller et al., 2002).

Figure 1. Simplified geologic map of the northern Colorado River extensional corridor (CREC) showing location of the Aztec Wash pluton (modified from Faults, 2001). Boxed area in inset shows regional location of CREC. AW = Aztec Wash pluton, BRP = Basin and Range province, CP = Colorado Plateau, N = Nelson pluton.

THE AZTEC WASH PLUTON

The Aztec Wash pluton is approximately 10 km wide, 5 km thick, and 6 km long. It was emplaced at a depth of 4–7 km, and is exposed over a region of 52 km². Due to structural tilting and climatic conditions, the pluton exhibits excellent top- to near-bottom exposure. Previous workers have broadly divided the Aztec Wash pluton into two major zones: a granite zone (GZ) and a heterogeneous zone (HZ) (Fig. 2) (Falkner et al., 1995; Patrick and Miller, 1997). The granite zone is composed of a felsic granite that has been designated as the main granite of the Aztec Wash pluton (Falkner et al., 1995; Patrick and Miller, 1997). The granite spans a narrow compositional range of ~72–74% SiO₂, although dikes and sills of more silica-rich granites are also locally present. Granites in the granite zone range from coarse-grained, feldspar-rich, and quartz-poor to medium-grained and fine-grained variants richer in quartz, but of similar mineralogy and composition. The most felsic material (up to 77% SiO₂), a leucogranite with abundant miarolitic cavities, is present at the roof along the east-northeast margin of the pluton (Harper et al., 2004).

Rocks in the heterogeneous zone range from gabbros to granites that comprise a variety of textures, have variable mineralogy, and span a silica range of over 30 wt % (43–74% SiO₂) (Falkner et al., 1995; Patrick and Miller, 1997). The most mafic rocks of the heterogeneous zone are olivine-rich troctolites and gabbros, locally present as isolated 10–30 m-long and 3–6 m-thick pods within the HZ. The vast majority of mafic rocks have 50–52% SiO₂ and range from coarse-grained, massive and layered hornblende

Figure 2. Simplified map of the Aztec Wash pluton (modified from C. Koteas, 2005 personal communication). Boxed area indicates approximate extent of mafic lobe mapped and examined in detail in this study. Arrow indicates up direction in the pluton.

gabbros to trachybasalts. Intermediate rocks range from 53–68% SiO_2 and may be uniformly fine- to-medium grained or porphyritic in texture and heterogeneous in composition on hand-sample scale. Coarse-grained monzonites to quartz monzonites (56–65% SiO_2) form 1 cm–30 m-thick sheets and lenses interlayered with mafic rocks. Granites (70–74% SiO_2) are locally present as irregular masses and as late dikes within the heterogeneous zone.

PURPOSE AND OBJECTIVES

A hallmark feature of the Aztec Wash pluton is abundant chemical, textural, and structural evidence for open-system magma interaction between mafic and felsic magmas that has been documented in previous work (Falkner et al., 1995; Patrick and Miller, 1997; Robinson and Miller, 1999; Miller and Miller, 2002; Cates et al., 2003; Coiner et al., 2003; Harper et al., 2003; Koteas et al., 2003; Miller et al., 2003; Harper et al., 2004). A detailed study of the structurally deepest mafic lobe was undertaken to better identify and constrain the physical and chemical processes of pluton construction and magma reservoir evolution in the Aztec Wash pluton. The data attained through mapping field relationships and examining petrography, elemental geochemistry, and isotope geochemistry contribute to similar work that has been done in bordering regions (Falkner et al., 1995; Patrick and Miller, 1997; Robinson and Miller, 1999; Miller and Miller, 2002; Cates et al., 2003; Coiner et al., 2003; Harper et al., 2003; Koteas et al., 2003, Miller et al., 2003; Harper et al., 2004). This study will specifically address the following unresolved issues: (1) Were multiple inputs of isotopically distinct felsic and mafic magmas injected into the reservoir? (2) What role did the fractionation of mafic magmas play in the overall chemical evolution of the magma reservoir? (3) What mechanical and/or chemical processes occurred to produce the wide array of hybridized rocks in the pluton? (4) Are hybridized rocks the products of single- or multi-stage episodes of hybridization? (5) What thermal and/or chemical perturbations resulted from repeated injection of mafic magmas into the reservoir? The new isotopic data presented in this

study are especially significant because they place important constraints upon these questions, and provide a test of the most current model (e.g., Harper et al., 2004) for the evolution of the Aztec Wash pluton.

MAPPING AND FIELD RELATIONSHIPS

The granite zone (GZ) makes up approximately one-third of the Aztec Wash pluton; the heterogeneous zone (HZ) comprises the remaining two-thirds (Fig. 2). The granite zone is composed almost entirely of granites that show textural and compositional variation. Granite zone units are designated following Harper et al. (2004), and those pertaining to this study include the following: chilled border granite, miarolitic leucogranite, fine- to medium-grained granite, coarse-grained, quartz-poor granite, and felsic to intermediate enclaves. Unit descriptions are detailed in Figures 3–4. The heterogeneous zone is composed of at least three km-scale mafic lobes that tongue into the granites of the granite zone (Figs. 2–3). Late, km-scale, north–south- striking dikes (~15.5 Ma) cut the granite zone and the heterogeneous zone (Harper et al., 2004). The dikes are predominately microgranite and rhyolite, but composite dikes, with mafic magma quenched and pillowed in a felsic matrix, are also present.

As mentioned previously, this work examines in detail the upper portion of the lowermost of the heterogeneous zone mafic lobes, which is approximately 0.5 x 2.5 km in extent. This portion of the lobe is truncated to the west by a km-scale, approximately north–south-trending fault that displaces the lower portion of the lobe to the west. The lobe, along with the rest of the heterogeneous zone and granite zone, has been moderately tilted to the east-northeast (Fig. 1) (Coiner et al., 2003; Harper et al., 2004). The mafic lobe was mapped on a 1:6000 scale because of the great compositional and textural heterogeneity present among the exposed units of the heterogeneous zone (Fig. 4). Units

Figure 3. Map of the Aztec Wash pluton detailing units of the granite zone (GZ) (modified from Harper et al., 2004). Boxed region indicates approximate extent of heterogeneous zone (HZ) mafic lobe examined in this study.

Figure 4. Map showing heterogeneous zone and granite zone units and field relationships. Region to the east of the area mapped in this study were mapped by Koteas et al. (2003) at a scale of 1:12,000. In eastern region, greater outcrop areas of intermediate rocks are present than in area shown; general geologic relations are otherwise similar.

GZ FELSIC ☐ COARSE-GRAINED GRANITE ☐ MEDIUM- TO FINE-GRAINED GRANITE	
HZ FELSIC ☒ FINE-GRAINED GRANITE: Locally contains sparse, randomly oriented, 3-7 mm feldspar phenocrysts.	
HZ INTERMEDIATE ☐ FINE- TO MEDIUM-GRAINED QUARTZ MONZONITE: ranges from texturally and compositionally homogeneous and essentially aphyric to containing abundant ~1 mm bladed biotite crystals ☐ FINE-GRAINED QUARTZ MONZONITE: 3-10 mm feldspar phenocrysts present as individual, randomly oriented crystals or as cm to 0.5 m seams and lenses ☐ FINE-GRAINED QUARTZ MONZONITE: abundant 3-10 mm feldspars, 2-3 mm biotite phenocrysts, and 0.5 to 3 cm mafic enclaves. ☐ COARSE-GRAINED MONZONITE-QUARTZ MONZONITE: 3-10 mm subhedral to euhedral K-feldspar and plagioclase that form a closely-packed, touching framework. Rapakivi K-feldspars are present in low to high concentrations. 10-15% biotite and minor hornblende is present. Unit locally has 1-3 cm aggregates of acicular hornblende and/or bladed biotite. Fine-grained cm-scale mafic enclaves are locally present. ☐ HETEROGENEOUS MONZODIORITE-QUARTZ MONZODIORITE: fine-grained with up to 5% feldspar, hornblende, and/or biotite phenocrysts. Plagioclase phenocrysts are 3-10 mm in size and may have hornblende coronas. Biotite phenocrysts are elongate and bladed to skeletal or euhedral 3-5 mm crystals that cluster in aggregates. Hornblende phenocrysts range from acicular to more equidimensional 3-7 mm euhedral crystals. Fine-grained cm-scale mafic enclaves are locally present. ☒ MONZODIORITE-QUARTZ MONZODIORITE: medium- to fine-grained and compositionally and texturally homogeneous	
HZ MAFIC ☐ TRACHYBASALT: clinopyroxene, hornblende, and plagioclase, with local biotite and acicular apatite ☐ HORNBLende GABBRO: euhedral to subhedral 2-5 mm clinopyroxene and hornblende, 1-3 mm plagioclase, local biotite and accessory apatite and sphene. Layered to massive. ☒ HORNBLende TROCTOLITE-OLIVINE GABBRO: abundant olivine and hornblende, with variable concentrations of orthopyroxene and minor clinopyroxene and plagioclase	

STRUCTURAL ORIENTATIONS <div style="margin-bottom: 5px;"> ☒ mineral layering in gabbro </div> <div style="margin-bottom: 5px;"> ☒ sheet orientation </div> <div style="margin-bottom: 5px;"> ☐ pipe </div> <div> ☒ brittle fault </div>	MAP SYMBOLS <div style="margin-bottom: 5px;"> ☐ concentration of mafic enclaves </div> <div style="margin-bottom: 5px;"> ☒ solidified felsic blocks </div> <div> ☐ pipe locale </div>
--	---

SHEET COHERENCY	
highly coherent	
☒ coherent	
☐ incoherent	

Figure 4. (Continued)

within the heterogeneous zone span a continuum from hornblende troctolite to granite. The maximum compositional gap between successive units is no greater than 2.2 wt % SiO_2 . These units are described briefly in Figure 4, and in greater detail in Results.

The mafic lobes of the heterogeneous zone are constructed of a series of mafic sheets of variable composition and felsic interlayers of variable composition capped by coarse-grained, quartz-poor granite of the granite zone (Figs. 3–5). The mafic sheets of the lowermost lobe, examined in this study, range from 0.25 m to no more than 4 m in thickness. The sheets at the southern end of the lobe and nearest the base of the lobe have average strikes ranging from $325\text{--}335^\circ$ and average dips ranging from $35\text{--}45^\circ$ to the northeast. This general orientation of sheets is similar to that seen at structurally higher levels in the southern region. With movement north, and with increasing stratigraphic height, the majority of sheet strikes swing to the northeast and eventually establish more north-south orientations. The best “way-up” indicators are provided by granitic pipes, which are discussed in detail below (Wiebe and Collins, 1998; Wiebe et al., 2002, 2004), and are generally oriented perpendicular to mafic sheets. These field relationships are thus consistent with eastward tilting of sheets that were initially intruded horizontally at the base of a magma reservoir. The stacked sheets reach stratigraphic thicknesses of tens of meters, and are variable in texture, composition, and coherency on all scales. Structurally higher mafic lobes (Fig. 3) contain mafic sheets that are vertically oriented to slightly overturned (Koteas et al., 2003). The sheets in the lobe mapped in this study are divided into highly coherent, coherent, and incoherent sequences based upon their lateral and vertical coherency (Figs. 4–5). Each 10–30 m-thick sequence is composed of

Figure 5. Schematic representation of map area (compare with Fig. 4). Note that the most mafic and coherent sheets occur at the structurally deepest levels of the pluton.

stacked mafic sheets with felsic interlayers. Sheets have the highest degree of coherency to the south, and disaggregate to the north into coarse-grained quartz monzonite and coarse-grained, quartz-poor granite. Sheet coherency also tends to decrease with upward stratigraphic position.

Mafic sheets and felsic interlayers may be composed of trachybasalt with coarse-grained monzonite to quartz monzonite, coarse-grained hornblende gabbro with coarse-grained monzonite to quartz monzonite, or fine- to medium-grained monzodiorite to quartz monzodiorite with interlayers of coarse- to fine-grained quartz monzonite variants. Lateral and vertical compositional and textural variations are prevalent. Thicknesses of felsic interlayers range from < 1 cm–1 m.

Highly Coherent Sheeted Sequences

Sheeted sequences described as highly coherent are primarily composed of trachybasalt sheets with coarse-grained monzonite to quartz monzonite interlayers (Fig. 6). They have a planar geometry, sharp contacts, and are the most laterally continuous of the sheeted sequences. The mafic sheets in highly coherent sequences are generally 0.5–1 m thick and commonly exhibit pillowed, quenched bases and tops (Fig. 7). Flame and load-cast structures are prevalent. The sheets are fine-grained at the margins and coarsen slightly toward the sheet interior. Monzonite interlayers are generally on the order of 2–15 cm thick. Quenched mafic material is commonly molded around plagioclase and K-feldspars in the monzonite, and some sheets contain sparse, randomly oriented 3–10 mm-long plagioclase and K-feldspar phenocrysts. At the boundary between mafic and felsic

Figure 6. Highly coherent mafic-felsic sheeted sequences. Sequences are composed of 0.5–1 m-thick trachybasalt sheets with 2–15 cm-thick, coarse-grained monzonite interlayers.

Figure 7. (A) Detail of mafic-felsic sheeted sequence. Note pillowed mafic layers with crenulate margins and flame structures. Hammer is 39 cm long. (B) Detail of pillowed mafic sheet showing 1–5 cm thick felsic selvages. Pen is 15 cm long.

interlayers, the trachybasalt sheets locally exhibit fine-grained, 1–3 cm-thick felsic selvages (Fig. 7B).

Pillowed trachybasalts and fine-grained monzodiorites that are 0.5–5 m in diameter are present at the northern tips of mafic sheets. At this location, the mafic sheets come into contact with GZ coarse-grained granite. Mafic pillows are also present within intermediate rock throughout the lobe. Basaltic pillows typically have quenched, fine-grained rims and coarsen toward the interior. Margins may be crenulate or rounded. Mafic pillows are commonly of the same composition as the nearby mafic sheets. They are surrounded by coarse-grained granite or fine-grained quartz monzonite that locally contains abundant large (3–10 mm long) feldspars. Some pillows contain large feldspar phenocrysts as well (Fig. 8). The pillows may be surrounded by 1–5 cm-thick felsic selvages containing clusters of euhedral and/or tabular biotite. In rare instances, the tips of the mafic sheets form uniformly fine-grained, feathery splays that finger into the granite. They have quenched margins, and the ends of the splays are molded around individual plagioclase and K-feldspar crystals (Fig. 9).

Coherent Sheeted Sequences

Mafic sheets in coherent sequences may be composed of trachybasalt, hornblende gabbro, or fine- to medium-grained monzodiorite to quartz monzodiorite. The sheets may contain randomly oriented, conspicuously larger plagioclase and K-feldspars. Mafic sheet thicknesses range from approximately 0.5–5 m. Both bases and tops of thinner, more fine-grained mafic sheets may have finely crenulate margins and sharp contacts.

Figure 8. Mafic pillows in a matrix of coarse-grained granite at the northernmost end of the mafic lobe. Pillow margins exhibit crenulate and angular textures. Pillows locally contain sparse, 3–10 mm-long feldspar phenocrysts, examples of which are denoted by arrows. Notebook is 19 x 12.5 cm.

A

B

Figure 9. (A) Isolated, uniformly fine-grained mafic sheet tip in coarse-grained granite at northern end of heterogeneous zone lobe. Pencil is 15 cm long. (B) Detail of sheet tip highlighting dendritic textures and molding of basalt around individual plagioclase and K-feldspar grains.

Flame and load-cast structures are common at the bases. The bases of some mafic sheets cut obliquely across the intermediate or felsic layers of underlying gradational sequences at angles of 20–40°. Sheets greater than 1 m thick commonly exhibit chilled bases and gradational tops. The tops grade upward into fine- to medium-grained intermediate rock or are in sharp contact with coarse-grained monzonite or quartz monzonite. Hornblende gabbros with mineral-defined layering are locally present in thicker, coarse-grained mafic sheets (Fig. 10). Thicker sheets composed of coarse-grained gabbro may also contain 10–20 cm-diameter pockets and 10–30 cm-long seams of felsic material (Fig. 11). Contacts between coarse-grained gabbro and intermediate material commonly have 1–5 cm-wide gradational zones with abundant acicular hornblende and biotite, or aggregates of biotite or hornblende at the interface between the mafic sheet and the overlying interlayer. Sphene is often abundant. Large (3–7 mm long), euhedral hornblende or biotite phenocrysts locally form well-developed, planar schlieren bands in some monzodiorite sheets (Fig. 12). These bands are present at the contact between mafic sheets and felsic interlayers within stacked sequences, and are broadly parallel to the strike and dip of the mafic-felsic layers.

The felsic interlayers of coherent sheeted sequences may be composed of coarse-grained monzonite to quartz monzonite or of fine-grained quartz monzonite with up to 15% porphyritic plagioclase and K-feldspar phenocrysts. Coarse-grained monzonite to quartz monzonite interlayers are ~3–20 cm thick. They may contain ~1 cm-diameter fine-grained mafic enclaves and commonly have relatively high concentrations of hornblende and biotite (Fig. 13). The highest concentrations of mafic minerals are

Figure 10. Mineral layering in hornblende gabbro sheet component of mafic-felsic sheeted sequence. Hornblende crystals are 2–5 mm in diameter. Hammer is 39 cm long.

Figure 11. (A) Seams and pockets of felsic material in coarse-grained gabbro. Chisel is 16 cm long. (B) Same as (A). Pen is 14 cm long.

Figure 12. Hornblende-defined schlieren in monzodiorite layer. Lateral extent of layers ranges up to 25 m. Notebook is 19 x 12.5 cm. Hornblende crystals are euhedral and 3–7 mm in length.

Figure 13. Hand sample of coarse-grained, feldspar-rich monzonite with 1–3 cm-diameter aggregates of elongate to acicular hornblende.

typically found along contacts between the felsic and mafic interlayers. Felsic interlayers are laterally continuous (50–200 m) to discontinuous (5–20 m), and are more likely to be discontinuous when sheets are thicker and coarse-grained.

As coherency decreases, sheets may disaggregate into fine-grained mafic to intermediate sheets and blobs within a matrix of fine- to coarse-grained felsic material. In general, coherency decreases at higher structural/stratigraphic levels. However, coherent mafic sheets are still found at higher levels within the lobe and may be present above blob-like and disaggregated sheets. Both mafic sheets and felsic interlayers generally have thicknesses of 1–2 m and are composed of fine- to medium-grained monzodiorite to quartz monzodiorite resting atop coarse-grained monzonite to quartz monzonite. Flame structures may be present at the sheet bases.

Incoherent Sheeted Sequences

Sequences defined as incoherent have limited lateral continuity or structural coherency and show much evidence for physical interaction with adjacent material. The mafic sheets in incoherent sequences are composed of medium-grained monzodiorite to fine-grained quartz monzonite with high to intermediate concentrations of mafic minerals. Felsic interlayers consist of coarse-grained quartz monzonite with lower concentrations of mafic minerals.

Sheets labeled as incoherent form coarse-grained, discontinuous mafic–intermediate sheets, blobs, or pillows in a matrix of more felsic, coarse-grained monzonite to quartz monzonite. Sheets are identified by thin (1–3 cm in width) but fairly

continuous felsic interlayers. Intact, compositionally discrete portions of incoherent sheets typically range from < 1–5 m in length, but the sheets that contain these compositionally discrete portions may be laterally traceable for distances of up to tens of meters. Incoherent sheets, cm-scale mafic blobs, and mafic pillows are disaggregated into, and are physically intermingled with, veins and lenses of coarse-grained monzonite to quartz monzonite. The greatest degree of disaggregation is found at the highest structural levels in the lobe, where sheets are highly discontinuous to absent. Where no definable sheet base is present, relict sheets may be identified by cm- to m-scale lenses of coarse-grained monzonite to quartz monzonite and cm-scale seams of plagioclase and potassium feldspar crystals within fine-grained quartz monzonite that can be traced for centimeters to several meters along strike. At the interface between the heterogeneous zone and the GZ coarse-grained granite, the fine-grained quartz monzonite may form small, discrete blobs within the granite, or larger masses that intermingle with the granite.

Quartz monzonite that contains abundant 3–10 mm-long plagioclase and potassium feldspars, 2–3 mm-long biotite phenocrysts, and 1–2 cm-diameter fine-grained mafic enclaves is most prominent toward the northern end of the lobe. This unit forms a 5–10 m thick, laterally continuous layer stratigraphically above the region where the tips of mafic sheets disaggregate into surrounding felsic material, and beneath the coarse-grained GZ granite that caps the lobe to the north. It is locally present as smaller, discrete lenses throughout the lobe. In areas where the quartz monzonite comes into contact with coarse-grained GZ granite, complex interactions are observed. The coarse-grained

granite may surround the quartz monzonite, isolating it into discrete pods; the quartz monzonite may surround the granite; or, the two may intertwine in convoluted patterns.

At the northern boundary between the heterogeneous zone and the GZ coarse-grained granite, lenses of fine-grained granite are found in association with the coarse-grained granite and the intermediate material. Contacts range from irregular and convoluted to sharp and planar. Locally, plagioclase and potassium feldspar crystals from the GZ coarse-grained granite have been incorporated into the fine-grained granite.

Pipes in Sheeted Sequences

Cylindrical to irregularly-shaped pipes 10–20 cm in diameter, with variable textures and compositions, protrude from underlying, more felsic material into overlying mafic material at structurally low levels within the lobe (Fig. 14). Pipes range from pegmatitic and silicic to coarse-grained and choked with subhedral to euhedral, 3–10 mm-long plagioclase and K-feldspars. The majority of pipes intrude coarse-grained hornblende gabbros and fine-grained trachybasalt to monzodiorite sheets and pillows. They most commonly intrude coarse-grained gabbro. The largest concentration of pipes (approximately 40) is found within a zone of coarse-grained hornblende gabbro ~10 m thick and 10–20 m in lateral extent at structurally deep levels within the pluton. Pipes are more commonly found in groups of 2–3 or 5–6 within mafic-silicic sheeted sequences. The majority of pipes are well-formed and cylindrical, but some have a blob-like and irregular form (Fig. 15). The blob-like, poorly formed pipes are commonly connected to silicic veins contemporaneous with the mafic sheets that form discontinuous, sinuous

Figure 14. (A) 10–20 cm-diameter pipes protruding through coarse-grained gabbro. Approximately 40 pipes intrude coarse-grained gabbro in the region and range from coarse-grained quartz monzonite to silicic pegmatite. (B) Detail of coarse-grained quartz monzonite pipe, ~10 cm in diameter, intruding coarse-grained gabbro. Pen is 14 cm long.

Figure 15. (A) Poorly-formed pegmatitic pipes intruding gabbro. Notebook is 19 x 12.5 cm. (B) Same as (A). Pen is 14 cm long.

ribbons through the mafic material (Fig. 16). Pipes are also found at the northern end of the lobe, where they intrude pillowed trachybasalt and monzodiorite. Contacts between the pipes and surrounding mafic material vary from abrupt, with no apparent interaction between the two materials, to having 1–3 cm-thick reaction zones surrounding the pipes. These zones commonly contain concentrations of mafic minerals, felsic minerals, biotite, and/or acicular hornblende.

Mafic Enclaves

Mafic enclaves are pervasive throughout the heterogeneous zone. Two general size divisions can be made: small (5 mm–5 cm diameter), and large (10 cm–1 m diameter). Small enclaves are composed of basalt or diorite and are found throughout the GZ felsic and intermediate units. Large enclaves are also basaltic to dioritic in composition. They may be randomly dispersed, or form clusters within fine-grained felsic or intermediate rock or coarse-grained granite. Margins are most commonly rounded, but may also be crenulate or angular. Felsic selvages 1–3 cm wide are common around large enclaves and many contain fine-grained, acicular hornblende and/or bladed biotite that concentrate near the margins. Larger enclaves are typically fine-grained at the margins and coarsen toward the interior. They may contain large (3–10 mm) plagioclase or K-feldspar phenocrysts, particularly when they are in close association with coarse-grained monzonite or coarse-grained granite (Fig. 17).

A wide variety of enclaves of variable texture and composition is observed throughout the field area. Mafic enclaves are typically found within masses of

Figure 16. (A) Poorly-formed pipes interconnected with silicic veins in mafic interlayer of mafic-felsic sheeted sequence. Arrows indicate location of interconnected pipes. Notebook is 19 x 12.5 cm. (B) Detail of synplutonic silicic veins. Veins have convoluted patterns and may exhibit cross-cutting relationships.

Figure 17. Large, ~0.5 m diameter, mafic enclave (SAW19) with 3–10 cm-long plagioclase and K-feldspar phenocrysts in a matrix of coarse-grained monzodiorite with mm-scale acicular hornblende and bladed biotite. The enclave is located structurally above a layer of coarse-grained, layered hornblende gabbro. Pen is 14 cm long.

intermediate to felsic units. In many instances, small enclaves are closely associated with larger, variably disaggregated mafic blobs that range from diorite to gabbro in composition. In one such case, a fine-grained diorite blob shows evidence for disaggregation into a coarse-grained quartz monzonite in the form of small (~1 cm diameter), fine-grained mafic enclaves within the quartz monzonite. Enclaves interpreted to be in close proximity to their source region (Fig. 17) are typically located less than a few meters from mafic or intermediate rocks with textures and compositions very similar to the enclaves. In other cases, concentrations of enclaves are not in close proximity to any mapped or exposed larger mafic mass.

Intermediate and Felsic Enclaves

Light gray enclaves with compositions slightly more mafic than that of the host are widespread throughout the granite zone. The enclaves are aphanitic to very fine-grained phaneritic. The majority are porphyritic, with plagioclase, K-feldspar, and/or biotite phenocrysts. They are generally ~2–10 cm in diameter, but may reach maximum dimensions of several meters in diameter (Harper et al., 2004).

Isolated Mafic–Ultramafic Pods

Isolated, 10–15 m-diameter pods of coarse-grained rock ranging in composition from hornblende troctolite to olivine gabbro are locally present at varying levels within the heterogeneous zone lobe (Fig. 4). These mafic to ultramafic units are much richer in mafic minerals than the gabbros elsewhere in the lobe. The pods are surrounded by

coarse-grained granite or by intermediate rock of varying composition and texture. Sharp margins mark all contacts between the mafic rock and surrounding units.

“Clasts” of Intermediate Rock

Chaotic zones containing cm- to m-scale “clasts” of texturally and compositionally distinct rock in a matrix of coarse-grained GZ granite are in the granite zone near the contact with the heterogeneous zone (Fig. 4). The clasts are fine-grained and compositionally similar to intermediate units in the heterogeneous zone. They have angular to rounded margins and are blocky to rectangular in shape. These clasts are distinguished from the felsic enclaves found elsewhere in the granite zone by their composition, shape, and angular margins. Clasts of varying size concentrate in zones that resemble sedimentary breccias. The breccia zones are 2–20 m wide, and range from clast-supported to matrix-supported (Fig. 18).

Figure 18. Fine-grained clasts (1–1.5 m diameter) of intermediate composition in GZ coarse-grained granite located near the boundary between the heterogeneous zone and granite zone. Pencil is 14 cm long.

ANALYTICAL METHODS

The new data presented in this study were obtained from the upper portion of the lowermost heterogeneous zone (HZ) mafic lobe and from varying locations within the granite zone (GZ). This study also includes pre-existing data for the Aztec Wash pluton, some of which have been published previously (e.g., Falkner et al., 1995; Harper et al., 2004). The new isotopic analyses in this study were conducted by the author at the University of California, Santa Cruz. All other new geochemical analyses were conducted at Washington State University.

Petrography

In this study, thin sections were cut and mounted for 21 samples from the upper portion of the lowermost lobe of the heterogeneous zone and from the granite zone to the north and east of the lobe (Fig. 4). All thin sections were examined for texture and mineralogy. Mineral modal percentages were estimated for all samples.

Major and Trace Element Geochemistry

Fifty-seven samples from the granite zone and heterogeneous zone have been analyzed for major and trace elements, including 21 new major and trace element analyses conducted at the GeoAnalytical Lab at Washington State University. Weathered exterior surfaces of whole rock samples were removed using a hammer and saw. Each sample was jaw crushed. The major elements and some trace elements were analyzed

using X-ray fluorescence spectrometry (XRF). Analytical errors are $< 0.2\%$ for major elements and < 12 ppm for trace elements analyzed using XRF (Johnson et al., 1999). The rare earth elements and all other trace elements were analyzed using inductively coupled plasma mass spectrometry (ICP-MS). Analytical errors are < 0.045 ppm for rare earth elements and < 0.259 ppm for trace elements analyzed using ICP-MS (Knaack et al., 1994). Replicate analyses on splits of the same sample yield results well within the quoted uncertainty.

Isotope Geochemistry

In total, 35 samples from the Aztec Wash pluton have been analyzed for Sr isotopes, including 21 samples from selected units of the granite zone (GZ) and heterogeneous zone (HZ) that were analyzed during the course of this study. Thirty samples have been analyzed for Nd isotopes, including 21 GZ and HZ samples analyzed in this study. Twenty-eight samples have been analyzed for Pb isotopes, including 20 GZ and HZ samples analyzed in this study. Whole rock powders were used for isotopic analysis. Weathered exterior surfaces of whole rock samples were removed using a hammer and saw. Each sample was jaw crushed and powdered in an alumina ceramic shatterbox. Isotopic analysis was performed at the University of California, Santa Cruz.

Teflon bombs used for sample digestion were cleaned in baths of detergent, HCl, and HNO₃ using trace metal grade acids, and then cleaned in the oven with 24M HF and 7–8M HNO₃. Following cleaning, 100 mg of powdered sample were loaded into each bomb. Prior petrographic analysis determined the presence of calcite in some samples.

These samples were soaked in a bath of 0.25M HCl to dissolve the calcite. Following calcite removal, 4 ml of concentrated HF and 0.5 ml of concentrated HNO₃ were added to each sample, and the sample was placed on a hot plate for open digestion until dry. Four ml of HF and 0.5 ml of HNO₃ were added to the dried powder, and the sample was bombed in the oven for 4–5 days. Upon removal, the sample was dried on the hot plate, taken up in 6 ml of 6M HCl, and rebombed in the oven for 12–24 hours. The sample was then transferred to a Savillex vial cleaned by soaking in detergent, HCl, and HNO₃, and dried on the hot plate in preparation for cation exchange columns.

One ml of 1M HBr was added to each sample for Pb column chemistry. Teflon Pb columns with 250 µl of AG1-x8 anion resin were used for Pb separation. Samples were loaded and other elements removed using 1M HBr. Pb was collected in 6M HCl.

Glass columns with 8 ml AG50-8x cation resin were used for Sr collection. Samples were loaded and Sr was collected in 2.5M HCl. Rare earth elements were collected in 6M HCl. Nd was collected using 3 ml HDEHP resin (Ln-Spec) in glass columns. Samples were loaded and Nd was collected in 0.25M HCl.

Pb, Sr, and Nd analysis was performed on a VG Sector 54 Thermal Ionization Mass Spectrometer (TIMS) equipped with nine Faraday collectors. Samples were analyzed for Pb on the TIMS in static mode. Samples of > 200 ng Pb were loaded with silica gel and H₃PO₄ onto single Re filaments. Uncorrected results for NBS 981 during 2003–2004 are: $^{206}\text{Pb}/^{204}\text{Pb} = 16.896 \pm 0.056$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.438 \pm 0.049$, and $^{208}\text{Pb}/^{204}\text{Pb} = 36.537 \pm 0.151$ (2σ external reproducibility). The mass fractionation

correction applied to unknowns based on standards is 1.0 ± 0.1 per mil per amu. Total processing blanks, including column chemistry, were < 150 pg Pb.

Sr measurements were made on the TIMS in dynamic mode, with ^{88}Sr beams of 2–3 V. Samples of 100–500 ng Sr were loaded with a Ta activator onto single Re filaments. Typical internal error (2 std error) was < 0.00001 for 100 ratios. Data were corrected for internal mass bias to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$. Correction was made for ^{87}Rb interference by monitoring ^{85}Rb and assuming $^{85}\text{Rb}/^{87}\text{Rb} = 2.5926$. Results were normalized to 0.710250. Results from mid-2003 onward for NBS 987 were 0.710229 ± 23 (2σ external reproducibility). Total processing blanks, including column chemistry, were < 300 pg.

Nd measurements were made on the TIMS in dynamic mode. Samples of 100–500 ng Nd were loaded with H_3PO_4 onto side Re filaments and were run using triple Re filaments. Samples yielded ^{144}Nd beams of 0.5–2 V and unnormalized $^{146}\text{Nd}/^{144}\text{Nd}$ ratios of 0.721–0.723. Typical internal error (2 std error) was < 0.000015 for 150 ratios. Data were corrected for internal mass bias to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. Correction was made for ^{143}Sm interference by monitoring ^{147}Sm and assuming $^{144}\text{Sm}/^{147}\text{Sm} = 0.20637$. Results for La Jolla during 2004 were 0.511851 ± 0.000009 (2σ external reproducibility). $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{145}\text{Nd}/^{144}\text{Nd}$ were found to be too low in unknowns when Ba was present; consequently, ^{138}Ba and $^{145}\text{Nd}/^{144}\text{Nd}$ were monitored, and results were not accepted unless $145/155 = 0.34840\text{--}41$. Total processing blanks, including column chemistry were < 300 pg.

RESULTS

Petrography

Broad modal comparisons of heterogeneous zone (HZ) units and selected granite zone (GZ) units are given in Table 1. This table also documents textural variations within the units. The discussion that follows emphasizes features that are distinctive within the units.

Mafic–Ultramafic Units of the Heterogeneous Zone

The most mafic rocks of the heterogeneous zone are coarse-grained, hornblende-rich troctolites and olivine gabbros. A characteristic feature of the mafic-ultramafic units is the presence of abundant olivine. Olivine crystals are subhedral to euhedral, and are commonly enclosed by anhedral hornblende (Fig. 19). Plagioclase is enclosed by hornblende as well. Locally, hornblende is partially replaced by biotite. Plagioclase is typically anhedral, although some prismatic grains are present.

Mafic Units of the Heterogeneous Zone

Mafic units range from coarse-grained hornblende gabbros to trachybasalts. In contrast to the hornblende troctolites and olivine gabbros that comprise the mafic-ultramafic unit, mafic units have minor to no olivine. Clinopyroxene in hornblende gabbros is subhedral with corroded margins; in many cases it has been partially replaced by hornblende and/or biotite. Hornblende is subhedral to anhedral, and locally has been

TABLE 1. MODES AND TEXTURAL VARIABILITY OF HETEROGENEOUS ZONE (HZ) AND GRANITE ZONE (GZ) UNITS.

	Troctolite/ olivine gabbro	Hornblende gabbro	Trachybasalt	Monzodiorite- quartz monzodiorite	CG monzonite- quartz monzonite	Pipes	FG- to MG- quartz monzonite	CG GZ granite	FG HZ granite
Quartz	-	<1	<1	<1	5-10	<1	10-15	15-20	25-30
K-feldspar	-	<1	<3	10-15	30-35	35-60	25	35-40	40-45
Plagioclase	10	30-35	30	35-45	40-45	35-60	35	30-35	20-25
Biotite	<1	15-20	10-15	10-15	10-15	2-5	10-15	5	3-5
Hornblende	40	40-45	30-35	30-35	<3	-	0-3	<1	-
Clinopyroxene	<3	10	20-25	5	-	-	-	-	-
Orthopyroxene	<5	-	-	-	-	-	-	-	-
Olivine	50	<3	<3	-	-	-	-	-	-
Apatite	-	X	X	X	X	X	X	X	X
Sphene	X	X	X	X	X	X	X	X	X
Zircon	X	X	X	X	X	X	X	X	X
Opauques	X	X	X	X	X	-	X	X	X
Mantled quartz	-	-	-	X	X	-	-	-	-
Corroded plagioclase	-	-	-	-	X	-	X	-	-
Rapakivi K-feldspar	-	-	-	X	X	X	X	X	-
Mafic enclaves	-	-	-	-	X	-	X	-	-
Felsic enclaves	-	-	-	-	X	-	X	-	-
% phenocrysts	-	-	-	-	-	-	-	X	-
(aphyric-crystal-rich)	-	-	-	0-5	-	-	0-20	-	1-3
Bladed biotite/ acicular hornblende	-	-	X	X	X	X	X	-	-
Bladed plagioclase	-	-	X	-	-	-	-	-	-

Note: Modes are listed by percentage (e.g., 30-35), presence (X), or absence (-). CG = coarse-grained; MG = medium-grained; FG = fine-grained.

Figure 19. Olivine gabbro with hornblende (brown) enclosing subhedral to euhedral olivine.

partially replaced by biotite. The majority of plagioclase crystals are small (~1 mm), euhedral, and equant, although some larger (~3 mm), subhedral crystals are also present. Apatite forms tabular, subhedral to euhedral crystals and acicular needles.

Trachybasalts contain skeletal clinopyroxene or anhedral clinopyroxene that is commonly fine-grained and replaced by biotite and/or hornblende. Hornblende is anhedral and locally contains clinopyroxene cores. Plagioclase may be equant and zoned, but is generally bladed, euhedral to subhedral, ~1 mm or smaller, and not zoned. Bladed plagioclase frequently forms radial clusters or aggregates. Stubby to elongate tabular biotite is a minor constituent. K-feldspar is late and interstitial, and locally encloses earlier-formed minerals. Minor quartz is interstitial. Abundant apatite is prismatic to acicular, and locally forms radial splays.

Intermediate Units of the Heterogeneous Zone

Intermediate units cover a broad range of compositions and have textural variability on all scales. Units have been subdivided into four categories based upon commonalities in texture and composition, with each grouping representative of a continuum: monzodiorite to quartz monzodiorite, coarse-grained monzonite to quartz monzonite, coarse-grained quartz monzonite pipes, and heterogeneous fine- to medium-grained quartz monzonite of variable composition and texture.

Monzodiorites–Quartz Monzodiorites Monzodiorites are fine- to coarse-grained. They may be texturally and compositionally homogeneous, or may host phenocrysts of

plagioclase or K-feldspar, hornblende, and/or biotite in a fine- to medium-grained matrix (Fig. 20A). Plagioclase phenocrysts commonly have hornblende coronas (Fig 20B). Hornblende may be euhedral and up to ~3 mm in length, or acicular and up to 1 cm in length. Tabular crystals enclose plagioclase and clinopyroxene. Hornblende also replaces or locally mantles clinopyroxene. Biotite replaces hornblende and clinopyroxene, and is either bladed to skeletal, or euhedral and tabular. Clinopyroxene is anhedral and locally mantles quartz and plagioclase. Plagioclase may be euhedral, but is more commonly subhedral with irregular boundaries (Fig. 21). The majority of plagioclase is zoned. Abundant apatite forms stubby euhedral hexagonal crystals and acicular crystals. Anhedral poikilitic masses of K-feldspar enclose plagioclase, biotite, and sphene. Quartz is interstitial and locally forms granophyric textures with K-feldspar (Fig. 22).

Coarse-Grained Monzonites–Quartz Monzonites Coarse-grained monzonites–quartz monzonites contain euhedral to subhedral plagioclase 3–10 mm in size. Crystals may be zoned, and some exhibit anhedral cores and strong resorption textures. Inner zones are commonly rounded. Polysynthetic twins are common. K-feldspar is large (3–10 mm long) and is subhedral to anhedral. Microcline twins are common, and some crystals exhibit perthitic exsolution. Varying concentrations of rapakivi K-feldspars are present in the majority of monzonites–quartz monzonites (Fig. 23). Patchy intergrowths of K-feldspar, plagioclase, and quartz are locally present and exhibit myrmekitic or granophyric textures. Biotite is euhedral to subhedral and ranges from stubby and

Figure 20. (A) Coarse-grained monzodiorite (SAW18) with 3–10 mm-long plagioclase phenocrysts exhibiting hornblende coronas (denoted by arrows). Pen is 14 cm long. (B) Detail of plagioclase phenocrysts with hornblende coronas.

Figure 21. Irregular grain boundaries of subhedral plagioclase in monzodiorite. Note also larger plagioclase crystal at top of photomicrograph showing pronounced zoning.

Figure 22. Euhedral hornblende and granophyre in monzodiorite.

Figure 23. Rapakivi K-feldspars (3–10 mm) in coarse-grained monzonite. Concentrations of rapakivi K-feldspar are variable in the heterogeneous zone; high concentrations are present in this sample.

rectangular to elongate and bladed. Some crystals are skeletal and corroded, and some are bent or deformed around other grains (Fig. 24), but the rocks lack any other obvious evidence of subsolidus deformation. Hornblende is subhedral and skeletal to acicular. Clinopyroxene cores are locally present in hornblende. A small percentage of monzonites–quartz monzonites contain aggregates of acicular hornblende and/or bladed biotite 3–5 cm in diameter. Apatite is prismatic, and sphene and zircon are abundant. Coarse-grained monzonites–quartz monzonites locally contain ~1 cm-diameter mafic enclaves.

Coarse-Grained Quartz Monzonite Pipes Of the pipes discussed in Mapping and Field Relationships, two quartz monzonite pipes containing abundant coarse-grained feldspars were examined (Fig. 14). These pipes are composed primarily of K-feldspar and plagioclase in varying proportions accompanied by minor quartz, biotite, and accessory sphene and apatite. Plagioclase (~3–10 mm long) is euhedral to subhedral, has corroded margins, and is commonly zoned. Grains are patchy with numerous inclusions. K-feldspar is large (~3–10 mm long), subhedral to anhedral, and patchy and contain numerous plagioclase and quartz inclusions. Anhedral masses of K-feldspar enclose biotite and plagioclase. Biotite is subhedral and equant to skeletal and ranges from ~0.25–2 mm in length. Some crystals appear broken or kinked.

Heterogeneous Quartz Monzonites Fine- to medium-grained quartz monzonites exhibit a wide range of textures. They may be aphyric. Some are fine-grained, have

Figure 24. Kinked biotite in coarse-grained quartz monzonite.

1–3 mm-long hornblende phenocrysts, or contain up to 3 cm-diameter aggregates of bladed or euhedral biotite. They may contain sparse, randomly oriented plagioclase or K-feldspar phenocrysts (Fig. 25A), or cm-scale seams of 3–10 mm-long plagioclase and K-feldspar. The most heterogeneous variant consists of 10–15% plagioclase and K-feldspar phenocrysts (3–10 mm long), 5–10% biotite phenocrysts (2–3 mm long), and 5–10%, mafic enclaves (5 mm–1 cm diameter) in a fine-grained quartz monzonite groundmass (Fig. 25B). Feldspar phenocrysts within all fine- to medium-grained quartz monzonites are equant to rounded with corroded margins. K-feldspar is predominantly microcline and locally has plagioclase overgrowths (i.e., rapakivi). Subhedral to anhedral plagioclase phenocrysts may have anhedral cores and/or appear strongly resorbed (Fig. 26). Plagioclase in the matrix is small (< 1 mm long) and equant. Biotite is typically bladed; larger, equant phenocrysts (~2 mm) are less common. Quartz forms small grains and is interstitial. Abundant sphene forms euhedral and subhedral skeletal crystals. Apatite is equant to tabular.

Felsic Units of the Heterogeneous Zone and Granite Zone

Felsic units comprise coarse-grained GZ granites and fine-grained HZ granites. Coarse-grained granites contain 3–7 mm-long euhedral to subhedral K-feldspars. Rapakivi and granophyric textures are present, and microcline twinning and perthitic exsolution are common. Plagioclase is 3–7 mm long, euhedral to subhedral, and commonly zoned. Quartz is typically interstitial and may have a worm-like texture. Anhedral quartz is locally present. Biotite is equant to elongate and skeletal, and occurs

Figure 25. Representative hand samples of HZ fine- to medium-grained quartz monzonite variants. (A) Sample containing sparse plagioclase and K-feldspar phenocrysts. (B) Sample displaying abundant 3–10 mm-long plagioclase and K-feldspar phenocrysts, 2–3 mm-diameter biotite phenocrysts, and 0.5–3 cm-diameter mafic enclaves.

Figure 26. Anhedral plagioclase phenocryst in fine-grained quartz monzonite showing anhedral core and resorption features (e.g., abundant inclusions and patchy zoning).

as inclusions in K-feldspar and plagioclase. Abundant, euhedral to subhedral sphene locally forms clusters. Apatite typically forms small elongate grains, although some are stubby and subhedral.

Fine-grained granites are present at the boundary between the heterogeneous zone and granite zone. In these granites, K-feldspar (1–2 cm diameter) is subhedral to anhedral, and may poikilitically enclose biotite crystals. Subhedral crystals locally exhibit rapakivi texture. Granophyric texture is also present. Quartz forms anhedral grains. Plagioclase is subhedral and bladed. Biotite is small (1–2 mm long) and subhedral to anhedral or elongate and skeletal. Sphene and apatite are sparse. Zircons are small and equant.

Major and Trace Element Geochemistry

Samples from the heterogeneous zone (HZ) are divided into eight groups: mafic-ultramafic (42.7–46.4% SiO₂), mafic (49.7–51.6% SiO₂), monzodiorite-quartz monzodiorite (53.0–60.3% SiO₂), coarse-grained monzonite-quartz monzonite (55.4–64.8% SiO₂), quartz monzonite pipes (60.7–62.5% SiO₂), heterogeneous quartz monzonite (61.3–68.3% SiO₂), granite (69.6–70.3% SiO₂) (Tables 2–3). Large, km-scale, late, intermediate (66.2% SiO₂) and felsic (70.1–74.8% SiO₂) dikes cut the heterogeneous zone and the granite zone. Granite zone (GZ) samples are subdivided into five groups: felsic to intermediate enclaves (67.3–71.4% SiO₂), chilled border granite (69.7–73.2% SiO₂), coarse-grained, relatively quartz-poor granite (71.6–72.8% SiO₂), medium- to fine-grained granite (72.3–73.9% SiO₂), miarolitic leucogranite (76.3–76.7% SiO₂). Felsic, intermediate, and/or mafic samples from the heterogeneous zone and granite zone exhibit curvilinear trends for all major elements when plotted versus SiO₂ (Fig. 27). Trace element vs. SiO₂ trends are curvilinear as well, but exhibit considerably more scatter than do major element trends (Figs. 28–29).

Mafic-Ultramafic Units of the Heterogeneous Zone

The HZ olivine gabbro has high concentrations of transition metals (~1100 ppm Ni, ~2000 ppm Cr) (Table 2; Fig. 28). In all the analyzed troctolites and olivine gabbros, large ion lithophile elements (Rb, Sr, Ba) are more scattered than other elements, but Rb is uniformly < 30 ppm (Figs. 28–29). Chondrite-normalized rare earth element profiles exhibit fairly smooth, downward-sloping trends with gently sloping to flat heavy rare

TABLE 2. ANALYTICAL DATA FOR HETEROGENEOUS ZONE (HZ) UNITS.

Unit	Mafic- UM	Mafic- UM	Mafic- UM	Mafic- UM	Mafic- UM	Mafic- UM	Mafic	Mafic	Mafic	Mafic	Mafic
Sample	AW 500	AW 568	AW 152	SAW 09	AW 320	KH 108	SAW 17	SAW 52	SAW 04	SAW 19	AW 281
SiO ₂	42.7	44.0	44.1	44.8	46.0	46.4	49.7	50.3	50.4	51.3	51.6
Al ₂ O ₃	7.5	7.1	10	6.5	13.6	14.1	15.1	17.8	17.2	16.6	13.7
TiO ₂	0.9	0.9	0.9	0.8	0.8	1.5	1.6	1.2	2.1	1.9	1.2
FeO	13.8	13.3	14	12.6	11.1	12.9	10	6.9	9.9	9.7	9.6
MnO	0.18	0.17	0.18	0.19	0.16	0.19	0.17	0.12	0.18	0.2	0.14
CaO	3.9	4.2	6.2	4.0	7.1	9.3	8.4	11.6	7.4	7.7	9.3
MgO	28.3	27.6	22.2	28.6	17.9	12.4	9.4	7.4	5.5	6.3	9.2
K ₂ O	0.8	1.1	0.5	1	0.8	0.7	2	1.3	2.9	2	1.8
Na ₂ O	1.7	1.4	1.6	1.2	2.1	2.4	3.1	3.1	3.8	3.9	2.9
P ₂ O ₅	0.22	0.34	0.23	0.34	0.25	0.32	0.53	0.32	0.60	0.47	0.59
Rb	17	24	20	23	29	11	38	28	64	58	43
Sr	290	452	360	483	590	410	701	1296	790	790	876
Ba	224	642	250	611	410	280	659	579	941	499	890
Y				13		20	28	23	31	29	25
Zr	107	129	100	123	100	140	222	179	288	213	180
Cr				1932			180	247	39	45	200
Ni				1090			151	123	38	36	
Cu				23			48	71	43	18	
La	16	33		33		21	38	28	50	44	
Ce	33	66		63		45	76	58	96	75	
Pr	4	7		7			9	7	11	8	
Nd	15	28		29		23	38	31	44	33	
Sm	3	5		5		5	8	7	9	7	
Eu	1	1		1		2	2	2	2	2	
Gd	3	4		4			7	6	8	6	
Tb	0	1		1		1	1	1	1	1	
Dy	2	2		3			5	5	6	6	
Ho	0	0		0			1	1	1	1	
Er	1	1		1			3	2	3	3	
Yb	1	1		1		2	2	2	3	2	
Lu	0	0		0		0	0	0	0	0	
⁸⁷ Sr/ ⁸⁶ Sr _(i)							0.7078				0.7101
ε _{Nd}							-6.3				-9.9
²⁰⁶ Pb/ ²⁰⁴ Pb							18.54				
²⁰⁷ Pb/ ²⁰⁴ Pb							15.59				
²⁰⁸ Pb/ ²⁰⁴ Pb							38.85				

Notes: Mafic-UM = mafic-ultramafic hornblende troctolite to olivine gabbro. Mafic = hornblende gabbro to trachybasalt. SAW19 is a mafic enclave. MD-QMD = monzodiorite to quartz monzodiorite. CG M-QM = coarse-grained monzonite to quartz monzonite. Pipe = coarse-grained quartz monzonite pipe. H QM = heterogeneous fine- to medium-grained quartz monzonite variant. Textural variation ranges from uniform to fine-grained with feldspar phenocrysts, clusters of hornblende and/or biotite, and 1-2 cm-diameter, fine-grained mafic enclaves. Granite = fine- to medium-grained granite. Late dikes are large, km-scale dikes that cut both the HZ and GZ. TAW102A = felsic component of composite dike; SK46D

TABLE 2. (CONTINUED)

Unit	MD- QMD SAW	MD- QMD AW	MD- QMD AW	MD- QMD SAW	MD- QMD SAW	MD- QMD AW	MD- QMD SAW	MD- QMD SAW	CG M-QM TP	CG M-QM AW
Sample	11c	23B	3B	18	20	73B	15	16	5B	TG
SiO ₂	53.0	53.5	54.0	54.1	56.4	56.4	56.5	60.3	55.4	56.8
Al ₂ O ₃	17.4	16.3	15.3	17.6	17.5	16.8	17.5	18.9	16	19.4
TiO ₂	1.8	1.7	1.4	1.7	1.6	1.7	1.2	1	1.3	1.1
FeO	8.6	8.3	7.8	8.3	7.3	7.6	5.9	4.7	7.9	6.4
MnO	0.13	0.14	0.13	0.13	0.16	0.15	0.09	0.06	0.13	0.08
CaO	7.5	8	7.3	7.4	5.1	5.5	5.8	3.8	6.3	5.8
MgO	4	4.6	6.4	3.7	3.2	3.4	3.3	1.7	5.1	2.5
K ₂ O	2.2	3.1	3.3	2.2	3.6	3.5	4.6	4.2	3.6	2.8
Na ₂ O	4.3	3.5	3.5	4.2	4.4	4.1	4.1	5.0	3.4	4.7
P ₂ O ₅	1.1	0.81	0.76	0.6	0.84	0.83	1.01	0.41	0.98	0.44
Rb	49	72	100	50	71	89	89	77	100	63
Sr	1213	1250	1350	818	845	1360	1530	865	1070	1050
Ba	1312	1300	1600	953	1651	1900	1802	1701	2000	1300
Y	31	23	29	34	54	13	34	37		40
Zr	265	260	310	314	532	330	413	571	470	520
Cr	1	54	57	29	7		31	3		22
Ni	9	25	65	16	5		26	4		21
Cu	38	57	20	40	22		64	24		26.2
La	76	94	86	55	116		120	96		70.4
Ce	146	180	170	106	209		229	179		148
Pr	17	20	23	12	23		26	20		18
Nd	68	73	86	49	87		99	73		65.8
Sm	13	13	14	10	16	2	17	13		12.5
Eu	3	4	3	3	4		4	3		3.46
Gd	10	12	8	8	13		11	9		11.1
Tb	1	1	1	1	2		1	1		1.5
Dy	7	6	5	7	10		7	7		6.5
Ho	1	1	1	1	2		1	1		1.28
Er	3	3	2	3	5		3	3		3.3
Yb	2	2	2	3	5		2	3		3
Lu	0	0	0	0	1		0	0		0.45
⁸⁷ Sr/ ⁸⁶ Sr _(i)			0.7081	0.7079		0.7093		0.7084	0.7088	0.7090
ε _{Nd}			-7.6	-7.1				-8.2	-9.1	-9.4
²⁰⁶ Pb/ ²⁰⁴ Pb			18.26	18.42		18.15		18.34		
²⁰⁷ Pb/ ²⁰⁴ Pb			15.57	15.61		15.57		15.60		
²⁰⁸ Pb/ ²⁰⁴ Pb			38.90	38.97		38.79		38.94		

Notes: (Continued) and NAWZ13 = microgranite dike; TAW113 = rhyolite dike. Major element data are normalized on a 100 wt % volatile-free basis. All analytical totals for major element analyses in this table sum to > 97.3%, with the exception of SAW09, at 95.7%. ⁸⁷Sr/⁸⁶Sr_(i) and ε_{Nd} are age-corrected for 15.7 Ma. Pb ratios are uncorrected for in-situ decay.

TABLE 2. (CONTINUED)

Unit	CG M-QM	CG M-QM	CG M-QM	CG M-QM	Pipe	Pipe	H QM	H QM	H QM	H QM
Sample	IP 104A	NAWZ 16	SAW 22	SAW 21	SAW 13B	SAW 14	AW 02	SAW 23	AW 73C	SAW 12
SiO ₂	59.0	60.0	63.5	64.8	60.7	62.5	61.3	62.6	62.7	64.2
Al ₂ O ₃	18.9	19.1	18.5	18.5	19.7	19.8	17.1	17.3	16.3	17.3
TiO ₂	1	1	0.7	0.4	0.6	0.2	0.9	0.8	1	0.8
FeO	5.8	5.2	3.4	2.3	3.1	1	5.2	5	5.1	3.5
MnO	0.07	0.06	0.05	0.04	0.03	0.02	0.09	0.08	0.09	0.03
CaO	4.8	4.3	4.1	2.6	3	5.4	4.6	3.9	4.1	3.2
MgO	2.3	1.8	1.5	1	1.5	0.5	2.4	2.5	2.4	1.8
K ₂ O	3.3	2.8	3.4	5.2	4.8	1.7	3.6	3.6	4.1	4.0
Na ₂ O	4.5	5.3	4.7	4.9	6.3	8.8	4.3	3.8	3.9	4.8
P ₂ O ₅	0.41	0.32	0.23	0.15	0.27	0.02	0.37	0.34	0.34	0.34
Rb	100	58	75	64	93	32	88	87	96	81
Sr	1180	880	880	803	940	1419	1010	691	680	1058
Ba	1600	1146	1476	1996	1270	1009	1800	1741	1300	1661
Y		59	35	18	23	10	45	24	18	21
Zr	480	700	476	282	693	225	340	317	310	329
Cr			11	2	210		73	68		10
Ni			11	7	19	17		3		31
Cu			11	1	45	3		2		6
La		124	92	52	96	89	81	65		77
Ce		304	171	97	160	115	148	117		135
Pr		34	19	11	16	10	16	12		14
Nd		125	69	40	56	29	63	46		49
Sm		24	13	7	9	4	9	8		8
Eu		4	3	2	2	2	2	2		2
Gd		18	9	5	6	2	6	6		6
Tb		3	1	1	1	0	1	1		1
Dy		14	7	4	4	2	4	5		4
Ho		2	1	1	1	0	1	1		1
Er		6	3	2	2	1	2	2		2
Yb		5	3	1	2	1	2	2		2
Lu		1	0	0	0	0	0	0		0
⁸⁷ Sr/ ⁸⁶ Sr _(i)	0.7093	0.7089	0.7096		0.7083		0.7095	0.7097	0.7089	
ε _{Nd}	-9.5	-9.2	-11.0		-7.9		-11.3	-11.7	-10.0	
²⁰⁶ Pb/ ²⁰⁴ Pb		18.08	18.41		18.29		18.24	18.38	18.20	
²⁰⁷ Pb/ ²⁰⁴ Pb		15.55	15.65		15.56		15.57	15.60	15.57	
²⁰⁸ Pb/ ²⁰⁴ Pb		38.82	39.23		38.79		38.98	39.09	39.04	

TABLE 2. (CONTINUED)

Unit	H QM SAW 24	H QM JSAW 041	H QM AW 73D	Granite AW 38C	Granite AW 23A	Granite SAW 64	Late Dike TAW 102A	Late Dike SK 46D	Late Dike NAWZ 13	Late Dike TAW 113
SiO ₂	64.4	66.8	68.3	69.6	70.3	73.5	66.2	70.1	73.9	74.8
Al ₂ O ₃	16.8	16.7	15.9	15	15.2	14.3	15.7	15.5	14.3	13.8
TiO ₂	0.7	0.5	0.5	0.5	0.4	0.2	0.8	0.4	0.2	0.2
FeO	4.3	2.7	2.6	2.6	2.2	1.4	4.2	2.6	1.3	0.9
MnO	0.08	0.04	0.05	0.05	0.04	0.03	0.07	0.04	0.03	0.03
CaO	3.8	2.3	2.1	1.7	1.5	1.4	2.9	2.2	1.5	0.5
MgO	2	1	0.9	0.9	0.7	0.5	1.4	0.8	0.5	0.2
K ₂ O	3.7	5.6	5.2	5.6	5.4	5.0	4.4	4.5	4.4	5.7
Na ₂ O	3.8	4.3	4.5	3.8	4.1	3.5	3.8	3.7	3.8	3.9
P ₂ O ₅	0.29	0.17	0.15	0.16	0.11	0.07	0.34	0.14	0.06	0.02
Rb	86	139	127	140	142	137	103	109	129	183
Sr	629	578	570	530	410	381	554	486	417	158
Ba	1223	1675	1300	1200	1100	1453	1593	1508	1284	208
Y	22	25	14	20	12	15	26	15	14	10
Zr	294	305	270	270	240	147	322	196	124	181
Cr	120	9		51		2		5		30
Ni	25	9				7		7		13
Cu	57	8				3		10		8
La	68	102			73	46	62	50	37	54
Ce	113	166			126	76	121	91	63	79
Pr	11	16			11	7	12	8	7	5
Nd	41	55			42	25	46	29	22	15
Sm	7	9	4		6	4	8	5	4	2
Eu	2	2			1	1	2	1	1	0
Gd	6	6			6	3	6	4	3	1
Tb	1	1			1	0	1	0	0	0
Dy	4	5			3	3	5	3	2	1
Ho	1	1			1	1	1	0	0	0
Er	2	2			2	1	3	1	1	1
Yb	2	2			2	2	2	1	2	1
Lu	0	0			0	0	0	0	0	0
⁸⁷ Sr/ ⁸⁶ Sr _(i)			0.7097	0.7100			0.7097	0.7108	0.7112	0.7095
ϵ_{Nd}							-9.4	-13.5	-12.9	-9.3
²⁰⁶ Pb/ ²⁰⁴ Pb			18.15	18.05			18.16	17.83	18.09	18.05
²⁰⁷ Pb/ ²⁰⁴ Pb			15.56	15.55			15.54	15.51	15.60	15.50
²⁰⁸ Pb/ ²⁰⁴ Pb			38.86	38.93			38.89	38.57	39.36	38.70

TABLE 3. ANALYTICAL DATA FOR GRANITE ZONE (GZ) UNITS.

Unit	Enclave	Enclave	Enclave	Enclave	Border granite	Border granite	Border granite	CG granite	CG granite	CG granite
Sample	DAW 11	DAW 9	DAW 2	DAW 38	DAW 06	CAWZ 106	NAWZ 53	AW 13	HAW 5	SAW 63
SiO ₂	67.3	70.7	71.3	71.4	69.7	71.8	73.2	71.6	71.7	72.8
Al ₂ O ₃	14.7	15.4	14.7	14.9	15	14.5	14.1	14.5	14.6	14.4
TiO ₂	0.5	0.3	0.4	0.4	0.5	0.3	0.3	0.4	0.4	0.3
FeO	5.7	1.7	2.4	1.8	2.5	1.9	1.7	2.1	1.9	1.5
MnO	0.07	0.04	0.06	0.04	0.05	0.04	0.04	0.05	0.04	0.03
CaO	1.6	1.2	2	1.3	1.4	1.4	1.4	1.5	1.5	1.4
MgO	0.8	0.4	0.8	0.4	0.9	0.8	0.5	0.7	0.6	0.5
K ₂ O	5.2	5.8	4.1	5.4	6.7	5.5	5.2	4.8	5.1	5.3
Na ₂ O	4	4.4	4.2	4.2	3.1	3.5	3.4	4.2	4	3.7
P ₂ O ₅	0.19	0.06	0.12	0.17	0.13	0.09	0.07	0.1	0.11	0.08
Rb	148	187	144	138	205	152	154	153	149	142
Sr	324	299	366	318	390	325	331	380	300	299
Ba	1239	867	1092	919	1193	854	1321	870	830	807
Y	21	18	12	16	22	16	15	13	18	18
Zr	377	291	207	250	330	248	169	200	211	209
Cr		2	11	3	9	4		30	5	6
Ni		2	9	5	7	8		13	3	8
Cu		11	11	10	19			8		8
La	73	79	55	81	76	54	53	71	72	76
Ce	151	143	95	144	142	99	89	118	121	120
Pr	14	11	7	12	12	8	9	12	13	11
Nd	56	43	29	44	52	29	29	40	40	36
Sm	9	6	4	7	8	5	5	6	6	6
Eu	2	1	1	1	1	1	1	1	1	1
Gd	6	4	3	4	6	3	3	4	4	4
Tb	1	1	0	1	1	0	0	1	1	1
Dy	4	3	2	3	4	3	3	3	3	3
Ho	1	1	0	1	1	0	1	1	1	1
Er	2	2	1	2	2	2	2	2	2	2
Yb	2	2	2	2	2	2	2	2	2	2
Lu	0	0	0	0	0	0	0	0	0	0
⁸⁷ Sr/ ⁸⁶ Sr _(i)	0.7099	0.7089	0.7116	0.7092	0.7105	0.7105	0.7110	0.7101	0.7102	
ε _{Nd}	-10.3	-8.5	-14.5	-8.9	-11.3	-10.3	-13.2		-10.9	
²⁰⁶ Pb/ ²⁰⁴ Pb	18.10	18.19	17.96	18.21	17.99		17.94	18.13	18.18	
²⁰⁷ Pb/ ²⁰⁴ Pb	15.58	15.56	15.54	15.58	15.56		15.56	15.56	15.58	
²⁰⁸ Pb/ ²⁰⁴ Pb	39.12	38.87	38.79	39.06	39.15		39.10	38.89	38.96	

Notes: Enclave = felsic to intermediate enclaves in GZ granites. Border granite = aphanitic and porphyritic chilled margin granite. CG granite = coarse-grained, quartz-poor granite. MG-FG granite = medium- to fine-grained granites. Leucogranite = fine-grained miarolitic leucogranite. All major element data are normalized on a 100 wt % volatile-free basis. All analytical totals for major element analyses in this table sum to > 97.3%.

TABLE 3. (CONTINUED)

Unit	MG-FG Granite	MG-FG Granite	MG-FG Granite	MG-FG Granite	Leucogranite	Leucogranite
Sample	AW 04	SAW 00	AWZ 1A	NAWZ 50	AWZ 1B	NAWZ 26
SiO ₂	72.3	72.4	73.2	73.9	76.3	76.7
Al ₂ O ₃	14.1	14.1	13.9	13.7	12.7	12.8
TiO ₂	0.4	0.3	0.3	0.3	0.2	0.1
FeO	2.2	1.8	1.7	1.6	1.1	0.8
MnO	0.05	0.05	0.03	0.03	0.02	0.03
CaO	1.3	1.5	1.1	1	0.7	0.6
MgO	0.7	0.6	0.5	0.5	0.3	0.2
K ₂ O	4.8	5.6	5.6	5.6	5.4	5.1
Na ₂ O	4.1	3.5	3.5	3.4	3.3	3.7
P ₂ O ₅	0.09	0.09	0.07	0.07	0.04	0.02
Rb	143	175	178	206	185	206
Sr	280	286	206	180	85	45
Ba	700	799	580	540	240	121
Y	27	18	24	13	15	12
Zr	200	200	190	177	130	125
Cr		6	3		< 2	
Ni		6	4		2	
Cu		13	3.2		3.9	
La	78	54	57.2	61	45.4	42
Ce	130	97	105	96	68.3	64
Pr	13	10	11	9	5.9	6
Nd	42	33	33.8	29	15.5	15
Sm	6	6	5.5	4	2.1	2
Eu	1	1	1.06	1	0.441	0
Gd	4	4	4.9	3	2	1
Tb	1	1	0.7	0	0.3	0
Dy	3	3	2.8	2	1.2	2
Ho	1	1	0.56	0	0.27	0
Er	2	2	1.5	1	0.8	1
Yb	2	2	1.7	2	1.1	2
Lu	0	0	0.26	0	0.19	0
⁸⁷ Sr/ ⁸⁶ Sr _(i)	0.7102		0.7105	0.7104	0.7114	0.7111
ε _{Nd}	-10.1		-10.5	-9.0		-10.5
²⁰⁶ Pb/ ²⁰⁴ Pb	18.12			18.19		18.17
²⁰⁷ Pb/ ²⁰⁴ Pb	15.58			15.58		15.57
²⁰⁸ Pb/ ²⁰⁴ Pb	38.99			39.03		38.97

Figure 27. Major elements versus SiO_2 for heterogeneous zone (HZ) and granite zone (GZ) samples. (A) MgO, CaO, Al_2O_3 , and FeO vs. SiO_2 . (B) (see p. 65) K_2O , Na_2O , P_2O_5 , and TiO_2 vs. SiO_2 .

Figure 27. (Continued)

Figure 28. Plots of selected trace elements versus SiO_2 for heterogeneous zone (HZ) and granite zone (GZ) samples. (A) Rb, Ba, Sr, and Ce vs. SiO_2 . (B) (see p. 67) Zr, Y, Ni, and Cr vs. SiO_2 .

Figure 28. (Continued)

Figure 29. Plots of Ba, Rb, and Zr vs. Sr, and Zr vs. Ba for heterogeneous zone (HZ) and granite zone (GZ) samples.

earth element patterns (Fig. 30).

Mafic Units of the Heterogeneous Zone

Fine-grained trachybasalts and coarse-grained hornblende gabbros of the heterogeneous zone have approximately 50–52% SiO₂, 6–9% MgO, 7–10% FeO, 1–3% K₂O, and 14–18% Al₂O₃ (Fig. 27). With the exception of one outlier, Sr concentrations range from ~700–900 ppm. Ba concentrations (~500–900 ppm) show somewhat greater spread, as do Rb concentrations (~30–60 ppm) (Figs. 28–29). Chondrite-normalized rare earth element profiles for mafic samples exhibit smooth, gently sloping negative trends with moderate light rare earth element enrichment (Fig. 30). Some samples exhibit very slight negative Eu anomalies.

Intermediate Units of the Heterogeneous Zone

On plots of major elements vs. SiO₂, intermediate samples exhibit curvilinear trends (Fig. 27). Some scatter is present among samples containing high concentrations of P₂O₅ and the alkalis, suggesting control by accessory mineral accumulation (e.g., apatite). The range of trace element variability in intermediate rocks is particularly noteworthy, especially among feldspar compatible trace elements such as Ba and Sr (Figs. 28–29). A large group of HZ intermediate samples have highly elevated Ba (~1100–2000 ppm) and Sr (~800–1500 ppm) concentrations, and the majority of intermediate samples plot above all other heterogeneous zone and granite zone samples on plots of Ba vs. Sr (Fig. 29). Zr and Y concentrations are highly variable, and samples

Figure 30. (A) Chondrite-normalized rare earth element profiles for heterogeneous zone (HZ) mafic-ultramafic samples. (B) Chondrite-normalized rare earth element profiles for HZ mafic samples. Normalization to values of McDonough and Sun (1995).

with ~800–1200 ppm Sr and ~1100–1700 ppm Ba have high Zr concentrations of ~500–700 ppm. Samples of coarse-grained quartz monzonite trapped in pipes are outliers on the majority of major and trace element plots. The quartz monzonite pipes show considerable variation in trace element concentrations, as do the coarse-grained monzonites–quartz monzonites, suggesting strong control by accessory mineral accumulation. Chondrite-normalized rare earth element patterns for HZ intermediate samples broadly exhibit downward-sloping trends (Fig. 31). Again, the quartz monzonite pipes and coarse-grained monzonites–quartz monzonites exhibit the greatest amount of variation. The heterogeneous fine- to medium-grained quartz monzonite variants span a fairly narrow range of rare earth element concentrations. All samples show strong light rare earth element enrichment. One sample has a positive Eu anomaly; others have negative Eu anomalies. Heavy rare earth element profiles range from negatively sloping to flat to concave-upward.

Felsic Units of the Heterogeneous Zone and Granite Zone

Major elements for the felsic units are generally strongly linear, although alkali trends show some scatter (Fig. 27). Large ion lithophile concentrations (Ba, Sr, Rb) show a moderate amount of variation (Figs. 28–29). Chondrite-normalized rare earth element patterns for felsic samples exhibit strong light rare earth element enrichment (Figs. 32–33) and gently sloping to flat middle to heavy rare earth element patterns. The majority of samples exhibit slight negative Eu anomalies. The late rhyolite dike (Fig. 32) and the high-silica miarolitic granites (Fig. 33) display strong depletion in rare earth elements,

Figure 31. Chondrite-normalized rare earth element profiles for heterogeneous zone (HZ) intermediate samples. Normalization to values of McDonough and Sun (1995).

Figure 32. Chondrite-normalized rare earth element profiles for late dikes and granite zone (GZ) enclaves. Normalization to values of McDonough and Sun (1995).

Figure 33. Chondrite-normalized rare earth element profiles for granite zone (GZ) and heterogeneous zone (HZ) felsic samples. Normalization to values of McDonough and Sun (1995).

particularly Eu and the middle and heavy rare earth elements. They also have the lowest Ba and Sr concentrations and among the highest Rb concentrations in the data set. The late microgranite dikes plot near the GZ granites in major and trace element composition.

Whole-Rock Isotope Geochemistry

$^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ vs. SiO_2 and ϵ_{Nd} vs. SiO_2

Initial $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵ_{Nd} values are highly variable throughout the heterogeneous zone (HZ) and granite zone (GZ). Heterogeneous zone samples analyzed for isotopes range from 49.7–69.6% SiO_2 , $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ 0.7078–0.7101, and ϵ_{Nd} -6.3 to -11.7. Within the granite zone, analyzed samples range from 67.3–76.7% SiO_2 , $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ 0.7089–0.7116, and ϵ_{Nd} -8.5 to -14.5. Dikes cutting both the heterogeneous zone and granite zone range from 66.2–74.8% SiO_2 , $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ 0.7095–0.7112, and ϵ_{Nd} -9.3 to -13.5. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ values show a broadly positive correlation with increasing SiO_2 (Fig. 34). Epsilon Nd values exhibit a broadly negative correlation with increasing SiO_2 , and have a fan-shaped distribution in which felsic values show the most spread (Fig. 34).

The two hornblende gabbros analyzed have very different isotopic compositions (49.7% SiO_2 , $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ 0.7078, ϵ_{Nd} -6.3; 51.6% SiO_2 , $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ 0.7101, ϵ_{Nd} -9.9). The HZ intermediate samples (53.0–68.3% SiO_2) show a spread in $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ (0.7079–0.7097) comparable to that seen in the gabbros, but have a somewhat larger spread in ϵ_{Nd} (-7.1 to -11.7). The km-scale, late dikes cutting the heterogeneous zone and parts of the granite zone have highly variable isotopic compositions, as do the granite zone enclaves (67.3–71.4% SiO_2 , $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ 0.7089–0.7116, ϵ_{Nd} -8.5 to -14.5). Among the granite samples analyzed, the chilled border granites (69.7–73.2% SiO_2) exhibit notable variation in isotopic composition ($^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ 0.7105–0.7110, ϵ_{Nd} -10.3 to -13.2).

On a plot of $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ vs. SiO_2 , a broadly linear trend extends from the lowest- SiO_2 HZ hornblende gabbro to a group of felsic granite zone samples (Fig. 34); the other

Figure 34. $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$, ϵ_{Nd} , and $^{206}\text{Pb}/^{204}\text{Pb}$ vs. SiO_2 ; ϵ_{Nd} vs. $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$; $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ for granite zone (GZ) and heterogeneous zone (HZ) samples. Dashed lines on $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ indicate ranges for Mojave and Arizona basement rocks. Cross-hatched regions represent overlap in Mojave and Arizona ranges (Wooden et al., 1988).

analyzed gabbro falls distinctly off this trend. The group of felsic granite zone samples includes coarse- to fine-grained granites, chilled border granites, the two microgranite dikes, and the miarolitic leucogranites. The remaining dikes plot within the felsic scatter. On ϵ_{Nd} vs. SiO_2 , the low- SiO_2 hornblende gabbro marks the high- ϵ_{Nd} end of the loosely defined negative array, and the other gabbro again falls off the main trend of the data. The low- ϵ_{Nd} end is defined by the two microgranite dikes, one GZ chilled border granite, and one GZ enclave. The remaining GZ chilled border granites plot at higher ϵ_{Nd} values within a group of GZ felsic samples. The GZ miarolitic leucogranite, composite dike, and gray aphanitic dike also plot within this scatter of data at the high- SiO_2 end of the array. Granite zone medium- to fine-grained granites exhibit greater scatter on ϵ_{Nd} vs. SiO_2 than on $^{87}\text{Sr}/^{86}\text{Sr}_{(\text{i})}$ vs. SiO_2 . On $^{87}\text{Sr}/^{86}\text{Sr}_{(\text{i})}$ vs. SiO_2 , GZ enclaves exhibit considerable scatter, and only one sample plots within the trend. Two enclaves fall below, and one plots above. On ϵ_{Nd} vs. SiO_2 , three of the four GZ enclaves plot within the GZ felsic scatter above the scattered negative trend, and one plots near the GZ chilled border granites at the low- ϵ_{Nd} end of the array. Overall, granite zone samples exhibit greater spread than heterogeneous zone samples, and show a great deal of scatter on both $^{87}\text{Sr}/^{86}\text{Sr}_{(\text{i})}$ vs. SiO_2 and ϵ_{Nd} vs. SiO_2 .

On $^{87}\text{Sr}/^{86}\text{Sr}_{(\text{i})}$ vs. SiO_2 and ϵ_{Nd} vs. SiO_2 , HZ intermediate samples lie along the trend defined by the primitive hornblende gabbro and the group of GZ granites described above. Like the felsic samples, the intermediate samples exhibit significant scatter with SiO_2 , particularly among the HZ fine- to medium-grained quartz monzonites.

ϵ_{Nd} vs. $^{87}Sr/^{86}Sr_{(i)}$

Although some modest scatter is present, there is a well-developed negative correlation between ϵ_{Nd} and $^{87}Sr/^{86}Sr_{(i)}$ (Fig. 34). The low-SiO₂ end of the trend is defined by the low-SiO₂ HZ hornblende gabbro, which is followed by HZ fine- to coarse-grained monzodiorites and the coarse-grained quartz monzonite frozen as a pipe in the heterogeneous zone. Compared to the other samples in the data set, the monzodiorites in general plot at lower ϵ_{Nd} for a given $^{87}Sr/^{86}Sr_{(i)}$.

Four of the five HZ coarse-grained monzonites to quartz monzonites ($^{87}Sr/^{86}Sr_{(i)}$ 0.7088–0.7093, ϵ_{Nd} -9.1 to -9.5) cluster near each other; the fifth has comparatively higher $^{87}Sr/^{86}Sr_{(i)}$ (0.7096) and lower ϵ_{Nd} (-11.0). These samples, two of the four GZ enclaves, and the composite and gray aphanitic dikes plot at intermediate locations on the trend. Overall, GZ enclaves are widely distributed and form a negatively correlated linear array within the larger data set.

Granite zone coarse- to fine-grained granites cluster loosely together. They are similar in $^{87}Sr/^{86}Sr_{(i)}$ (0.7102–0.7105) but show greater spread in ϵ_{Nd} (-9.0 to -10.5). The higher-SiO₂ HZ hornblende gabbro plots near the GZ granites and near one GZ enclave, and covers over half the distance along the Sr–Nd array. Two chilled border granites plot near the GZ granite group. The remaining chilled border granite clusters with the two GZ microgranite dikes near the high- $^{87}Sr/^{86}Sr_{(i)}$, low- ϵ_{Nd} end of the spectrum. The highest $^{87}Sr/^{86}Sr_{(i)}$ and lowest ϵ_{Nd} end of the correlation is anchored by one GZ enclave.

$^{206}\text{Pb}/^{204}\text{Pb}$ vs. SiO_2

Samples broadly exhibit a negative correlation of $^{206}\text{Pb}/^{204}\text{Pb}$ with increasing silica content, but a fair amount of scatter is present, particularly toward the felsic end of the spectrum (Fig. 34). Heterogeneous zone samples range in $^{206}\text{Pb}/^{204}\text{Pb}$ from 18.05–18.54, and GZ samples from 17.94–18.21. Late dikes range from $^{206}\text{Pb}/^{204}\text{Pb}$ 17.85–18.16. Samples from the heterogeneous zone and granite zone overlap in $^{206}\text{Pb}/^{204}\text{Pb}$ composition, but the majority of heterogeneous zone samples lie toward the higher end of the $^{206}\text{Pb}/^{204}\text{Pb}$ spectrum, and the majority of granite zone samples toward the lower end of the spectrum. The end-members defining the loosely-established trend are the low-silica HZ hornblende gabbro and the GZ chilled border granites.

Heterogeneous zone monzodiorites group loosely together with a range of $^{206}\text{Pb}/^{204}\text{Pb}$ compositions ($^{206}\text{Pb}/^{204}\text{Pb}$ 18.15–18.42); the quartz monzonite pipe ($^{206}\text{Pb}/^{204}\text{Pb}$ 18.29) lies within this grouping. Heterogeneous zone monzonite to quartz monzonite samples plot far from each other and bound the intermediate samples, having concentrations slightly higher ($^{206}\text{Pb}/^{204}\text{Pb}$ 18.41) and slightly lower ($^{206}\text{Pb}/^{204}\text{Pb}$ 18.08) than the monzodiorites (Fig. 34).

Granite zone coarse-grained ($^{206}\text{Pb}/^{204}\text{Pb}$ 18.13–18.18) and fine- to medium-grained granites ($^{206}\text{Pb}/^{204}\text{Pb}$ 18.12–18.19) have similar $^{206}\text{Pb}/^{204}\text{Pb}$ values. These units, two GZ enclaves, the GZ miarolitic leucogranite, two dikes (one microgranite and one rhyolite), one HZ monzodiorite, and one HZ quartz monzonite, form an ovoid cluster that plots just above the GZ chilled border granites. The rhyolite dike plots within this loosely defined trend, and the other microgranite dike falls below the trend.

$^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$

Samples show a broad positive correlation between $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ (Fig. 34). Heterogeneous zone samples range in $^{207}\text{Pb}/^{204}\text{Pb}$ from 15.55–15.65. Granite zone samples range in $^{207}\text{Pb}/^{204}\text{Pb}$ from 15.54–15.58. Late dikes range from $^{207}\text{Pb}/^{204}\text{Pb}$ 15.50–15.60. Samples from the heterogeneous zone and granite zone thus show considerable overlap. Heterogeneous zone intermediate samples define an approximately linear array that exhibits a positive correlation between $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$. The remainder of heterogeneous zone samples shows a great deal of scatter: HZ monzonites to quartz monzonites generally plot far from each other, and the HZ hornblende gabbro lies off the trend.

Granite zone coarse-grained and fine- to medium-grained granites plot near each other, but show a greater spread in $^{207}\text{Pb}/^{204}\text{Pb}$ values than in $^{206}\text{Pb}/^{204}\text{Pb}$ values. Three of the four GZ enclaves and the GZ miarolitic leucogranite plot near the granites. The fourth GZ enclave plots more closely to the GZ chilled border granite samples than to the other GZ enclaves. The four dikes also show a good deal of scatter.

 $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$

Heterogeneous zone samples range in $^{208}\text{Pb}/^{204}\text{Pb}$ from 38.79–39.23, and GZ samples from 38.79–39.15. Late dikes range from $^{208}\text{Pb}/^{204}\text{Pb}$ 38.57–39.36. Samples plotted as $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ exhibit a great deal of scatter, and no discernable trends are present (Fig. 34).

DISCUSSION

In the manner presented by Wiebe et al. (1996), the Aztec Wash pluton is inferred to have grown incrementally by repeated injections of mafic and felsic magma (Robinson and Miller, 1999), and was constructed by the accumulation of magma pulses over time. Evidence for incremental construction is typically preserved in the compositional and isotopic variation of the rocks in the pluton (Wiebe, 1996; Reid, 2003). These variations are recorded in the vertical stratigraphy of the pluton. In a stratified magma reservoir, the recharge magma ascends to the liquid portion of the reservoir without mixing with resident material. Differing rates of recharge lead to different kinds of interactions between the intruding magma and the host. At low intrusion rates, repeated bimodal magma recharge develops sheeted, mafic-felsic sequences (Wiebe, 1996). High intrusion rates allow for greater chances of mixing and greater sustainability of liquid regimes in the magma reservoir (Reid, 2003).

This study examined a mafic lobe of the Aztec Wash pluton to determine the effects of repeated injections of mafic and felsic magmas, the evolution of the magmas, and how mechanical and chemical processes operated to produce the wide array of observed rock types and their corresponding highly heterogeneous geochemical and isotopic signatures. Previous work has suggested that the Aztec Wash pluton experienced closed-system fractionation of mafic and felsic magmas (Falkner et al., 1995; Harper et al., 2004), and the pluton also retains a chemical, textural, and structural record of open-system behavior (Falkner et al., 1995; Patrick and Miller, 1997; Robinson

and Miller, 1999; Miller and Miller, 2002; Cates et al., 2003; Coiner et al., 2003; Harper et al., 2003; Koteas et al., 2003; Miller et al., 2003; Harper et al., 2004). Complex processes of mingling and hybridization took place within the reservoir, and isotopic analyses conducted in this study confirm that open-system processes were active within both the heterogeneous zone (HZ) and granite zone (GZ) of the Aztec Wash pluton. Although previous work has served to elucidate much regarding reservoir processes, several outstanding issues remain: (1) To what degree and by what mechanisms did fractional crystallization of mafic magmas play a role in the physical and chemical evolution of Aztec Wash magmas, particularly the evolution of felsic and intermediate magmas present above the mafic magmas? (2) What chemical and mechanical processes were responsible for producing the textural variability and wide range of compositional intermediates (i.e., to what extent and by what mechanisms did hybridization processes occur)? (3) How “open” was the magma reservoir in terms of basaltic, and especially felsic, inputs (i.e., are felsic rocks derived primarily from input and subsequent fractionation of compositionally and isotopically uniform magma, or was the magma system fed by felsic inputs from multiple sources)? The new Sr, Nd, and Pb isotope data presented in this study place important constraints upon the open and closed system processes operating in the Aztec Wash magma reservoir, and necessitate the re-evaluation of existing models for reservoir evolution.

Mafic Input Magmas

Previous work has shown that parental mafic magmas for the Aztec Wash pluton are trachybasalts to basaltic trachyandesites ($\sim 48\text{--}53\%$ SiO_2 , $\sim 1.3\text{--}3\%$ K_2O , $\text{Mg} \# 0.5\text{--}0.65$) with enriched mantle trace element and isotopic signatures (Falkner et al., 1995; Coiner et al., 2003). Falkner et al. (1995) determined that parental mafic magmas are derived from enriched lithospheric mantle formed in the Early Proterozoic. Of the mafic samples analyzed in this study, hornblende gabbro SAW17 (50% SiO_2 , $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ 0.7078, $\epsilon_{\text{Nd}} -6.3$), located near the base of the reservoir, has an isotopic composition appropriate for a mafic input magma with an enriched mantle signature (Fig. 35). This signature is similar to the proposed mantle isotopic source seen regionally in eastern California (Miller et al., 2000). The Aztec Wash pluton shows no evidence of the asthenospheric sources recorded in similar or slightly younger plutons and volcanic rocks in western Arizona (Metcalf, 1995; Feuerbach et al., 1993). Heterogeneous zone hornblende gabbro AW281 has the highest $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ of any unit within the heterogeneous zone and has very negative ϵ_{Nd} for its given SiO_2 content, suggesting that this sample was contaminated by Pre-Cambrian rock (Fig. 35).

Felsic Input Magmas

Felsic input magmas for the Aztec Wash pluton are inferred to be low-silica rhyolites ($\sim 73\%$ SiO_2 , 5% K_2O , 1300 ppm Ba, 350 ppm Sr, 130 ppm Rb) (Coiner et al., 2003; Harper et al., 2003, 2004; Ericksen et al., 2004). The GZ chilled border granites are interpreted by Harper et al. (2004) as input magmas that locally quenched along the

Figure 35. Isotopic compositions of heterogeneous zone (HZ) and granite zone (GZ) samples plotted with mantle and crustal source compositions (modified from Falkner et al., 1995). SAW17 and AW281 are labeled to accompany more detailed information about these samples in the text.

margin during the early stages of pluton formation, prior to any felsic fractionation. These units generally have similar elemental compositions. The late microgranite and rhyolite dikes that cut the Aztec Wash pluton have elemental compositions similar to those of the chilled border granites, and are also interpreted to be input magmas that continued to be injected into the system following pluton solidification (Coiner et al., 2003; Falkner et al., 1995; Harper et al., 2004; Steinwinder et al., 2004). Rare earth element patterns for the GZ felsic enclaves are similar to those of the chilled border granites and dikes, and thus the enclaves also represent potential felsic input magmas (Harper et al., 2004).

Despite similar compositions of inferred felsic input magmas, the chilled border units, dikes, and enclaves exhibit significant spread in Sr, Nd, and Pb isotopic compositions, indicating that they either originated from multiple sources, or experienced post-input isotopic modification by open-system processes. A group of potential felsic inputs containing two late microgranite dikes, a GZ enclave, and a chilled border granite have comparatively high $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ and low ϵ_{Nd} (Fig. 34). The close proximity of the two large, late dikes and the GZ enclave to the chilled border sample more strongly suggests that this group represents a distinct felsic input magma, one that has incorporated a greater volume of Pre-Cambrian material than the other potential felsic input magmas.

Pb isotope data confirm the involvement of different crustal sources in the production of felsic input magmas within the Mojave Desert region (Fig. 34) (Wooden et al., 1988; Feuerbach et al., 1993; Miller et al., 2000). Inferred felsic input magmas with high $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ for given $^{206}\text{Pb}/^{204}\text{Pb}$ have Pb isotopic signatures

indicative of Mojave basement crustal sources (Wooden et al., 1988; Miller et al., 2000). The elevated Pb isotopic signatures indicate that an Archean source was involved in the production of the Mojave basement (Wooden et al., 1988). The inferred felsic inputs with low $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ for given $^{206}\text{Pb}/^{204}\text{Pb}$ have signatures indicating that they originated from Arizona basement rocks. These basement rocks have low Pb isotopic ratios because they were derived from a MORB/oceanic-like mantle reservoir (Wooden et al., 1998). The Aztec Wash pluton lies within the Mojave terrane, but is close to the boundary between the two regions, which were joined together by 1.7 Ga (Wooden et al., 1998). Potential felsic input magmas for the Aztec Wash pluton show a great deal of scatter, and plot in fields that suggest contributions from both Mojave and Arizona basement rocks (Fig. 34).

In addition to hornblende gabbro AW281 (Fig. 35), certain other samples within the heterogeneous zone and granite zone appear to have been isotopically modified by Pre-Cambrian rock. The fractionated GZ miarolitic leucogranites at the roof of the reservoir and in contact with wall rock have elevated $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ compositions that suggest late-stage contamination by Pre-Cambrian rocks.

Felsic Magma Evolution in the Heterogeneous Zone

Harper et al. (2004) proposed that repeated inputs of crystal-poor felsic magma entered the initially unstratified magma chamber of the Aztec Wash pluton. The magma cooled and crystallized, depositing coarse-grained, euhedral plagioclase and K-feldspar crystals on the floor of the magma reservoir. This process formed a crystal-rich mush

composed of an interlocking framework of feldspar crystals and trapped interstitial melt (Wiebe and Collins, 1998). When mafic magma intruded the crystal-rich base of the reservoir, it punched through the crystal mush in a dike-like fashion until it reached the interface between the crystal-rich mush and the crystal-poor magma, which represents a rheological boundary (Wiebe, 1993, 1994; Bateman, 1995; Patrick and Miller, 1997; Wiebe and Collins, 1998; Waight et al., 2001; Wiebe et al., 2002). Because it was denser than the overlying silicic magma, the mafic magma did not rise into the reservoir, but flowed laterally over the crystal mush (Wiebe, 1993, 1996; Wiebe and Collins, 1998). The sheets thicken to the south and terminate to the north, indicating that the mafic magma flowed from the south (in present orientation) to the north (Harper et al., 2004). Multiple synplutonic injections of both mafic and felsic magma occurred following initial reservoir construction. Each mafic lobe in the heterogeneous zone was thus built from the bottom up by sequential injections of mafic magma into a resident granitic reservoir (Patrick and Miller, 1997; Miller and Miller, 2002; Coiner et al., 2003; Harper et al., 2004).

As the mafic magma ponded and cooled, its greater relative density compacted the underlying felsic mush. The trapped interstitial liquid was subsequently mechanically expelled by filter pressing (Wiebe, 1994; Chapman, 1996; Weinberg et al., 2001). The interstitial melt rose into the base of the overlying mafic sheet to form flame structures and veins within the sheet (e.g., Wiebe and Collins, 1998). The migration of interstitial melt left behind coarse-grained plagioclase and K-feldspar and mafic minerals with little interstitial silicic melt. This process occurred repeatedly within the heterogeneous zone

and formed the HZ coarse-grained monzonites to quartz monzonites, which are interpreted as felsic cumulates in this study and in previous work (Patrick and Miller, 1997; Robinson and Miller, 1999; Miller and Miller, 2002; Cates et al., 2003; Coiner et al., 2003; Harper et al., 2003; Miller et al., 2003; Harper et al., 2004). The HZ cumulates contain large (3–10 mm long), euhedral to subhedral plagioclase and K-feldspar that form a closely-packed, touching framework previously described as a cumulate texture (e.g., Irvine, 1982). They have very little quartz, variable concentrations of biotite and minor hornblende, and high concentrations of sphene, apatite, and zircon. The high accessory mineral concentrations correspond with the very high Sr, Ba, Zr, and rare earth element concentrations of the coarse-grained monzonites–quartz monzonites (i.e., felsic cumulates). Evidence that compaction aided in cumulate formation is found in the form of kinked biotite crystals (Fig. 24).

Felsic Magma Evolution in the Granite Zone

The model developed by Harper et al. (2004) suggests that granites in the granite zone were derived from the HZ cumulates by the multi-stage fractionation of initial felsic input magmas. The new isotopic data presented in this study place important constraints upon this model. Because potential felsic inputs encompass a broad range of Sr, Nd, and Pb isotopic compositions, the multi-stage model for evolution of the felsic units of the granite zone and heterogeneous zone must involve multiple felsic input sources. The granite zone, although entirely composed of granite, thus cannot represent a homogeneous, closed system, as isotopic values show appreciable heterogeneity.

According to Harper et al. (2004), the magma that fractionated from the HZ cumulates ascended to the roof of the reservoir and established a rheological boundary between an upper granite zone and a lower heterogeneous zone. The melt present in the granite zone subsequently fractionated coarse-grained granites, medium-grained granites, and highly fractionated miarolitic granite (Harper et al., 2004). Felsic cumulates in the heterogeneous zone have Ba, Sr, and Rb concentrations appropriate for feldspar-rich fractionates from input magmas with the composition of the chilled border granites (Harper et al., 2004). However, when compared to the GZ granites and to the majority of inferred felsic input magmas, isotopic data show that substantial variation exists between the granites and inferred felsic cumulates. The model proposed by Harper et al. (2004) thus must be modified to include additional open-system processes operating on the granites or HZ cumulates after or during fractionation and solidification in the reservoir.

Isotopic Constraints on Felsic Units of the Heterogeneous Zone and Granite Zone

A primary objective of this discussion is to determine which units in the heterogeneous zone can be related to the silicic part of the magma reservoir (i.e., the granite zone). The isotopic data are especially useful for testing possible relationships among HZ cumulates, GZ granites, and potential felsic inputs. In order to more clearly illustrate some of these relationships, two diagrams showing isotopic composition versus SiO₂ (see Fig. 34 from Results) are reproduced here in modified form (Fig. 36). These diagrams indicate that the HZ cumulates show limited isotopic overlap with the GZ units, especially in $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$. Among the granite zone units that could be most directly related

Figure 36. ϵ_{Nd} vs. SiO_2 and $^{87}\text{Sr}/^{86}\text{Sr}$ vs. SiO_2 for samples in the heterogeneous zone (HZ) and granite zone (GZ). Horizontal arrows on graphs indicate fractionation trends; triangular fields represent mixing trends.

to the HZ cumulates are two GZ enclaves with higher ϵ_{Nd} and lower $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ than the majority of GZ units. These enclaves are potential felsic input magmas that are isotopically similar to the majority of HZ cumulates. The majority of GZ units plot closer to the potential felsic input magmas represented by the chilled border granites and late microgranite dikes. This could mean that the felsic input magma that formed the HZ cumulates is not the same magma that produced the granites of the granite zone. The two GZ enclaves may be representative of the parent magma from which the HZ cumulates formed. These enclaves are located at structurally different levels within the reservoir, indicating that felsic input magma with this composition was injected into the system at different times during the development of the reservoir.

Because the trace element and rare earth element data strongly support a genetic relationship between the HZ cumulates and the GZ felsic units, the lack of agreement in isotopic composition may suggest that the HZ cumulates were isotopically modified in the crystal mush stage of their formation. The two GZ enclaves discussed above have low $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ in comparison to other rocks of similar bulk composition, suggesting that they too may have experienced isotopic modification.

Heterogeneous Zone Cumulate Contamination

Figure 36 shows that on the ϵ_{Nd} vs. SiO_2 plot, the HZ cumulates overlap with potential felsic inputs and some GZ granites as well. On $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ vs. SiO_2 , the majority of HZ cumulates overlap with the two GZ enclaves discussed above, and only one HZ cumulate overlaps with the remaining GZ units. These relationships may be the result of

both magma mixing in the deeper parts of the reservoir and diffusive modification of felsic magma during mafic recharge.

During mingling of felsic and mafic magma, Sr isotopic concentrations are shifted more easily than Nd isotopic concentrations because Sr isotopes diffuse at a faster rate than Nd isotopes (Leshner, 1994). And, in general, the Sr isotopic composition of silicic magma will be modified by diffusive contamination during mafic input because the mafic magma has a much higher Sr concentration than the felsic magma (Snyder and Tait, 1998). In contrast, the Nd isotopic composition of silicic magma will be less affected because the Nd concentrations of silicic and mafic magmas are similar. The overlap in ϵ_{Nd} may therefore suggest that the initial isotopic ratios of the HZ cumulates were similar to those of units in the granite zone, but were modified at some later stage during or after their formation.

An important consideration in the model proposed here for the isotopic evolution of the HZ cumulates is that their very feldspar-rich compositions, and correspondingly high Sr concentrations, make modification by mafic contamination processes (diffusive and/or mixing) difficult. Invading mafic magmas could not easily modify the Sr isotopic composition of the HZ cumulates if the cumulate feldspars had formed from uncontaminated silicic melt with higher $^{87}Sr/^{86}Sr_{(i)}$. Viable mechanisms through which the HZ cumulates could become contaminated are discussed below.

Silicic Melt Migration

The cumulates may have acquired their more mafic isotopic signatures by settling into silicic melt contaminated by invading mafic magmas. Experimental modeling demonstrates that when mafic magma flows laterally over the existing floor of a magma reservoir, it traps a layer of silicic liquid beneath (Snyder and Tait, 1995, 1998; Bleick et al., 2005) (Fig. 37). This layer of silicic magma has a volume roughly equal to that of the mafic sheet above it (Snyder and Tait, 1998). The silicic liquid migrates through the flowing mafic liquid because it is less dense (Snyder and Tait, 1998; Bleick et al., 2005). Synplutonic veins within the mafic-felsic sheeted sequences of the heterogeneous zone provide field evidence for this process (Fig. 16).

During upward migration, the silicic magma becomes both elementally and isotopically contaminated by the mafic magma. Lateral flow promotes isotopic and chemical exchange between the invading mafic magma and the silicic liquid in the chamber because it allows for dispersion of the silicic liquid over a greater surface area (Snyder and Tait, 1998; Wiebe et al., 2002). Additionally, as the silicic magma migrates through the basaltic magma, water, Na, and K preferentially leave the silicic melt to enter the mafic melt, and Fe leaves the mafic melt to enter the silicic melt (Wiebe, 1996; Snyder and Tait, 1998; Waight et al., 2001). Late biotite and hornblende growth at the interface between the mafic and felsic sheets probably reflects this process. The contaminated, relatively anhydrous silicic melt becomes denser than the uncontaminated silicic melt above the mafic sheet, and thus does not convect through the reservoir, but ponds above the newly formed mafic sheet (Fig. 37) (Snyder and Tait, 1998). Crystals

Figure 37. Cartoon illustrating HZ cumulate contamination by silicic melt migration. (A) Lateral flow (direction indicated by horizontal arrow) of mafic magma traps a layer of underlying silicic magma. Silicic magma becomes contaminated as it migrates through overriding mafic magma (vertical arrows). (B) A layer of contaminated silicic melt ponds above the mafic sheet. (C) Crystals settle into the contaminated melt, forming a layer of HZ cumulate.

settle into this layer of contaminated melt, acquiring the signature of the contaminated melt through later stages of growth that may follow partial resorption. Any contaminated interstitial liquid that was not expelled during filter pressing could also cause the HZ cumulates to acquire $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ compositions that are shifted toward the more mafic magmas (trachybasalts and gabbros). The two potential felsic input GZ enclaves that are isotopically similar to the HZ cumulates may have been formed from silicic magma that was contaminated in the heterogeneous zone by this process and then later dispersed to the granite zone, possibly by convection.

With increasing structural height in the lobe, the volume of mafic magma significantly decreases; consequently, the volume of contaminated silicic melt decreases. The contamination of the HZ cumulates thus decreases with increasing structural height in the lobe. One HZ cumulate has higher $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ (0.7096) and lower ϵ_{Nd} (-11.0) than the others (Fig. 36). This sample is located at a structurally high level in the reservoir, 10–15 m beneath the boundary between the heterogeneous zone and the granite zone, providing supporting field evidence for a decrease in contamination with increasing height.

Fractionated Mafic Melt Migration

Silicic magma may also become contaminated by the process of gas-driven filter pressing (Sisson and Bacon, 1999). In this process, gas exsolved from hydrous mafic magma during solidification creates a pressure gradient that drives residual felsic melt out of the mafic sheet (Sisson and Bacon, 1999) and into the overlying silicic magma. The

felsic selvages (Fig. 7B) that commonly border trachybasaltic sheets are evidence for the expulsion of fractionated mafic melt from the rapidly cooling sheets. The gas filter-pressed melt should have the isotopic composition of the gabbroic sheets and be hydrous and buoyant. It therefore could mix with and modify the isotopic composition of melt overlying the mafic sheets. Coarse-grained gabbroic sheets commonly have irregular cm-scale felsic seams and pockets likely formed by the segregation of fractionated melt (Fig. 11). This melt may also contribute to the contamination of the silicic magma. The formation of the hornblende troctolites may also be important in the contamination of the silicic magma, as discussed below.

Felsic Pipe Formation in the Heterogeneous Zone

Field evidence indicates that the pipes transport material of variable compositions and textures. Some pipes are pegmatitic (Fig. 15), indicating that they were fluid-rich and likely to have compositions representative of the trapped silicic liquids from beneath mafic sheets. These pipes may have formed in response to the density inversion created by the flow of mafic magma over silicic magma (Snyder and Tait, 1998; Wiebe et al., 2002). In some cases, the pipes are poorly formed (Fig. 15) and may be interconnected with silicic veins (Fig. 16). Experiments by Snyder and Tait (1998) demonstrate that trapped liquids migrate through the overriding mafic magma as veins when the mafic magma is actively flowing because the mafic magma is undergoing shear. Once lateral flow and shear have ceased, the trapped silicic magma migrates through the mafic magma

as a diapir, forming pipes (Snyder and Tait, 1998). The interconnected network of veins and pipes shown in Figure 16 may thus represent a period of slowed to completed flow.

The two pipes analyzed in this study represent remobilized cumulate (Fig. 14). They are coarse-grained, choked with plagioclase and K-feldspar, and have isotopic signatures that more closely approximate intermediate rocks in the heterogeneous zone than felsic rocks in the granite zone. The pipes formed in response to compaction by overriding sheets. The heat transferred to the underlying cumulate would aid in pipe formation, as it would allow the cumulate to remain mobile (Wiebe et al., 2002).

Fractionation of Mafic Magma

This study confirms the earlier findings of Falkner et al. (1995) that the HZ hornblende troctolites are a cumulate assemblage, removed from hypothesized mafic input magmas represented by trachybasaltic sheets and enclaves. Hornblende-troctolite cumulates are coarser-grained and richer in mafic minerals than the gabbroic sheets and masses of the heterogeneous zone. They have high concentrations of Ni and Cr, high Mg numbers, and low incompatible element concentrations (Figs. 28–30). The presence of mafic cumulates indicates that fractional crystallization played a role in the evolution of the mafic liquid (Falkner et al., 1995). The fractionation of plagioclase-poor, olivine-rich hornblende troctolites from input mafic magmas would drive fractionated liquid to high levels of incompatible elements. Very high levels of melt fractionation (leaving behind 80–90% cumulate) could produce a residual liquid with extremely high Sr and Ba levels (2000 ppm and 5000 ppm respectively), particularly if the mafic input magma was

already enriched in LIL elements, as is apparent from trace element data. Such evolved melts would be especially potent contaminants of overlying silicic magma in the scenario outlined above for the isotopic modification of the HZ cumulates.

The fractionation of mafic magma appears to span a continuum. At the most mafic end are the hornblende troctolites and olivine gabbros. These mafic cumulates may have formed from the injection of a comparatively larger volume of mafic magma, allowing more time for slow cooling and fractionation. Or, they may have formed in a region that experienced mafic recharge over shorter periods of time than the rest of the reservoir, allowing for repeated mafic fractionation and replenishment. At the more felsic end is the fractionated melt expelled from quenched mafic sheets (Fig. 7B) and segregated from coarse-grained gabbros (Fig. 11). These units presumably formed from smaller volumes of melt, and cooled too quickly to allow efficient segregation of early-formed mafic silicates.

Hybridization in the Heterogeneous Zone

The Aztec Wash pluton has experienced the repeated intrusion of both mafic and felsic magmas, and a wide variety of intermediate magmas has resulted from interactions between these magmas. The extent to which two magmas can interact is controlled largely by their relative volumes and temperatures and by the relative timing of intrusion (Frost and Mahood, 1987). Mingling is favored for small relative differences in temperature and viscosity, and for high relative volumes of mafic magma (Frost and Mahood, 1987; Vernon et al., 1988).

Within the heterogeneous zone, there are intermediate rocks that span a wide range of major and trace element compositions. Field relationships, petrography, geochemistry, and isotopic composition allow for the interpretation of these rocks as single- or multi-stage hybrids spawned by mafic and felsic interaction. Examples of the hybrids are shown in Figures 20 and 25. Repeated episodes of corrosion and rimming within the margins of zoned plagioclase crystals (Fig. 26) provide evidence for multiple episodes of resorption and regrowth (Hibbard, 1991). Rapakivi textures, as shown in Figure 23, signify the interaction of already-formed K-feldspars with newly introduced, more mafic melt. The presence of abundant acicular apatite and radial splays of biotite and acicular hornblende (Fig. 13) in the hybrids indicates undercooling and rapid growth upon mingling of mafic and felsic magmas (Hibbard, 1991).

HZ hybrids span a compositional spectrum of 53.0–68.3% SiO₂. The Sr and Ba concentrations of the hybrids are of special interest, as these concentrations, combined with isotopic constraints, can be used to infer the petrogenesis of the hybrids. Trace element plots, particularly Ba vs. Sr and Rb vs. Sr (Fig. 29), show that mixing is not a simple binary process, and isotopic data (Fig. 34) confirm that simple closed-system fractionation or binary mixing between mafic and felsic input magmas could not have generated the full suite of intermediate rocks within the heterogeneous zone. The full suite of hybrids most likely formed through multi-stage processes involving mafic fractionation, replenishment, and mixing with silicic liquids and cumulate plagioclase and K-feldspar. In an attempt to explain their petrogenesis, the hybrid rocks have been

divided into three fields based upon their trace element, SiO_2 , and isotopic compositions (Figs. 38–39).

Field 1 on Figure 38 represents rocks formed by a combination of mafic magma fractionation and recharge of parental mafic magma. The elevated Sr and Ba concentrations of the samples in Field 1 indicate that fractionation from a mafic parent was involved in their petrogenesis. To reach the appropriate Ba and Sr concentrations of these samples through fractionation alone would require 50–65% fractionation of an olivine gabbro from a basalt parent, as shown by the olivine, clinopyroxene, and plagioclase fractionation vectors on Figure 38. However, the fractionated liquid would be too silicic to generate the observed SiO_2 concentrations (53–57% SiO_2) of the high Sr, high Ba hybrids in Field 1. These hybrids may have instead been produced by the mixing of fractionated gabbroic liquid with fresh mafic input liquid supplied by repeated injection. As shown by Point C on the “mafic parent + mafic fractionate” vector on Figure 38, a mixture of fractionated mafic magma and parental basalt at proportions of 30% fractionate and 70% input basalt yields mafic hybrids that approach the observed high Sr and Ba levels. The isotopic (Sr, Nd, Pb) signature of one sample in Field 1 is close to that of the inferred mafic parent magma, supporting formation by mixing of fractionated mafic melt with newly input mafic magma. Rocks in Field 1 likely represent the hybrid liquids that contributed to the isotopic contamination of the HZ cumulates.

The hybrid samples in Field 2 on Figure 38 may have formed from the mixing of fractionated mafic magma and/or hybridized mafic magma (e.g., Field 1 mafic hybrids), with silicic magma and/or HZ cumulate. The Sr and Ba concentrations of the hybrids lie

Figure 38. Plot of Ba vs. Sr including fractional crystallization model for mafic magma. Fields represent different mixing scenarios for mafic and felsic units of the heterogeneous zone (HZ). Field 1 = mafic magma fractionation and recharge of parental mafic magma. Field 2 = multi-component mixing of mafic magma, HZ cumulate, and silicic liquid. Field 3 = multi-stage hybridization processes involving hybrid liquid and silicic liquid, with some HZ felsic cumulate incorporation. Fractional crystallization model for Ba and Sr evolution in melt and coexisting solid applying Rayleigh fractional crystallization equation model $C_1/C_0 = F^{(D-1)}$ (C_1 = concentration of element in melt; C_0 = initial concentration of element in melt; $D = D^{s/l}$ = bulk partition coefficient of element for crystallizing assemblage versus melt). Olivine ($D_{Ba} = 0.010$; $D_{Sr} = 0.014$), clinopyroxene ($D_{Ba} = 0.026$; $D_{Sr} = 0.060$), plagioclase ($D_{Ba} = 0.230$; $D_{Sr} = 1.830$), and hornblende ($D_{Ba} = 0.420$; $D_{Sr} = 0.460$) for an initial melt composition of 50% SiO_2 , 812 ppm Ba, 708 ppm Sr (the average of samples SAW04 and SAW17). For all trend lines except mafic parent/fractionate mixture: F = fraction of melt remaining, plotted in increments of $F = 1.0, 0.9, 0.7, 0.5$. For mafic/parent fractionate mixture, trend line was generated by modeling the mixing of varying proportions of basalt with an initial melt composition of 50% SiO_2 , 812 ppm Ba, and 708 ppm Sr with a mafic fractionate with a composition of 70% SiO_2 , 5000 ppm Ba, and 3000 ppm Sr. Points on the trend line represent varying proportions of parent/fractionate mixture. Point of origin represents 100% parent basalt and 0% mafic fractionate. Point A = 90% parent, 10% fractionate. Point B = 80% parent, 20% fractionate. Point C = 70% parent, 30% fractionate. From this trend, it can be seen that a melt with the approximate composition of 70% parent and 30% fractionate could generate the observed high Sr and Ba concentrations for the highlighted mafic samples (see Fig. 39). The samples AW02, SAW16, and SAW18 are labeled on the diagram to accompany more detailed discussions in the text.

Figure 39. Chart depicting mixing scenarios for hybrid rocks in Fields 1, 2, and 3 on Figure 38. Where available, SiO₂, $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$, and ϵ_{Nd} values for mixing components are provided.

on a mixing line between the inferred felsic input magmas and the mafic parent + mafic fractionate magmas (Fig. 38). The SiO₂ concentrations of these rocks range from 54–64%, and their isotopic compositions are closer to the compositions of the HZ cumulates and mafic magmas than the inferred felsic magmas (Fig. 39). The majority of samples in Field 2 are medium-to coarse-grained and contain xenocrystic plagioclase and K-feldspars that were incorporated into the mafic magma from the HZ cumulate.

Magma mixing may occur through double-diffusive convection, which is a primary cause of hybridization in mafic-felsic sheeted sequences (Wiebe and Wild, 1983; Wiebe, 1996; Waight et al., 2001; Wiebe et al., 2002). Convection occurs at the boundary between the mafic sheet and the overlying silicic magma, causing thermal, elemental, and isotopic exchange at the interface between mafic and felsic liquids, and producing in-situ hybrid liquids (Wiebe and Wild, 1983; Wiebe, 1996; Wiebe et al., 2002) with trace element and isotopic signatures indicative of mafic and felsic magma mixing.

In addition to double-diffusive convection, the formation of many rocks in Field 2 involved mechanical mixing, as indicated by the xenocrystic feldspars in many hybrids. Lateral flow aids in mechanical mixing by generating flow-front instabilities that promote hybridization between the mafic sheet and felsic interlayer (Wiebe and Wild, 1983; Wiebe, 1994; Wiebe and Collins, 1998; Wiebe et al., 2002; Bleick et al., 2005). Experimental models show that the flowing mafic magma forms a fingerlike morphology (Snyder and Tait, 1998; Bleick et al., 2005). The mafic magma intermingles with the crystal mush and mechanically incorporates plagioclase and K-feldspar (Snyder and Tait,

1998; Wiebe et al., 2002). Double-diffusive convection and HZ cumulate incorporation generated the sequence of gradational hybridized rocks that are shown in Figure 40 and lie within Field 2.

Where temperatures are high enough to permit melting, mafic influx may also melt cumulate crystals into mafic liquid. Heat released by cooling and crystallization of the mafic magma is transferred to the felsic magma, which then becomes hotter and less viscous (Vernon et al., 1988; Wiebe, 1994). This rapid heat exchange may locally melt crystals within hot, liquid-rich cumulate mush that would then mix with the mafic liquid.

Field 3 on Figure 38 represents rocks formed by multi-stage hybridization processes involving hybrid liquids and silicic liquids, with some incorporation of mafic liquids and HZ felsic cumulate. The hybrids in Field 3 have Ba and Sr concentrations that suggest multi-stage formation involving the mixing of Field 2-type hybrid liquids with felsic magma. The presence of mafic enclaves in some rocks indicates that mafic magmas were locally incorporated into Field 3 hybrids. The Field 3 hybrids that incorporate felsic cumulate have, on average, higher SiO_2 than those in Field 2 (Fig. 39), and those analyzed in this study have a fine-grained matrix. The formation of these hybrids may also have occurred at the interface between mafic and silicic magmas through double-diffusive convection. The resulting hybrid liquid would be less dense than the mafic magma, and would ascend to higher levels in the reservoir. The influx of fresh mafic input magma would further drive less dense fractionated and/or hybridized liquids to higher levels of the reservoir as the newly input magma began to cool and crystallize (Sisson and Bacon, 1999). The hybrid liquid may then mix with ambient

Figure 40. (A) Field photo of gradational sequence depicting progressive hybridization of mafic material due to convective stirring at the interface between invading mafic magma and overlying silicic liquid. SAW17 = coarse-grained hornblende gabbro; SAW18 = coarse-grained mafic hybrid with plagioclase exhibiting disequilibrium coronas (see Fig. 20); SAW16 = coarse- to medium-grained intermediate hybrid with abundant acicular biotite and hornblende crystals; SAW19 = gabbroic enclave with entrained plagioclase crystals (see Fig. 17). (B) Cartoon illustrating field photo. White squiggles represent seams of fractionated fluid trapped within the gabbro.

felsic liquid present at these higher levels to form the Field 3 hybrids. The hybrids within this field are located at structurally high levels within the reservoir, and include the sample shown in Figure 25B. This sample contains mafic enclaves and has incorporated plagioclase and K-feldspar crystals from the HZ cumulate. Hybrid rocks such as these may have formed by mechanical mixing triggered by structural instabilities within the reservoir.

Mechanical mixing may also have produced the hybrid outlier, AW02, that plots near Field 2 on Figure 38. This sample has higher $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ and lower ϵ_{Nd} than any felsic cumulate, and is composed of coarse-grained plagioclase and K-feldspar in a fine-grained matrix. AW02 is located at a structurally high level in the mafic lobe, near the contact between the heterogeneous zone and overlying GZ coarse-grained granite. Its composition suggests formation by mechanical mixing of HZ cumulate with intermediate hybrid magma (Miller et al., 2003).

Mechanical Hybridization in Breccia Zones

Although the heterogeneous zone-granite zone contact is sharp, the breccia zones discussed in Mapping and Field Relationships provide evidence for interaction between the zones. The clasts of felsic and intermediate rock in the breccia zones are interpreted to be deposits of heterogeneous zone material within the granite zone (Fig. 18) (Miller et al., 2003). The breccias appear to have formed from the collapse of partially crystallized hybrid sheets in the heterogeneous zone that resulted in the gravity-driven, down-slope deposition of the clasts. The within-reservoir collapse was likely triggered by the

repeated injection of mafic material (Miller et al., 2003). Mafic-felsic sheeted sequences may have formed a within-reservoir “volcano” with sloping sides (Miller et al., 2003). At high structural levels in the reservoir, near the heterogeneous zone–granite zone interface, gravitational instabilities on these sloping sides are inferred to have led to the mechanical disaggregation of heterogeneous zone material into the GZ coarse-grained granites (Fig. 41) (Miller et al., 2003; Harper et al., 2004).

Construction of a Mafic Lobe

After the initial injections of felsic magma (Fig. 41A) and the deposition of HZ felsic cumulate (Fig. 41B), mafic magma was injected into the magma reservoir (Fig. 41C). The stacked, sheeted sequences formed because there was sufficient time between mafic injections to allow for repeated cooling, crystallization, and deposition (Wiebe, 1993, 1994). Each mafic layer thus represents a discrete injection of magma (Snyder and Tait, 1998). Multiple injections generated a layered stratigraphy of meter-scale mafic sheets (Figs. 6, 41) (Wiebe, 1993, 1994; Bateman, 1995; Patrick and Miller, 1997; Waight et al., 2001; Wiebe et al., 2002). The well-formed, fine-grained mafic sheets are the most laterally coherent and are interpreted to be among the earliest pulses of magma into the reservoir because of their quenched texture and location near the stratigraphically lowest levels of the lobe (Fig. 41C–D). The bases of well-formed, chilled sheets exhibit flame and load-cast structures formed by the density contrast between chilled mafic magma and less dense underlying silicic liquid (Fig. 7) (Wiebe, 1993; Wiebe and Collins, 1998; Wiebe et al., 2002, 2004). The flame and load-cast structures, and the

Figure 41. Cartoon depicting formation of GZ and HZ. Stages of development are determined from general structural and map/stratigraphic relations in this lobe as well as in other lobes farther to the east as examined by previous workers in the Aztec Wash pluton. Isotope data show the range in isotopic composition for lithologic units represented on cartoon. (A) Felsic magmas are injected into an initially unstratified reservoir. (B) Heterogeneous zone felsic cumulates form and settle to the base of the reservoir. (C) Mafic magma is injected into the base of the reservoir to form mafic-felsic sheeted sequences. (Note: As shown in Fig. 5, sheets are thicker to the south and thin out and terminate to the north.) Reservoir becomes stratified into HZ and GZ. (D) Repeated injection over time leads to increased hybridization of sheeted sequences. Mechanical disturbances create breccia zones at the HZ–GZ boundary.

paleovertical felsic pipes, act as way-up indicators (Wiebe and Collins, 1998; Wiebe et al., 2002, 2004). They indicate that the roof of the pluton is to the east-northeast (Harper et al., 2003). As shown on Figure 41D, HZ felsic cumulate interlayers of highly coherent sheets at the base of the lobe have isotopic compositions indicative of contamination by mafic magma. The felsic cumulate interlayers in incoherent sheets are less contaminated because of the lower volume of mafic magma at higher structural levels in the reservoir. Sheeted sequences lose coherency upward and show greater physical and chemical evidence for within-reservoir hybridization than at deeper levels in the lobe (Fig. 41D). With increasing stratigraphic height, felsic interlayers range from uncontaminated felsic cumulate to hybridized felsic cumulate to medium- to fine-grained felsic hybrids. The continued injection of mafic magma into the system may have induced convection in the overlying silicic magma and created an environment in which the sheeted sequences were heated and able to physically mix with the more felsic magma (Wiebe, 1994; Bateman, 1995; Weinberg et al., 2001). The wide variety of hybridized felsic, intermediate, and mafic material within the reservoir, and the increased hybridization with movement upward through the lobe indicates that processes were repeated and that heat buildup in the interior of the lobe eventually led to hybridization of sheets and cumulate (Wiebe, 1994; Weinberg et al., 2001).

At the northern end of the lobe, the well-formed mafic sheets disaggregate into pillows and enclaves of mafic material with crenulate to rounded margins (Fig. 8). They range from fine- to coarse-grained and from gabbroic to dioritic in composition (Patrick and Miller, 1997; Harper et al., 2003, 2004). The matrix for the mafic material is coarse-

grained GZ granite cumulate. In locations where the volume of felsic material far overwhelms that of the mafic, dendritic projections of basalt finger into the granite and are commonly molded around individual feldspar phenocrysts (Fig. 9). These structures form by viscous fingering in locations where there is a strong viscosity contrast between the two magmas (Perugini and Poli, 2005). In general, the pillows, which are found in areas that have a greater volume of mafic material, are more prevalent than the dendritic structures shown in Figure 9. This suggests that the heating of silicic magma by mafic sheets decreased the viscosity contrast between the two magmas near the mafic-silicic interface, which would have helped facilitate mixing of mafic and silicic magmas to produce hybrids (e.g., Fig. 40).

CONCLUSIONS

The Aztec Wash pluton records the protracted evolution of a magma reservoir that experienced bimodal (mafic-felsic) replenishment. New Sr, Nd, and Pb isotopic data confirm that multiple sources of felsic input magma contributed to reservoir construction, and that simple, closed-system fractionation models cannot be applied to the formation of felsic units within the pluton. HZ cumulates were formed from the fractionation of initial felsic input liquids, but their isotopic compositions indicate that significant open-system interaction occurred within the heterogeneous zone. The HZ cumulates may have formed from an isotopically distinct input felsic magma, one preserved in the granite zone as felsic enclaves. Alternatively, the isotopically distinct HZ cumulates and GZ enclaves may have experienced late-stage contamination in the heterogeneous zone by invading mafic magmas.

The data also demonstrate that hybrid rocks within the Aztec Wash pluton are the products of within-reservoir hybridization. Hybrids were formed by multi-stage processes involving the fractionation of both mafic and felsic magmas: (A) Fractionation of mafic input magmas produced mafic cumulates and fractionated liquids with highly elevated Ba and Sr compositions. (B) Mafic fractionation combined with recharge generated the low-SiO₂, high-Ba, high-Sr hybrids. (C) Double-diffusive convection at the interface between mafic and felsic magmas was responsible for the formation of many hybrid rocks. (D) Lateral flow of mafic magma aided in the formation of the hybrid rocks, as it allowed for mechanical integration of HZ cumulates and trapped

residual liquid into the mafic magma. The repeated replenishment of both mafic magma and felsic magma contributed to hybrid production. Hybridization was accomplished by varying degrees of mechanical mixing and diffusive chemical and isotopic exchange, and was promoted by the thermal influence of repeated injection of mafic magma into the heterogeneous zone.

REFERENCES CITED

- Bateman, R., 1995, The interplay between crystallization, replenishment, and hybridization in large felsic magma chambers: *Earth Science Reviews*, v. 39, p. 91–106.
- Bennett, V.C., and DePaulo, D.J., 1987, The definition of crustal provinces in the southern Rocky Mountain region using Sm-Nd isotopic characteristics: *Geological Society of America Abstracts with Programs*, v. 16, p. 214.
- Bleick, H.A., Miller, C.F., Furbish, D.J., Koteas, C., Ericksen, S.M., Miller, J.S., Gualda, G., and Walker, B.A., 2005, Production and distribution of hybridized magma in a replenished, open-system magma chamber: Aztec Wash pluton, Eldorado Mountains, Nevada: *Geological Society of America Abstracts with Programs*, v. 37, no. 4, p. 66.
- Cates, N.L., Miller, J.S., Miller, C.F., Wooden, J., Ericksen, S.M., and Means, M., 2003, Longevity of plutonic systems: SHRIMP evidence from Aztec Wash and Searchlight plutons, Nevada: *Geological Society of America Abstracts with Programs*, v. 35, no. 4, p. 63.
- Chapman, M., 1996, Petrogenesis of a silicic magma chamber periodically invaded by basaltic magma: The Isle au Haut igneous complex, Maine [Ph.D. thesis]: University of Massachusetts, Amherst, MA, US, 238 p.
- Coiner, L.V., Cates, N.L., Miller, C.F., and Harper, B.E., 2003, Cyclic Stratigraphy in the Aztec Wash pluton, Nevada: Vertical Construction of a Composite Intrusion: *Geological Society of America Abstracts with Programs*, v. 35, no. 4, p. 63.
- D'Andrea-Kapp, J., Miller, C.F., Miller, J.S., 2002, Ireteba pluton, Eldorado Mountains, Nevada: Late, deep-source, peraluminous magmatism in the Cordilleran Interior: *The Journal of Geology*, v. 110, p. 649–669.
- Ericksen, S.M., Miller, J.S., Miller, C.F., Harper, B.E., and Aggarwal, J.K., 2004, Isotopic constraints on the evolution of felsic magma in the Aztec Wash pluton, Eldorado Mountains, Nevada: *Geological Society of America Abstracts with Programs*, v. 36, no. 4, p. 8.
- Falkner, C.M., Miller, C.F., Wooden, J.L., Heizler, 1995, Petrogenesis and tectonic significance of the calc-alkaline, bimodal Aztec Wash pluton, Eldorado Mountains, Colorado River extensional corridor: *Journal of Geophysical Research*, v. 100, p. 10453–10476.
- Faulds, J.E., 1993, Miocene stratigraphy of the central Black Mountains, northwestern Arizona: Variations across a major accommodation zone, *in* Sherrod, D.R., Nielson, J.E., eds., *Tertiary stratigraphy of highly extended terranes, California, Arizona, and Nevada*: U.S. Geological Survey Bulletin, v. 2053, p. 37–44.

- Faulds, J.E., Feuerbach, D.L., Miller, C.F., and Smith, E.I., 2001, Cenozoic evolution of the northern Colorado River extensional corridor, southern Nevada and northwest Arizona: Pacific Section of the American Association of Petroleum Geologists Publication GB 78 (also Utah Geological Association Publication 30), p. 239–272.
- Feuerbach, D.L., Smith, E.I., Walker, J.D., Tangeman, J.A., 1993, The role of the mantle during crustal extension: Constraints from geochemistry of volcanic rocks in the Lake Mead area, Nevada and Arizona: Geological Society of America Bulletin, v. 105, p. 1561–1575.
- Frost, T.P., and Mahood, G.A., 1987, Field, chemical, and physical constraints on mafic-felsic magma interaction in the Lamarck Granodiorite, Sierra Nevada, California: Geological Society of America Bulletin, v. 99, p. 272–291.
- Gans, P.B., Landau, B., Darvall, P., 1994, Ashes, ashes, all fall down, Caldera-forming eruptions and extensional collapse of the Eldorado Mountains, southern Nevada: Geological Society of America Abstracts with Programs, v. 26, no. 2, p. 53.
- Harper, B.E., Miller, C.F., Wiebe, R.A., Cates, N.L., and Cribb, W., 2003, Granite accumulation and fractionation in a dynamic, open-system magma chamber, Aztec Wash pluton, Eldorado Mountains, Nevada: Geological Society of America Abstracts with Programs, v. 35, no. 4, p. 63.
- Harper, B.E., Miller, C.F., Koteas, G.C., Cates N.L., Wiebe, R.A., Lazzareschi, D.S., and Cribb, J.W., 2004, Granites, dynamic magma chamber processes, and pluton construction: the Aztec Wash pluton, Eldorado Mountains, Nevada, USA: Transactions of the Royal Society of Edinburgh: Earth Sciences, v.95, p. 277–295.
- Hibbard, M.J., 1991, Textural anatomy of twelve magma-mixed granitoid systems, *in* Didier, J., and Barbarin, B., eds., *Enclaves and Granite Petrology*: New York, New York, Elsevier, p. 431–444.
- Irvine, T.N., 1982, Terminology for layered intrusions: Journal of Petrology, v. 23, p. 127–162.
- Johnson, D.M., Hooper, P.R., and Conrey, R.M., 1999, XRF analysis of rocks and minerals for major and trace elements on a single low dilution Li-tetraborate fused bead: Advances in X-ray Analysis, vol. 41, p. 843–867.
- Knaack, C., Cornelius, S., and Hooper, P., 1994, Trace element analyses of rocks and minerals by ICP-MS, GeoAnalytical Library, Washington State University: Pullman, Washington State University: <http://www.wsu.edu/~geology/geolab/note/icpms.html>, last accessed January 2006.

- Koteas, C., Miller, C.F., Cates, N.L., Harper, B.E., and Wiebe, R.A., 2003, Granites, dynamic magma chamber processes, and pluton construction: Aztec Wash pluton, Eldorado Mountains, Nevada: Geological Society of America Abstracts with Programs, v. 35, no. 6 p. 138.
- Leshner, C.E., 1994, Kinetics of Sr and Nd exchange in silicate liquids: Theory, experiments, and applications to uphill diffusion, isotopic equilibration, and irreversible mixing of magmas: Journal of Geophysical Research, v. 99, p.9585–9604.
- McDonough, W.F., and Sun, S.-s., 1995, The composition of the Earth: Chemical Geology, v. 120, p. 223–253.
- Metcalf, R.V., 1995, Geochemistry of Proterozoic plutonic rocks of the central Santa Fe Range, northern New Mexico: Trace element signature of subduction zone magmatism: New Mexico Geological Society 46th Guidebook, p. 185–191.
- Miller, C.F., and Miller J.S., 2002, Contrasting stratified plutons exposed in tilt blocks, Eldorado Mountains, Colorado River Rift, NV, USA: Lithos, v. 61, p. 201–224.
- Miller, C.F., Koteas, C., Erickson, S.M., Steinwinder, T.R., Miller, J.S., Wiebe, R.A., Wooden, J.L., Faulds, J.E., Cates, N.L., Coiner, L.V., and Harper, B.E., 2003, Depositional history of a bimodal, recharging magma chamber: Construction of the Aztec Wash pluton, Nevada, USA: Hutton Symposium V, The origin of granites and related rocks, Abstracts with Program, Geological Survey Of Japan, Interim Report 29, p. 91.
- Miller, J.S., Glazner, A.F., Farmer, G.L., Suayah, I.B., and Keith, L.A., 2000, A Sr, Nd, and Pb isotopic study of mantle domains and crustal structure from Miocene volcanic rocks in the Mojave Desert, California: Geological Society of America Bulletin, v. 112, p. 1264–1279.
- Patrick, D.W., and Miller, C.F., 1997, Processes in a composite, recharging magma chamber: Evidence from magmatic structures in the Aztec Wash pluton, Nevada, *in* Li, Z., et al., eds., Proceedings of the 30th International Geologic Congress, Igneous Petrology, v. 15, p. 121–135.
- Perugini, D., and Poli, G., 2005, Viscous fingering during replenishment of felsic magma chambers by continuous inputs of mafic magmas: Field evidence and fluid-mechanics experiments: Geology, v. 33, p. 5–8.
- Reid, M.R., 2003, Timescales of magma transfer and storage in the crust, *in* Rudnick, R.L. et al., eds., The Crust: Volume 3, Treatise on Geochemistry: Oxford, Elsevier-Pergamon, p. 167–193.

- Robinson, D.M., and Miller, C.F., 1999, Record of magma chamber processes preserved in accessory mineral assemblages, Aztec Wash pluton, Nevada: *American Mineralogist*, v. 84, p. 1346–1353.
- Sisson, T.W., and Bacon, C.R., 1999, Gas-driven filter pressing in magmas: *Geology*, v. 27, p. 613–616.
- Snyder, D., and Tait, S., 1995, Replenishment of magma chambers: Comparison of fluid-mechanic experiments with field relations: *Contributions to Mineralogy and Petrology*, v. 122, p. 230–240.
- Snyder, D., and Tait, S., 1998, The imprint of basalt on the geochemistry of silicic magmas: *Earth and Planetary Science Letters*, v. 160, p. 433–445.
- Steinwinder, T.R., Miller, C.F., Faulds, J.E., Koteas, G.C., and Ericksen, S.M., 2004, Transition from plutonism to voluminous diking in the Eldorado Mountains, northern Colorado River extensional corridor: *Geological Society of America, Abstracts with Programs*, v. 36, no. 4, p. 8.
- Vernon, R.H., Etheridge, M.A., and Wall, V.J., 1988, Shape and microstructure of microgranitoid enclaves: Indicators of magma mingling and flow: *Lithos*, v. 22, p. 1–11.
- Waight, T.E., Wiebe, R.A., Krogstad, E.J., and Walker, R.J., 2001, Isotopic responses to basaltic injections into silicic magma chambers: A whole-rock and microsampling study of macrorhythmic units in the Pleasant Bay layered gabbro-diorite complex, Maine, USA: *Contributions to Mineralogy and Petrology*, v. 142, 323–335.
- Weinberg, R.F., Sial, A.N., and Pessoa, R.R., 2001, Magma flow within the Tavares pluton, northeastern Brazil: Compositional and thermal convection: *Geological Society of America Bulletin*, v. 113, p. 508–520.
- Wiebe, R.A., 1993, The Pleasant Bay layered gabbro-diorite, coastal Maine: Ponding and crystallization of basaltic injections into a silicic magma chamber: *The Journal of Petrology*, v. 34, p. 461–489.
- Wiebe, R.A., 1994, Silicic magma chambers as traps for basaltic magmas: The Cadillac Mountain intrusive complex, Mount Desert Island, Maine: *Journal of Geology*, v. 102, p.423–427.
- Wiebe, R.A., 1996, Mafic-silicic layered intrusions: The role of basaltic injections on magmatic processes and the evolution of 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.
- Wiebe, R.A., and Wild, T., 1983, Fractional crystallization and magma mixing in the Tigalak layered intrusion, the Nain anorthosite complex, Labrador: *Contributions to Mineralogy and Petrology*, v. 83, p. 327–344.
- Wiebe, R.A., Blair, K.D., Hawkins, D.P., Sabine, C.P., 2002, Mafic injections, in situ hybridization, and crystal accumulation in the Pyramid Peak granite, California: *Geological Society of America Bulletin*, v. 114, p. 909–920.
- Wiebe, R.A., Manon, M.R., Hawkins, D.P., and McDonough, W.F., 2004, Late-stage mafic injection and thermal rejuvenation of the Vinalhaven granite, coastal Maine: *Journal of Petrology*, v. 45, p. 2133–2153.
- Wooden, J.L., and Miller, D.M., 1990, Chronologic and isotopic framework for early Proterozoic crustal evolution in the eastern Mojave Desert region, SE California: *Journal of Geophysical Research*, v. 95, no. B12, p. 20,133–20,146.
- Wooden, J.L., Stacey, J.S., and Howard, K.A., 1988, Lead isotopic evidence for the formation of Proterozoic crust in the southwestern United States, *in* Ernst, W.G., ed., *Metamorphism and crustal evolution in the western United States (Rubey Volume VII)*: Englewood Cliffs, New Jersey, Prentice-Hall, p. 69–86.