Time scales and processes of Cordilleran batholith construction and high-Sr/Y magmatic pulses: Evidence from the Bald Mountain batholith, northeastern Oregon

Joshua J. Schwartz1,*, Kenneth Johnson2, Paul Mueller3, John Valley4, Ariel Strickland4, and Joseph L. Wooden5
1Department of Geology, California State University, Northridge, 18111 Nordhoff Street, Northridge, California 91330, USA
2Department of Natural Sciences, University of Houston-Downtown, Houston, Texas 77002, USA
3Department of Geological Sciences, University of Florida, Gainesville, Florida 32611, USA
4WiscSIMS (Wisconsin Secondary Ion Mass Spectrometer Laboratory), Department of Geoscience, University of Wisconsin, 1215 W. Dayton Street, Madison, Wisconsin 53706, USA
5School of Earth Sciences, Stanford University, Stanford, California 94305, USA

ABSTRACT

Cordilleran granite batholiths (sensu lato) preserve information about time scales and processes of upper crustal magmatic arc construction during Mesozoic subduction and mountain building. The Bald Mountain batholith in northeastern Oregon (USA) is a classic example of a composite, incrementally constructed batholith that formed during terrane amalgamation outboard of the western U.S. Cordillera. Whole-rock geochemistry and zircon trace element, U-Pb, Lu-Hf, and Os isotopic data reveal that batholith construction occurred over ~15 Ma, commencing with the syncollisional emplacement of small, low-Sr/Y (<40) norite-granite plutons from 157 to 155 Ma. The next phase of magmatism was postcollisional and dominated by high-Sr/Y (>40) tonalite-granodiorite magmatism that produced the main mass of the batholith, including the granodiorite of Anthony Lake (147 Ma) and the tonalite of Bald Mountain (145–141 Ma). Zircons from the norite-granite suite display a narrow range in initial εHf of 7.2–7.7 and elevated δ18O (Zrn) ranging from 8.2‰ to 10.0‰, indicating a similar history of interaction with evolved crustal material. Modeling of whole-rock and zircon geochemistry indicates that both the low- and high-Sr/Y magmas composing the main phase of the batholith were generated by dehydration–partial melting of mafic arc crust (e.g., amphibolite), leaving behind a plagioclase-poor restite, which was garnet granulite in the case of the high-Sr/Y magmas. Final magma compositions in both suites were affected by assimilation of supracrustal material either at depth or during ascent. We suggest that high-Sr/Y magmas in the Bald Mountain batholith were generated by partial melting of thickened arc crust ~10 m.y. after arc–arc collision began at 159–154 Ma. Heat to drive lower crustal melting was conveyed by an increase in mantle power input as a result of renewed subduction-related magmatism. Mixing and homogenization in the lower crust involving mantle-derived basalts and crustally derived partial melts can account for the geochemical variation we observe in tonalites and granodiorites in the Bald Mountain batholith.

INTRODUCTION

Granitic batholiths (sensu lato) of the western U.S. Cordillera preserve a record of magmatic processes that operated at shallow- to mid-crustal depths during Mesozoic subduction and mountain building (Gromet and Silver, 1987; Bateman, 1992; Ducea, 2001; Saleeby et al., 2004; Michel et al., 2008). Zircons from the later granodiorite-tonalite suite show a similar range of initial εHf values (6.3–8.9) and δ18O (7.1‰–10.0‰), indicating a similar history of interaction with evolved crustal material. Modeling of whole-rock and zircon geochemistry indicates that both the low- and high-Sr/Y magmas composing the main phase of the batholith were generated by dehydration–partial melting of mafic arc crust (e.g., amphibolite), leaving behind a plagioclase-poor restite, which was garnet granulite in the case of the high-Sr/Y magmas. Final magma compositions in both suites were affected by assimilation of supracrustal material either at depth or during ascent. We suggest that high-Sr/Y magmas in the Bald Mountain batholith were generated by partial melting of thickened arc crust ~10 m.y. after arc–arc collision began at 159–154 Ma. Heat to drive lower crustal melting was conveyed by an increase in mantle power input as a result of renewed subduction-related magmatism. Mixing and homogenization in the lower crust involving mantle-derived basalts and crustally derived partial melts can account for the geochemical variation we observe in tonalites and granodiorites in the Bald Mountain batholith.

An increasing number of studies of volcanic and plutonic rocks have demonstrated that the growth of individual magma systems takes place incrementally over a variety of time scales (cf. Bacon et al., 2000; Reid and Coath, 2000; Vazquez and Reid, 2002; Schmitt et al., 2003; Coleman et al., 2004; Glazner et al., 2004; Oberli et al., 2004; Bacon and Lowenstern, 2005; Matzel et al., 2006; Bachmann et al., 2007; Walker et al., 2007; Barth et al., 2012; Reid, 2014). For example, Coleman et al. (2004) showed that the Tuolumne Intrusive Suite in the Sierra Nevada was constructed by emplacement of relatively small increments of magma over a period of 10 m.y. In the Mount Stewart batholith, the time of pluton assembly was also long, taking place over 5 m.y. (Matzel et al., 2006). However, in the Torres del Paine pluton in Patagonia, Michel et al. (2008) used high-precision chemical abrasion thermal ionization mass spectrometry zircon geochronology to document multiple pulses of magma emplacement over 90 ± 40 ka. Barboni and Schoene (2014) demonstrated that the transition from eruptible magma to solidification occurred in 10–40 k.y. These remarkably brief durations for pluton growth documented by Michel et al. (2008) and
Barboni and Schoene (2014) are similar to time scales of volcanic magma-chamber recharge and storage that are 0.1–100 k.y (e.g., Reid et al., 1997; Brown and Fletcher, 1999; Miller and Wooden, 2004; Vazquez and Reid, 2004; Bacon and Lowenstern, 2005; Charlier et al., 2005; Bachmann et al., 2007; Reid, 2014).

Studies of large silicic volcanic fields that commonly form during ignimbrite flare-ups also provide insights into the construction of granitic batholiths in the shallow to middle crust (de Silva and Gosnold, 2007; Lipman, 2007). Voluminous eruptions of silica-rich magma during caldera-forming eruptions provide unequivocal evidence for the existence of large magma chambers (100–1000 km³), although direct geochemical and geophysical links between large plutons and silicic ignimbrites remain tentative (Lipman, 2007; Glazner et al., 2008). In the Altiplano-Puna volcanic complex, de Silva and Gosnold (2007) inverted erupted volumes and eruption durations to calculate the size and emplacement history of a putative subsurface granodiorite batholith that likely formed during the 1–10 m.y. ignimbrite flare-up; their results indicated that composite upper crustal batholiths can form episodically over several millions of years during flare-up events. These results from the Altiplano-Puna volcanic complex are remarkably similar to documented high-volume magmatic pulses in the Mesozoic Sierra Nevada batholith, where nearly 78% of the magmatic volume of the exposed arc was emplaced from ca. 100 to 85 Ma (Ducea, 2001). These studies of large silicic magma systems highlight the non-steady-state character of magmatism in arc settings whereby episodic and relatively short-lived, high-volume magmatic events significantly contribute to the overall budget of new crust added to the continental lithosphere (Kimbrough et al., 2001; Ducea, 2002; Ducea and Barton, 2007; de Silva and Gosnold, 2007; DeCelles et al., 2009). Such catastrophic and transient events can be triggered by an increase in mantle power and/or underthrusting of fertile continental crust, and can exert primary controls on orogenic belts, including widespread thermal and mass transfer from the mantle to the crust, vertical uplift and exhumation, and erosion at the surface.

In the Blue Mountains province of north-eastern Oregon, silicic plutonic rocks intruded island-arc crust during and following lateral terrane collisions, providing a window into the time scales and processes of batholith generation along a tectonically active continental margin. Recent U-Pb zircon geochronology of plutonic rocks coupled with volcanic stratigraphy of adjacent basins indicates that Mesozoic arc magmatism involved eruptions of mafic-intermediate magmas and emplacement of small plutons from ca. 190 to 154 Ma (Dickinson, 1979; Schwartz et al., 2011a, 2011b). This phase of magmatism terminated with a widespread, regional contraction event linked to the collision of the distal Wallowa island-arc terrane with the fringing Olds Ferry island-arc terrane (Schwartz et al., 2011a). Subsequent magmatism involved a transient pulse of silicic magmas emplaced during a brief interval from 148 to 140 Ma. Exhumed plutons and batholiths that formed during this pulse are dominantly tonalite to granodiorite in composition, and are geochemically characterized by elevated Na, Al, and Sr concentrations, and depletions in Y and heavy rare earth elements. These geochemical features are observed in so-called high-Sr/Y plutons and batholiths in convergent margins worldwide (e.g., Fiodland, New Zealand; Peninsular Ranges, USA; Cordillera Blanca, Peru; eastern Blue Ridge, USA; south Tibetan adakites in the Tibetan Plateau; e.g., Petford and Atherton, 1996; Tulloch and Kimbrough, 2003; Chung et al., 2003; Ingram, 2012), and represent a poorly understood phase of high-Sr/Y magmatism associated with continental crust construction along the western margin of the U.S. Cordillera.

The Bald Mountain batholith in the Blue Mountains province is a classic example of an incrementally constructed, composite Cordilleran batholith. Detailed field-based studies of the batholith over more than 45 years have documented a diverse suite of nested plutons, ranging in composition from norite to granite, that stitch accreted island-arc crust of the Wallowa island arc and Baker oceanic mélange terranes (Fig. 1; Taubeneck, 1957, 1995). This classic Cordilleran stitching batholith was constructed in a complexly faulted terrane boundary, and the age of its emplacement postdates collisional orogenesis in the region. Along its periphery, the batholith consists of several small mafic to felsic plutons; however, the interior of the batholith contains a large, compositionally zoned core of high-Sr/Y tonalite and granodiorite, which largely lacks internal intrusive contacts. Here we use a combination of whole-rock geochemistry, U-Pb zircon geochronology, and trace element and Hf-O isotope geochemistry of zircon to investigate time scales and processes of magma generation and composite Cordilleran batholith construction. Our results suggest that the Bald Mountain batholith was constructed over a 15 m.y. interval in 2 distinct episodes that span a period of terrane collision and plate reorganization along the western U.S. Cordillera. These two pulses involved (1) syncontractual emplacement of small, low-Sr/Y plutons at 157–155 Ma, and (2) postdeformational emplacement dominated by large, high-Sr/Y plutons from 147 to 141 Ma. We propose a model whereby low-Sr/Y plutons were generated by crystallization of hybrid, subduction-related mantle melts and/or melting of amphibolites at moderate pressure (<10 GPa) during the waning stages of subduction and terrane amalgamation. In contrast, the transient pulse of high-Sr/Y magmatism was triggered by an increase in mantle power that resulted in partial melting of orogenically thickened island-arc crust during a renewed phase of subduction-related magmatism. Our results from the Bald Mountain batholith highlight temporally evolving processes of low- and high-Sr/Y magmatism, crustal thickening, and the geochemical maturation of arc crust associated with terrane collisions and plate reorganization over a 15 m.y. interval along the western U.S. Cordillera.

**GEOLOGIC BACKGROUND**

The Blue Mountains province of northeastern Oregon and western Idaho (Fig. 1) is a complex collage of island-arc and related mélangé and/or sedimentary terranes that accreted to western North America in the Early Cretaceous (Selverstone et al., 1992; Getty et al., 1993; McKay, 2011). Terranes of the Blue Mountains province consist of the Permian to Early Jurassic Wallowa island arc, the Middle Triassic to Early Jurassic Olds Ferry island arc, the Permian to Early Jurassic Baker oceanic mélange terrane, and the Late Triassic to Late Jurassic Izee forearc–collisional basin (Brooks and Vallier, 1978; Dickinson and Thayer, 1978; Dickinson et al., 1979; Silberling et al., 1987; LaMaskin et al., 2009; Schwartz et al., 2010, 2011a). All terranes of the Blue Mountains province were faulted and folded during a widespread north–south–directed contractional event between 159 and 154 Ma, interpreted to record a short-lived episode of deformation related to the terminal collision of the distal Wallowa island arc with the fringing Olds Ferry island arc (cf. Figs. 2A–2C; Avel Lallemand, 1995; Ferns and Brooks, 1995; Schwartz et al., 2010, 2011a). Jurassic to Cretaceous magmatic activity in the region occurred during three main phases: (1) ca. 190–154 Ma; (2) 148–141 Ma; and (3) 133–118 Ma (Johnson and Schwartz, 2009; Schwartz et al., 2011b). The terminal portion of the ca. 190–154 Ma phase overlapped with contractional deformation, whereas the 148–141 Ma phase is characterized by postcontractional tonalite–granodiorite plutonism. A zircon age from a gabbronorite in an unspecified location within the Bald Mountain batholith yielded an age of ca. 143 Ma (no uncertainties given), suggesting that the batholith formed in part during the postcontractional phase (Walker, 1989).
Wall Rocks Surrounding the Bald Mountain Batholith

The Bald Mountain batholith intrudes the structurally complex boundary between the Baker oceanic mélange terrane (Bourne subterrane) and the Wallowa island-arc terrane (cf. Figs. 1 and 2C). In this complex fault zone, the Wallowa-Baker terrane boundary consists of a series of imbricated slabs of metaigneous rocks derived from the Wallowa island arc that were faulted into Early Jurassic to Permian Elkhorn Ridge Argillite of the Baker terrane along low- to moderately southward-dipping thrust faults (cf. Ferns and Brooks, 1995; Schwartz et al., 2010, 2011a). Host rocks to the batholith include chert, argillite, limestone, and tuffaceous argillite of the Elkhorn Ridge Argillite.
Figure 2. Schematic models for the evolution of the Blue Mountains province and the Bald Mountain batholith (after Schwartz et al., 2011b). (A, B) Doubly vergent subduction resulted in low-Sr/Y magmatism in both the Olds Ferry and Wallowa island-arc systems. S.L.—sea level; N.A.—North America. (C) Following regional contraction at 159–154 Ma, high-Sr/Y plutons formed in the orogenically thickened regions of the Baker terrane (gnt—garnet).
and hornblende metagabbros of the Wallowa island arc (Taubeneck 1957, 1995). Metagabbros are Triassic (241–225 Ma: Walker, 1995; Schwartz et al., 2010) and similar to rocks reported from other areas of the Wallowa terrane (Kurz et al., 2012). Pervasive, regional, greenschist facies metamorphism affected both Elkhorn Ridge Argillite and metaigneous units prior to batholith emplacement (Ferns and Brooks, 1995; Schwartz et al., 2010). The $^{87}$Sr/$^{86}$Sr values for the Elkhorn Ridge Argillite range from 0.7113 to 0.7128, and from 0.7032 to 0.7036 for the metaplastic thrust slices (recalculated to 147 Ma using data reported in Schwartz et al., 2010). Calculated εNd values for the Elkhorn Ridge Argillite at 147 Ma range from −6.9 to −10.0, and from +5.7 to +7.6 for the metaplastic thrust slices (using data reported in Schwartz et al., 2010).

Contact metamorphic mineral assemblages locally replace greenschist facies minerals in the Elkhorn Ridge Argillite and metagabbro thrust slices in the contact aureole. Relict greenschist facies mineral assemblages in the Elkhorn Ridge Argillite (outside the aureole) consist of quartz + plagioclase + carbonate ± chlorite ± white mica. Within the metamorphic aureole, mineral assemblages are quartz + plagioclase + biotite ± garnet ± cordierite ± orthoclase ± rutile ± andalusite ± sillimanite.

**Bald Mountain Batholith: Norite-Granite Suite**

The Bald Mountain batholith comprises a diachronous plutonic suite. The batholith was extensively mapped by Taubeneck (1957, 1995) and consists of two igneous units: an older, mafic-felsic suite of lesser areal extent and a younger, laterally extensive, tonalite-granodiorite suite (Fig. 3). The older suite includes norite, quartz diorite, and granite. Mafic units include two small intrusions (norite of Willow Lake and quartz diorite of Black Bear) and one larger unit termed the norite of Badger Butte, which has an area of ~6.5 km². Primary minerals in the norite of Badger Butte include plagioclase, hypersthene, augite, and minor quartz, hornblende, biotite, sphene, and zircon. In contrast to the tonalite-granodiorite suite, the norite of Badger Butte displays extensive silicic and pyritic alteration. Subsolidus deformational fabrics are characterized by recrystallization of plagioclase feldspar and microfracturing of pyroxene (see Taubeneck, 1957, 1995, for detailed descriptions of these units). One Rb-Sr analysis of the norite of Willow Lake by Armstrong et al. (1977) yielded an initial $^{87}$Sr/$^{86}$Sr value of 0.7037 (recalculated assuming 156 Ma crystallization and $\lambda^\text{Rb} = 1.42 \times 10^{-11}$ yr$^{-1}$). Only xenoliths of Elkhorn Ridge Argillite are reported in the norite-granite suite (Taubeneck 1957, 1995).

Felsic plutonic components of the older suite crop out along the northeastern margin of the batholith and include the granite of Anthony Butte and the quartz diorite of Wolf Creek. The granite of Anthony Butte extends over ~16 km², making it the largest granitic pluton in northeastern Oregon at the present level of exposure. It intrudes the quartz diorite of Wolf Creek on its northern margin and Elkhorn Ridge Argillite to the east. Primary accessory minerals include biotite, sphene, and zircon, and rare garnet, orthopyroxene, and cummingtonite. Subsolidus deformation is common in this unit and characterized by weak to strong undulose quartz, sutured quartz grain boundaries, microfracturing of plagioclase, and mineral alignment of biotite and potassium feldspar. The quartz diorite of Wolf Creek occupies an area of ~4.5 km². It is intruded by the granite of Anthony Butte, making it one of the oldest units in the northeastern section of the Bald Mountain batholith. Primary minerals include plagioclase, potassium feldspar, quartz, hornblende, biotite, augite, orthopyroxene, apatite, and zircon. Quartz and plagioclase feldspar also display sutured grain boundaries and undulose extinction.

**Bald Mountain Batholith: Tonalite-Granodiorite Suite**

The most extensive unit of the batholith is the tonalite of Bald Mountain (tonalite-granodiorite suite), which makes up >90% of surface exposures (~344 km²). Taubeneck (1995) subdivided the tonalite of Bald Mountain into three units based on modal mineralogy: a northern augite-bearing, biotite-hornblende tonalite (located north of intraplutonic contact A-B; Fig. 3), a central biotite-hornblende tonalite, and a southern hornblende-biotite tonalite (located west of intraplutonic contact C-D in the Monument salient area; Fig. 3). Rocks north of intraplutonic contact A-B crop out over 18 km² and are distinguished by the presence of augite cores in hornblende, whereas augite is absent in tonalite elsewhere in the batholith. Subsolidus deformational fabrics characterized by recrystallized plagioclase and quartz are also common near the intraplutonic contact in this area. Tonalites of the Monument salient (southwestern portion of the batholith; Fig. 3) are distinctively more silicic than the rest of the batholith and contain, on average, higher modal percentages of quartz and biotite, and lesser amounts of hornblende. Gold mineralization in the Bald Mountain batholith is also primarily located in and around the Monument salient region (Ferns et al., 1982). Armstrong et al. (1977) reported initial $^{87}$Sr/$^{86}$Sr values for the tonalite of Bald Mountain ranging from 0.7038 to 0.7043 (recalculated using new $^{206}$Pb/$^{238}$U zircon ages reported here and $\lambda^\text{Rb} = 1.42 \times 10^{-11}$ yr$^{-1}$).

The core of the batholith consists of the granodiorite of Anthony Lake. It is exposed over ~88 km² and has gradational contacts with the tonalite of Bald Mountain, except along its northern and eastern margins, where it displays a sharper mineralogical contrast against crystal-plastically deformed tonalite (Taubeneck 1957, 1995). Elsewhere, boundaries between tonalite and granodiorite are largely based on modal abundances of potassium feldspar, whereby core granodiorites typically have potassium feldspar abundances >4% (see Taubenbeck, 1995, fig. 2.13 therein). A $^{206}$Pb/$^{238}$U zircon age of 146.7 ± 2.1 Ma was reported for the granodiorite unit (Schwartz et al., 2011a). Recalculated initial $^{87}$Sr/$^{86}$Sr values range from 0.7043 to 0.7044 and overlap with those from the tonalite of Bald Mountain (Armstrong et al., 1977).

Both the tonalite and granodiorite units contain abundant xenoliths of country rock extending well into the interior of the batholith. Xenoliths include, in order of increasing abundance, calc-silicate rocks, cherty argillite, ribbon chert, and foliated metagabbro. Length dimensions for the xenoliths range to 22 cm for calc-silicates, 51 cm for cherty argillites, 89 cm for ribbon cherts, and 31 cm for foliated metagabbros (Taubeneck, 1995). Xenoliths of chert and cherty argillite commonly display irregular and subrounded boundaries. Many xenoliths of cherty argillite also display halos of iron oxide. Whereas xenoliths of cherty argillite are relatively common in the contact aureole of the batholith, they are less common in the interior of the batholith compared to other compositions. Foliated metagabbro xenoliths show little evidence for reaction with host tonalite and granodiorite.

Mafic enclaves are also common in the tonalite-granodiorite suite and are more voluminous than xenoliths. Mafic enclaves range from undeformed fine-grained hornblende microdiorite to porphyritic hornblende andesite; no garnet is observed in any mafic enclaves. Mafic enclaves are distinguished from Permio-Triassic xenoliths in that they are non-foliated, commonly subrounded to rounded, and show no signs of greenschist-facies alteration. Mafic enclaves range from 2 to 30 cm in length. The estimated volume percent of mafic enclaves in tonalite and granodiorite ranges from 0.32% to 0.35% (Taubeneck, 1995). Most enclaves are subrounded in shape and are not associated with symplutonic mafic dikes, although they occasionally form swarms (e.g., 0.5 km northwest of Mt. Ireland: Taubeneck, 1995). Chilled margins on the rims of mafic enclaves are also observed.
Figure 3. Simplified geologic map of the Bald Mountain batholith (after Taubeneck, 1995). Locations of samples discussed in text are shown by white stars along with zircon $^{206}$Pb/$^{238}$U ages, average initial $\varepsilon$Hf values, and range of $\delta^{18}$O (Zrn) values. Zircon isotopic data are summarized in Table 3.
TABLE 1. SUMMARY OF GEOCHEMICAL AND ISOTOPIC DATA FROM THE BALD MOUNTAIN BATHOLITH, BLUE MOUNTAINS PROVINCE, NORTHEASTERN OREGON

| Unit                     | Representative sample | Age (Ma) | Fe number (value) | MALI      | ASI       | SiO₂ (range) | -Sr (average) | Sr/Y (average) | δ¹⁸O (WR) (average) | δ¹⁸O (Zm) initial* (average) | δ²⁶⁴⁵Sr/²⁹⁸Sr initial* (average) | εH initial (Zm) (average) |
|--------------------------|-----------------------|----------|------------------|-----------|-----------|--------------|---------------|---------------|-------------------|-------------------------------|--------------------------------|---------------------------------|
| Norite of Badger Butte   | BM10-54               | 156.9    | magnesian (0.56–0.69) | calcic to calc-alkaline | metaluminous | 48–58        | 574           | 23             | 8.5              | 9.3                          | 0.7037                          | 7.2                             |
| Quartz diorite of Wolf Creek | BM10-48               | >155     | magnesian        | calc-alkaline | peraluminous | 71           | 178           | 8              | n.d.             | 9.7                          | n.d.                           | 7.7                             |
| Granoert of Anthony Butte | BM10-49               | 154.7    | magnesian (0.72–0.78) | calc-alkaline | peraluminous | 73–74        | 201           | 22             | 8.6              | 8.5                          | n.d.                           | 7.9                             |
| Granodiorite of Anthony Lake enclaves | BMO-1               | 146.7    | magnesian (0.65–0.70) | calcic    | metaluminous | 66–68        | 488           | 54             | 9.6              | 8.2                          | 0.7043–0.7044                     | 7.6                             |
|                           | BM-05-23B             |          | magnesian (0.60–0.66) | calcic to alkali-calcic | metaluminous | 54–59        | 475           | 13             | n.d.             | n.d.                          | n.d.                           | n.d.                            |
| Tonalite of Bald Mountain | BM10-53               | 140.9    | magnesian (0.46–0.75) | calcic    | metaluminous to peraluminous | 51–71 | 510           | 47             | 11.1             | 9.7                          | 0.7038–0.7043                     | 6.3                             |
|                           | BM10-55               |          |                  |            |            |              |               |                |                  |                               |                                 |                                 |
|                           | BM10-51               | 142.8    |                  |            |            |              |               |                |                  |                               |                                 |                                 |
|                           | BM10-50               | 145.1    |                  |            |            |              |               |                |                  |                               |                                 |                                 |
|                           | BMB-2C                |          | magnesian (0.59–0.67) | calcic    | metaluminous | 55–65        | 415           | 18             | 8.5              | n.d.                          | n.d.                           | n.d.                            |

Note: MALI—modified alkali lime index; ASI—aluminum saturation index; WR—whole rock; Zrn—zircon; n.d.—no data.

*Data from Armstrong et al. (1977).

†Nortie of Willow Creek (Taubeneck, 1957: Armstrong et al., 1977).

METHODS

Samples for whole-rock geochemistry were collected from the principal units of the Bald Mountain batholith. Samples for U-Pb zircon geochronology, zircon trace element, and Lu-Hf and O isotopic analyses consist of three samples from the tonalite of Bald Mountain and single samples from the granodiorite of Anthony Lake, the norite of Badger Butte, the granite of Anthony Butte, and the quartz diorite of Wolf Creek. Major and trace element abundances were determined by inductively coupled plasma–atomic emission spectroscopy at Texas Tech University and the University of Houston-Downtown. Rubidium abundances were determined by atomic absorption spectrometry at Texas Tech University. Whole-rock oxygen isotope analyses were conducted at Texas Tech University and the University of Wisconsin-Madison. Plagioclase and hornblende mineral analyses were conducted at the University of Wyoming using the 5-spectrometer JEOL JXA-8900 electron microprobe. Zircons for geochronology and geochemical analyses were separated following standard methods involving density (Gemini table and heavy liquids) and magnetic (Frantz isodynamic separator) separation techniques at the University of Alabama. Zircons were mounted in epoxy, ground and polished, and imaged on a Gatan MiniCL detector attached to a JEOL 8600 electron microprobe analyzer at the University of Alabama. U-Pb zircon geochronology and trace element analyses were conducted at the U.S. Geological Survey–Stanford SHRIMP-RG (sensitive high-resolution ion microprobe–reverse geometry) facility and the California State University Northridge LA-SF-ICP-MS (laser ablation–sector field–inductively coupled plasma–mass spectrometry) facility. Zircon Hf isotope geochemistry was performed by LA-MC-ICP-MS (MC—multicollector) at the University of Florida using a Nu Plasma MC-ICP-MS and a New Wave 213 nm laser. In situ zircon oxygen isotope ratios were measured at the University of Wisconsin-Madison using the Cameca IMS-1280 ion microprobe. Detailed descriptions of methods for whole-rock geochemistry, isotopic analysis, and sample locations are provided in the Supplemental File.

Whole-rock and mineral geochemical data are reported in the Supplemental File (see footnote 1), and summarized in Tables 1 and 2.

RESULTS

Zircon Geochronology

Zircons from both the norite-granite and tonalite-granodiorite suites display well-developed oscillatory zoning with minor indications of xenocrystic cores and younger overgrowths (Fig. 4). Xenocrystic cores were avoided whenever possible during analysis. Rare Late Jurassic inherited zircons are most common in the tonalite suite and are shown by dashed error ellipses in Figure 5 (also see Table 3). These analyses are excluded in error-weighted average age calculations.

Supplemental File. Zipped file containing detailed description of methods and supplemental figure and tables. If you are viewing the PDF of this paper or reading it online, please visit http://dx.doi.org/10.1130/GES01033.S1 or the full-text article on www.gsapubs.org to view the Supplemental File.

BATHOLITH, BLUE MOUNTAINS PROVINCE, NORTHEASTERN OREGON

1Supplemental File. Zipped file containing detailed description of methods and supplemental figure and tables. If you are viewing the PDF of this paper or reading it online, please visit http://dx.doi.org/10.1130/GES01033.S1 or the full-text article on www.gsapubs.org to view the Supplemental File.

Schwartz et al.

Geosphere, December 2014

1462

Downloaded from https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/2340212/1456.pdf by University of Wisconsin Madison user
A second sample from the northern pluton (BM10-50) yields 24 concordant to slightly discordant LA-SF-ICP-MS spot analyses. The common-Pb corrected, error-weighted average age is 145.1 ± 1.7 Ma (MSWD = 1.5; Fig. 5D), which overlaps within error the SHRIMP-RG spot date of 145.1 ± 1.7 Ma (MSWD = 0.3). This minor, older population likely represents zircons inherited from the norite-granite suite dated in this study (154.7 ± 1.3 Ma to 156.9 ± 1.4 Ma).

Two samples from the central and southwestern regions of the tonalite of Bald Mountain yield SHRIMP-RG error-weighted average ages of 141.2 ± 1.9 Ma (MSWD = 1.0) and 140.9 ± 2.0 Ma (MSWD = 0.5), respectively. Both samples also contained older zircons with individual spot dates of 149.7–146.6 Ma, similar to older, individual spot analyses observed in the northern tonalite (BM10-51).

WHOLE-ROCK GEOCHEMISTRY

Wall Rocks Surrounding the Bald Mountain Batholith

The Elkhorn Ridge Argillite ranges in composition from 74 to 83 wt% SiO₂ (Schwartz et al., 2010). It is characterized by low CaO (<0.5 wt%) and Sr (<300 ppm) concentrations, and low Sr/Y values (<25). Values of δ¹⁸O (whole rock, WR) range from 22.0‰ to 27.6‰ (n = 5). Metaigneous rocks occur as thrust slices of intermediate to felsic composition, a small negative Eu anomaly, and flat heavy rare earth element (HREE) abundances (Fig. 7A). The quartz diorite of Wolf Creek is similar to the norite of Badger Butte, with the exception of a pronounced negative Eu anomaly. The granite of Anthony Butte displays more steeply fractionated REE patterns, and a pronounced negative Eu anomaly. Compared to normal mid-oceanic ridge basalt (N MORB), all three units display large ion lithophile element (LILE) enrichment, and strong positive Pb anomalies in normalized trace element plots (Fig. 7B). Whereas the granite of Anthony Butte and the quartz diorite of Wolf Creek display weak negative Nb anomalies, the norite of Badger Butte displays a slightly positive anomaly. Average zircon and apatite saturation temperatures are 648 °C and 768 °C for the granite of Anthony Butte, 709 °C and 865 °C for the norite of Badger Butte, and 717 °C and 894 °C for the quartz diorite of Wolf Creek (Watson and Harrison, 1983; Harrison and Watson, 1984). Whole-rock δ¹⁸O values for the norite of Badger Butte range from 8.4‰ to 10.4‰ (n = 4), whereas the granite of Anthony Butte yielded a δ¹⁸O value of 10.6‰ (n = 1; see Supplemental File [see footnote 1]).

Tonalite-Granodiorite Suite (147–141 Ma)

Intrusive rocks that compose the majority of the Bald Mountain batholith (Elkhorn pluton of Taube neck, 1957) are generally tonalitic to granodioritic in composition, although some samples are dioritic. For simplicity, we refer to all of these rocks as the tonalite-granodiorite suite. The tonalite-granodiorite suite has variable SiO₂ contents ranging from 52 to 71 wt%, and Mg# values ranging from ~39 to 70. All tonalites and granodiorites are magnesian, calcic, and metaluminous to weakly peraluminous (Figs. 6A–6C). Based on Sr/Y values, REE concentrations, modal mineralogy and
Figure 4. Representative cathodoluminescence images of zircons from the norite-granite and tonalite-granodiorite suites of the Bald Mountain batholith. Locations of ion microprobe and laser ablation spots are shown along with data from each spot. Analysis spots are color coded: white—U-Pb age, green—Lu-Hf, purple—O. Scale bars are 100 µm.
Figure 5. (A–F) Tera-Wasserburg diagrams and error-weighted average age plots for zircons from plutonic rocks of the Bald Mountain batholith. Error ellipses and calculated ages are given at the 95% confidence level. MSWD—mean square of weighted deviates. Dashed error ellipses were excluded in weighted average age calculations.
field relationships, we recognize two subgroups that we classify as the type 1 high-Sr/Y tonalite-granodiorite suite and type 2 low Sr/Y tonalite suite.

Type 1 tonalites and granodiorites are typically located south of intraplate contact A-B (Fig. 3). They are distinguished from older batholithic rocks and the type 2 tonalite-granodiorite suite by high average Sr/Y values (>40), elevated Sr (>450 ppm), but lower than some older units as stated for the norite-granite rocks, and low Y concentrations (<11.6 ppm; Fig. 6D). They display significant drawdown across the middle REEs and HREEs and lack Eu anomalies (Fig. 7C). They also have lower average HREE (Yb < 1.0 ppm) abundances relative to the type 2 suite (Fig. 7D). Relative to NMORB, they are LILE enriched, have strongly positive Pb and Sr anomalies, and negative Nb anomalies (Fig. 7D). Four whole-rock samples from the tonalite of Bald Mountain yielded $\delta^{18}$O values of 9.1‰–12.1‰. Average zircon and apatite saturation temperatures are 728 °C and 885 °C for the type 1 suite, respectively (Watson and Harrison, 1983; Harrison and Watson, 1984).

Type 2 tonalites occur primarily within the norite-granite pluton, north of intraplate contact A-B in Figure 3 (e.g., BM10-51). These samples are distinct from the main batholith in having lower Sr/Y (<40), and higher Y (>15 ppm) and total REE concentrations at equivalent SiO$_2$ concentrations (Figs. 6 and 7). Type 2 samples also have an extended range of SiO$_2$ concentrations (52–70 wt%) that are some of the lowest values of the batholith. Two whole-rock samples yielded $\delta^{18}$O values of 12.7‰–13.1‰. Average zircon and apatite saturation temperatures are 740 °C and 901 °C, respectively, for the type 2 suite (Watson and Harrison, 1983; Harrison and Watson, 1984).

Plagioclase- and hornblende-bearing mafic enclaves are ubiquitous in the type 1 and 2 suites. They are magnesian and metaluminous, but are distinguished from their host rocks by being calc-alkaline to alkalic-calcic in composition, having lower Sr/Y (typically <20), and higher Y and REE concentrations (Figs. 6 and 7C). Mafic enclaves also display low SiO$_2$ (<60 wt%) concentrations relative to typical host rocks. Relative to NMORB, enclaves are LILE enriched, and have negative Nb and Ti anomalies. Two mafic enclaves from the tonalite of Bald Mountain yielded $\delta^{18}$O (WR) values of 8.4‰ and 8.5‰.

### Mineral Geochemistry

**Plagioclase-Hornblende Geochemistry**

We evaluated 14 hornblende-plagioclase pairs from 2 samples from the granodiorite core of the batholith near Anthony Lake for thermobarometry (Supplemental File [see footnote 1]). The average temperature from these coexisting pairs using the Holland and Blundy (1994) plagioclase-hornblende exchange thermometer is 683 ± 41 °C. Pressure is estimated at 0.9 ± 0.6 kbar using the Anderson and Smith (1995) Al-in-hornblende barometer.

**Zircon Trace Element Geochemistry**

We also investigated the relationship between Pb/U age and zircon trace element chemistry through time (Supplemental File [see footnote 1]). REE abundances are shown in Figure 8 and trace element abundances are plotted in Figures 9 and 10. Zircons from the type 1 and 2 tonalite-granodiorite suites are distinguished from older norite-granite zircons by higher average Hf concentrations and lower U and trivalent cation concentrations (Figs. 9A, 9B). Th/U values from the type 1 and 2 suites are slightly lower, but also overlap with those of zircons from older suites (Fig. 10C). Within the tonalite-granodiorite suite, type 2 zircons from the northernmost tonalite sample (BM10-51) consistently plot as a distinct population, displaying higher average U, Y, and HREE concentrations, and lower Eu/Eu* values versus type 1 zircons. These features are more similar to zircons from the older norite-granite suite.

### Zircon Lu-Hf Isotope Geochemistry

Lu-Hf isotopic data were collected from 58 zircons to evaluate possible changes in sources and petrogenetic processes through time (cf. Figs. 9C and 11A; Supplemental File [see footnote 1]). Data from the norite-granite and granodiorite-tonalite suites are summarized in Table 3. Magmatic zircons from the older, low-Sr/Y norite-granite suite yield error-weighted average (2σ) initial Hf values ranging from 7.0 to 7.8. Initial Hf values for type 1 and 2 zircons of the granodiorite-tonalite suite largely overlap with those from the norite-granite suite, yielding values ranging from 6.5 to 9.1. Average individual sample population errors are ~1.3 epsilon units for all samples and are very close to the long-term reproducibility of the standard (FC-1). This suggests that these magmas are fairly well described by these average values. Although there is little statistical difference at the 2σ level in initial εHf between the norite-granite and tonalite-granodiorite suites, average $^{186}$Lu/$^{176}$Hf values decrease from the older to the younger suite (Fig. 10E) regardless of SiO$_2$ concentration. This trend appears similar

### Table 3. Summary of Zircon U-Pb, Lu-Hf, and O Isotope Data

| Unit                  | Sample     | Pb/U zircon age ± 2SD (Ma) (MSWD; n) | Xenocrystic zircon? (age) | $\delta^{18}$O (zircon) average ± 2SD % (n) | $\delta^{18}$O (zircon) range (%) | εHf initial (zircon) weight average ± 2SD (MSWD; n) | εHf initial (zircon) range |
|-----------------------|------------|-------------------------------------|--------------------------|-------------------------------------------|----------------------------------|-------------------------------------------------|-----------------------------|
| Norite of Badger Butte| BM10-54    | 156.9 ± 1.4 (0.8, 10)              | Yes (ca. 164 Ma)          | 9.3 ± 0.5                                 | 9.0–9.6                          | 7.0 ± 1.0                                       | 4.7–10.6                   |
| Quartz diorite of Wolf Creek | BM10-48 | >155                                | No                        | 9.4 ± 1.0                                 | 8.9–10.0                         | 7.7 ± 1.3                                       | 7.5–7.8                    |
| Granite of Anthony Butte | BM10-49  | 154.7 ± 1.3 (1.0, 11)                | No                        | 8.5 ± 0.5                                 | 8.2–9.1                          | 7.8 ± 1.4                                       | 4.7–10.3                   |
| Granodiorite of Anthony Lake | BMO-1    | 146.7 ± 2.1 (1.3, 11)                | No                        | 8.2 ± 0.4                                 | 7.8–8.4                          | 7.6 ± 1.7                                       | 6.0–9.6                    |
| Tonalite of Bald Mountain | BM10-53  | 140.9 ± 2.0 (0.5, 7)                | Yes (ca. 147–150 Ma)       | 9.7 ± 0.4                                 | 9.3–10.0                         | 6.5 ± 1.3                                       | 3.5–9.8                    |
| BM10-55                | 141.2 ± 1.9 (1.0, 9)                | No                        | 9.2 ± 0.4                                 | 9.3–9.7                          | 6.5 ± 1.3                                       | 3.5–9.8                    |
| BM10-51                | 142.8 ± 1.5 (0.6, 8)                | Yes (ca. 146–147 Ma)        | 7.5 ± 0.5                                 | 7.1–7.8                          | 7.9 ± 1.3                                       | 4.8–10.7                   |
| BM10-50                | 145.1 ± 1.7 (1.5, 24)               | Yes (ca. 156 Ma)            | n.d.                                     | n.d.                             | n.d.                                           | n.d.                        |

Note: MSWD—mean square of weighted deviates; SD—standard deviation; n—number; n.d.—no data.
Figure 6. Selected major and trace element plots for plutonic rocks of the Bald Mountain batholith. (A) Fe-number versus SiO₂ illustrating the overall magnesian character of the batholith. (B) Modified alkali lime index (MALI). Mafic enclaves are calc-alkalic, whereas host rocks are calcic. (C) Shand (1947) rock classification index. Batholith rocks are largely metaluminous. (D) Sr/Y versus Y (ppm). Tonalites and granodiorites have high Sr/Y values (>40), whereas rocks of the norite-granite suite have generally lower Sr/Y. Mafic enclaves in type 1 and 2 tonalites and granodiorites overlap in composition and display low Sr/Y values.
to the pattern of higher average Hf contents and lower HREE concentrations in zircons from the tonalite-granodiorite suite. It is noteworthy that type 2 zircons from the northernmost tonalite sample (BM10-51) overlap, but extend to higher average $^{176}$Lu/$^{177}$Hf values compared to the more abundant type 1 zircons of the tonalite-granodiorite suite, despite similar SiO$_2$ contents.

**Zircon Oxygen Isotope Geochemistry**

We made 59 oxygen isotope measurements on 45 magmatic zircons from the Bald Mountain batholith (Figs. 11B and 12). Rock-average $\delta^{18}$O (Zrn) values are summarized in Tables 1 and 3. All individual analyses are provided in the Supplemental File (see footnote 1). Multiple spots were measured on a subset of zircons to test whether $\delta^{18}$O values vary systematically from cores to rims, but we did not observe systematic variations within the analytical precision of the data (cf. Fig. 4).

Cores and rims of magmatic zircon from the norite-granite suite have a mean $\delta^{18}$O of 9.3‰ ± 0.5‰ (norite of Badger Butte), 8.5‰ ± 0.5‰ (granite of Anthony Butte), and 9.7‰ ± 2.0‰.
Cordilleran batholith construction and high-Sr/Y magmatic pulses

Geosphere, December 2014 1469

One undated and possibly xenocrystic zircon from the quartz diorite of Wolf Creek yields an anomalous value of 12.0‰. Excluding this analysis gives a mean δ18O value of 9.4‰ ± 1.0‰ (n = 7).

In general, δ18O values for magmatic zircons from the tonalite-granodiorite suite partially overlap with values from the older granite-norite suite, but also extend to lower values (cf. Figs. 11B and 12; Table 3). Type 1 zircons from the granodiorite core of the batholith have a mean δ18O value of 8.2‰ ± 0.4‰. Type 1 zircons from the sample near the center of the tonalite of Bald Mountain (BM10-55 in Fig. 11) have a mean δ18O value of 8.2‰ ± 0.4‰. One zircon core gave an anomalously high δ18O value of 9.4‰ (Fig. 4). Excluding this value, the mean δ18O value of zircons from BM10-55 is 8.0‰ ± 0.5‰. These zircons have the lowest δ18O values from the batholith.

DISCUSSION

Timing of Batholith Construction

U-Pb zircon geochronology of the Bald Mountain batholith indicates that magmatic construction occurred over a protracted interval of ~15 m.y. and involved two distinct magmatic episodes involving emplacement of small, low-Sr/Y norites and granites from 157 to 155 Ma, and more areally extensive tonalites and granodiorites from 147 to 141 Ma. Our age determinations from the tonalite-granodiorite suite are consistent with

Downloaded from https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/3340212/1456.pdf by University of Wisconsin Madison user
the single age from Walker (1989), but also indicate that the pulse of tonalite-granodioritic magmatism was transient and restricted to a 6 m.y. interval. Moreover, our ages also demonstrate that although the low- and high-Sr/Y suites are geographically coincident, they are not temporally or genetically linked. From a regional perspective, the low-Sr/Y suite was emplaced during the final stages of arc-arc collision (159–154 Ma; Schwartz et al., 2011a). The amagmatic interval in the Blue Mountains province lasted for ~6 m.y. and was followed by a renewed phase of regionally extensive, high-Sr/Y magmatism that extended from the Blue Mountains in Oregon to the Klamath Mountains in northern California (Barnes et al., 1996, 2006; Schwartz et al., 2011b).

The primary batholith construction phase commenced with ca. 147 Ma intrusion of the high-Sr/Y granodiorite of Anthony Lake (Schwartz et al., 2011a), which is currently exposed in the core of the batholith. Subsequently, tonalitic magmas intruded the core granodiorite between 145 and 141 Ma, and involved emplacement of three large tonalite bodies (both type 1 and type 2 tonalite suites). Taubeneck (1957, 1995) distinguished these as separate intrusions based on apparent intraplutonic contacts (Fig. 3; A-B and C-D) and mineralogical differences. Within the resolution of our geochronologic data, we cannot distinguish whether these intrusions are distinct in age; however, we note that they are distinct in geochemistry (see following) and likely represent three separate, large magmatic units that exhibit subtle intraplutonic contacts.

**Magma Sources and the Role of Supracrustal Assimilation**

Norite-granite plutons in the Bald Mountain batholith are characterized by LREE and LILE enrichment, and weakly positive to negative Nb anomalies. Relative to the main tonalite-granodiorite suite (type 1), rocks from the norite-granite suite display low Sr concentrations (<400 ppm), Sr/Y (<40), and high Y (>15 ppm) values. One sample from the norite of Willow Lake yields a low initial $^{87}\text{Sr}/^{86}\text{Sr}$ (0.7037).
Figure 10. Selected zircon trace element and isotopic values versus $^{206}\text{Pb}/^{238}\text{U}$ age. Timing of arc-arc collision is shown by the blue field (Schwartz et al., 2011a). (A) Heavy rare earth element (HREE) (Dy + Er + Yb) (ppm) versus $^{206}\text{Pb}/^{238}\text{U}$ age. (B) Eu/Eu* versus $^{206}\text{Pb}/^{238}\text{U}$ age. (C) Th/U versus $^{206}\text{Pb}/^{238}\text{U}$ age. (D) Hf (ppm) versus $^{206}\text{Pb}/^{238}\text{U}$ age. (E) $^{176}\text{Lu}/^{177}\text{Hf}$ versus $^{206}\text{Pb}/^{238}\text{U}$ age. Zircons from postcollisional tonalites and granodiorites show lower concentrations of HREEs, higher Eu/Eu* values, and lower average Th/U values. They overlap, but also extend to higher Hf concentrations as well.
Apatite saturation temperatures for the norite-granite suite range from ~770 to 900 °C. These features are collectively similar to those found in magmas generated in oceanic island-arc settings and are indicative of hydrous partial melting of mantle peridotite and/or mafic-arc crust (Kelemen et al., 2003).

Although whole-rock trace element geochemical features discussed here suggest a mantle and/or mafic-arc crust source for these rocks, oxygen and Hf isotopic compositions of zircons also provide evidence for supracrustal contamination. For example, initial εHf values are moderately positive (+6.3–7.9), yet they are substantially lower than depleted mantle ca. 147 Ma (~15; Vervoort et al., 1999) and average modern island-arc values (~13; Dhuime et al., 2011; cf. Fig. 11A). Similarly, δ18O(Zrn) values (8.2‰–10.0‰) are much higher than values in modern island-arc values (~13; Dhuime et al., 2011; cf. Fig. 11A). Similarly, δ18O(Zrn) values (8.2‰–10.0‰) are much higher than values in 147 Ma (~15; Vervoort et al., 1999) and average modern island-arc values (~13; Dhuime et al., 2011; cf. Fig. 11A).

Assimilation of high δ18O Elkhorn Ridge Argillite would not only change oxygen and Hf isotopes, but would also change the whole-rock major and trace element composition of the parental magma. We test the validity of argillite assimilation by assuming a 3‰ increase in δ18O (WR) values from ~7‰–10‰ by bulk assimilation of average Elkhorn Ridge Argillite with a value of +25‰. With these parameters, bulk mass balance calculations suggest ~15% assimilation and/or exchange of Elkhorn Ridge Argillite oxygen. Using the compositions of a norite (BM10-54) and Elkhorn Ridge Argillite (DB-06–34; Supplemental File [see footnote 1]), whole-rock mass balance calculations yield realistic basaltic parental (pre-assimilation) magma compositions with the following values: SiO2, 47.6 wt%; Al2O3, 19.5 wt%; CaO, 11.6 wt%; FeO(total), 9.4 wt%; MgO, 6.8 wt%; Sr, 550 ppm; Ba, 378 ppm. The Elkhorn Ridge Argillite is characterized by low Al2O3 concentrations (<15.5 wt%), which are similar to or less than all plutonic rocks in the Bald Mountain batholith. Consequently, assimilation of Elkhorn Ridge Argillite has a modest effect on the major element (e.g., Al2O3) and trace element compositions and yields values consistent with a high Al-basaltic primary magma composition (see hypothetical calculated compositions herein). Compositions similar to those predicted here are also found in the norite of Badger Butte (e.g., BMB-10) and in the nearby North Fork pluton (Johnson and Schwartz, our data).

Tonalites and granodiorites from the type 1 suite have major and trace element characteristics similar to melts produced by dehydration–partial melting of garnet-bearing basaltic sources such as garnet amphibolite and/or eclogite at high pressures (>1.0 Gpa; e.g., Wolf and Wyllie, 1993, 1994; Rapp, 1995). For example, type 1 tonalites and granodiorites have low Mg numbers (~40–50) and high Al2O3 concentrations (>15 wt%) that overlap the range of experimental melts produced by dehydration–partial melting of amphibolites (Sen and Dunn, 1994, Rapp and Watson, 1995). Type 1 tonalites and granodiorites also display low HREE (Yb < 1.0 ppm) and Y (<11.6 ppm) abundances, high LREE/HREE (La/Yb > 13.9), high Sr abundances (>450 ppm), and high Sr/Y values (>40). Elevated Sr contents (>400 ppm) and a lack of Eu anomalies in whole rock, chondrite-normalized REE abundance patterns further suggest that plagioclase was not a residual phase in the restite or a prominent crystal fractionate. The lack of positive Eu anomalies, and Al2O3 and CaO concentrations <20 wt% and 10 wt%, respectively, also indicate that type 1 tonalites and granodiorites have not undergone significant crystal accumulation. Relatively low initial 87Sr/86Sr values of 0.7038–0.7044 are indicative of juvenile mafic crust as a potential source for members of the tonalite-granodiorite suite. These magma compositions are similar to hydrous melts produced by dehydration melting.
Cordilleran batholith construction and high-Sr/Y magmatic pulses

Figure 12. (A) Histogram of δ¹⁸O (Zrn) for low-Sr/Y, norite-granite suite. (B) Histogram of δ¹⁸O (Zrn) for high-Sr/Y, tonalite-granodiorite suite. Both suites are characterized by elevated δ¹⁸O values relative to the mantle; however, the tonalite-granodiorite suite extends to slightly lower δ¹⁸O values. Mantle-equilibrated zircon value of 5.3 ± 0.6 ‰ (2 standard deviation) is from Valley (2003). VSMOW—Vienna standard mean ocean water.

Experiments in which the residuum consists of a plagioclase-poor to absent, garnet + amphibole + clinopyroxene ultramafic assemblage. Such assemblages are common in granulite terranes that have undergone dehydration–partial melting of mafic sources (e.g., lower crust of Kohistan; Garrido et al., 2006), and garnet amphibolites occur within the Blue Mountains province in the Salmon River suture zone (Selverstone et al., 1992) and the Mine Ridge Mountains province in the Salmon River suture zone. Amphibolitic gneisses are also interpreted to be derived in large part from recycling of hydrothermally altered (high δ¹⁸O) oceanic crust and/or relatively young volcanic arc sedimentary rocks (Lackey et al., 2006). A possible origin for the high δ¹⁸O magmas of the Bald Mountain batholith may include partial assimilation of hydrothermally altered mafic arc crust (e.g., Wallowa-derived metagabbros) or supra-arc metasedimentary rocks (e.g., Elk Horn Ridge Argillite), both of which occur as xenoliths within the tonalite-granodiorite suite. Although partial assimilation from both sources is possible, field evidence reveals minor reaction textures and little to no migmatization of foliated metagabbro xenoliths (Taubeneck, 1995). Field observations indicate that some dioritic enclaves display fine-grained chilled margins against host granodiorites, suggesting that they are coeval magmas. Mafic enclaves are distinct from host rocks in being calc-alkaline to alkaline-calcic, having much higher Y and HREE concentrations (cf. Figs. 6 and 7), and having lower Sr/Y values (<40) at equivalent Mg# (Fig. 13C). Mafic enclaves also have lower δ¹⁸O values (WR = 8.4‰–8.5‰) than measured δ¹⁸O (WR) values for host tonalites and granodiorites (9.6‰–13.1‰). However, δ¹⁸O values of enclaves are still greater than expected for basaltic melts in equilibrium with mantle (Harmann and Hoefs, 1995), which is also consistent with minor assimilation of Elk Horn Ridge Argillite by the parental magma of the enclaves. The LILE enrichment and negative Nb and Ti anomalies suggest that the enclaves formed from subduction-related partial melting of mantle peridotite. These characteristics indicate that enclaves represent a distinct and unrelated magma to those that formed the tonalite-granodiorite suite. Further, the presence of mafic enclaves may indicate the presence of larger volumes of mafic magma at depth and would provide a heat source for partial melting of lower arc crust (see partial melting models discussion following).

Type 2 tonalities occur in the northernmost augite-hornblende pluton and are geochemically similar to low-Sr/Y mafic enclaves. They are both characterized by low average Sr/Y values (<40), and higher Y (>16 ppm) and HREE (Yb > 1.3 ppm) concentrations. Similarly, type 2 zircons are characterized by higher average U, Y, and HREE concentrations, and lower Eu/Eu⁺ values relative to type 1 zircons (Figs. 6 and 7).
Figure 13. (A, B) Results of partial melting calculations with a metagabbro source rock (B133A). Partial melting results in the generation of an amphibole + clinopyroxene (cpx) + garnet (gnt) restite. Abbreviation: hbl—hornblende, cpx—clinopyroxene, bio—biotite, apt—apatite, plag—plagioclase, qtz—quartz, zrc—zircon, sph—sphene, amph—amphibole. The partial melting curve describes the majority of the data and predicts a melt fraction between 10% and 40% for most samples. Several type 2 tonalite samples with low Sr/Y values (<40) are not well described by the partial melting curve and yield unrealistically large melt fractions (50%–80%). Binary mixture models (e.g., Fig. 13D) suggest that they may be mixtures of high- and low-Sr/Y magmas. (C) Sr/Y versus Mg#. Samples from the tonalite-granodiorite suite display decreasing Sr/Y values with decreasing Mg#, consistent with a plagioclase fractionation trend. Mafic enclaves are distinct from host tonalite-granodiorite with distinctly low Sr/Y at equivalent Mg#. Mg# is calculated as 100 × molar MgO/(MgO + FeOtot). (D) Results of binary mixture models between a high-Sr/Y tonalite end member and (1) a low-Sr/Y mafic enclave and (2) average Elkhorn Ridge Argillite. The binary mixture model involving high and low-Sr/Y magmas fairly accurately describes the composition of the low-Sr/Y type 2 tonalites from the northernmost pluton. Sample numbers are listed in Table 1.
plutonic rocks represent liquid compositions. Trace element and REE fractionation models use partition coefficients reported in Schwartz et al. (2011b) for consistency.

Results from our calculations demonstrate that low-pressure, fractionation of plagioclase + hornblende yield unacceptable results (ssr > 1); however, mass balance calculations involving assemblages fractionating at high pressure, including plagioclase + garnet ± clinopyroxene ± omphacite ± hornblende ± biotite ± sphene ± apatite, were successful (models 5A, 8A, 9A, 11A, 12A, 15A, 17A; Supplemental File [see footnote 1]). These assemblages were further tested with trace element and REE calculations. Whereas several models matched the Sr/Y variations observed in our sample suite, all models failed to reproduce Y and REE concentrations for the 1 high-Sr/Y tonalite-granodiorite rocks. Fractionation of plagioclase predicted by the high-pressure assemblage is also inconsistent with the high Sr concentrations and absence of Eu anomalies in the tonalite-granodiorite suite. No acceptable solutions were obtained for plagioclase-free, high-pressure fractionation assemblages containing garnet ± clinopyroxene ± omphacite ± hornblende. We conclude, therefore, that fractional crystallization of a low-Sr/Y mafic magma did not produce the 1 high-Sr/Y magmas in the Bald Mountain batholith.

For type 2 low-Sr/Y magmas, we use the composition of the same two primitive low-Sr/Y mafic enclaves (BMB-2C, BM2) as a parental composition, and the composition of a type 2 low-Sr/Y granodiorite (BMB-4A) as a daughter composition. Although garnet and clinopyroxene are not present in type 1 tonalite-granodiorite suites or in the mafic enclaves, we assume perfect Rayleigh fractionation and that

**Whole-Rock and Zircon Geochemical Modeling of Type 1 and 2 Tonalite-Granodiorite Magmas**

Magas with high Sr/Y can be generated in a variety of ways including (1) high-pressure partial melting of mafic crust (e.g., Drummond and Defant 1990; Barnes et al., 1996; Petford and Atherton 1996; Johnson et al., 1997), (2) high-pressure fractional crystallization (Arth et al., 1978; MacPherson et al., 2006; Alonso-Perez et al., 2009), and (3) magma mixing (Guo et al., 2007a, 2007b). Here we evaluate the origin of the high-Sr/Y, type 1 tonalites and granodiorites in the Bald Mountain batholith by investigating various fractional crystallization, partial melting, magma mixing, and energy-constrained, recharge-assimilation-fractional crystallization models. We also investigate the origin of the less abundant type 2 low-Sr/Y tonalitic magmas as products of either low-pressure partial melting of mafic crust and/or magma mixing between basaltic melts and high-Sr/Y, type 1 magmas.

**Fractional Crystallization Models**

Major element mass balance calculations (Bryan et al., 1969) were performed to test whether type 1 and 2 magmas could be generated by fractional crystallization of a common mafic magma. In the case of the high-Sr/Y, type 1 magmas, we use the composition of two primitive low-Sr/Y mafic enclaves (BMB-2C, BM2) as a parental composition, and the composition of a type 1 high-Sr/Y granodiorite (BMB-4A) as a daughter composition. Although garnet and clinopyroxene are not present in type 1 tonalite-granodiorite suites or in the mafic enclaves, we use values reported in Alonso-Perez et al. (2009) for our models to test whether extraction or retention of garnet + clinopyroxene at depth may have played a role in the generation of the type 1 suite. We also evaluate the role of omphacite as a possible fractionating phase because it is observed together with garnet in the deep roots of some mafic arcs (e.g., Fiordland, New Zealand: De Paoli et al., 2009). Models were considered successful if the sum of the square of the residuals (ssr) was <1.0, indicating low variation between the calculated and observed daughter compositions. In these calculations we assume perfect Rayleigh fractionation and that
the type 1 high-Sr/Y magma and mafic enclave demonstrate that 15%–25% mixing of mafic enclave with type 1 magma reproduces the composition of type 2 lower Sr/Y tonalites from the northern portion of the batholith (model 2B in Fig. 13D). Binary mixing models using major elements (e.g., SiO₂, Al₂O₃, CaO, Na₂O, K₂O) and the same type 1 tonalite and mafic enclave end members yield similar results, although in some cases the mixing does not reproduce the composition of sample BM10-50 (e.g., mixture model for Sr/Y versus SiO₂, not shown). In contrast, simple binary mixing of average Elkhorn Ridge Argillite with a high-Sr/Y magma does not satisfactorily reproduce the composition of the low-Sr/Y tonalites (Fig. 13D). These results suggest that the composition of the type 2 lower Sr/Y (<40) tonalites could result from mixing between a type 1 high-Sr/Y magma and a coeval, low-Sr/Y mafic magma. These results are also in agreement with the overall more mafic composition of the type 2 mafics (including the presence of augite as a phenocryst phase), and their lower δ¹⁸O (Zn) values compared to the type 1 tonalite-granodiorite suite. A problem with this model is that coeval mafic magmas are only present as enclaves and are nowhere found as separate physical entities (e.g., gabbro plutons). Where gabbros and norites are found, they are older (e.g., Badger Butte norite) and are geochemically unrelated. It is possible that enclaves were derived from more extensive basaltic magmas at depth, which are not exposed at the current level of erosion.

Energy-Constrained, Recharge-Assimilation-Fractional Crystallization Models

More complex and realistic models involving energy-constrained, recharge-assimilation-fractional crystallization (EC-RAFC) were developed to test magma evolution of the high-Sr/Y magmas. We use both whole-rock and zircon trace element and isotopic data and the Spéra and Bohrson (2002) EC-RAFC model to explore various scenarios. Input parameters for our models are given in Table 4. The εHf values for the assimilant (Elkhorn Ridge Argillite) were calculated from average εNd values reported in Schwartz et al. (2010) using the Verhoort et al. (1999) crustal Hf-Nd relationship; the latter is an empirical best-fit, linear relationship between Hf and Nd isotopes derived from a global study of sediments, continental basalts, granitoids, and juvenile crustal rocks. Although at the fine scale it is likely that Nd and Hf are decoupled, our calculated Hf isotopic values simply serve to approximate the isotopic composition of the Elkhorn Ridge Argillite as an end-member composition. Initial ε⁸⁷⁶⁶Sr values for wall rocks were calculated to 147 Ma from data in Schwartz et al. (2010). Meltus temperatures for tonalite and recharge magmas were calculated from whole-rock compositions using the MELTS algorithm (Ghiorso and Sack, 1995).

Figures 14A and 14B depict the geochemical evolution of the type 1 tonalite-granodiorite magma as it follows our modeled EC-RAFC path. As temperature decreases from an initial ~1050 °C, the Sr concentration of the magma decreases by fractional crystallization, during which time the wall rock (Elkhorn Ridge Argillite) gradually thermally equilibrates with the magma. When the magma reaches ~675 ppm Sr (or ~890 °C), the wall rock is heated above its solidus and anatectic melts form and are added to the magma, with the net result of increasing the Sr concentration of the magma. In general, the whole-rock geochemical models fairly accurately reproduce the trends we observe in our data; however, in our Sr versus ε⁸⁷⁶⁶Sr model (Fig. 14A), four data points are below the best-fit magma evolution line suggesting that a lower ε⁸⁷⁶⁶Sr value for the assimilant may be more appropriate for those samples. We also observe slightly more scatter in our measured whole-rock Sr-δ¹⁸O(WR) model (Fig. 14B), which may reflect some degree of low-temperature alteration of whole-rock oxygen isotopes by hydrothermal fluids associated with Tertiary volcanism in the region (Ferns and Taubenock, 1994).

Intracrystalline diffusion in zircon is very slow for oxygen and Hf, and isotope ratios will not be affected by low-temperature alteration in the absence of radiation damage and a fluid phase (cf. Cherniak et al., 1997; Cherniak and Watson, 2003; Page et al., 2007; Bowman et al., 2011). Thus, analyses of zircons allow us to investigate EC-RAFC models at the mineral scale. Using the same thermal parameters as in the whole-rock models (cf. Table 4), EC-RAFC models also reproduce the variation in our zircon Hf-O data (Fig. 15). We find that slight variations in the Hf concentration of the assimilant from 0.8 to 1.2 ppm encompass the majority of the natural sample variation. Since the Hf budget of the assimilant will largely be contained within detrital zircon, incomplete or partial

---

**TABLE 4. EC-RAFC PARAMETERS FOR Sr-O-Hf GEOCHEMICAL MODELS**

| Thermal parameters |                  |                  |
|--------------------|------------------|------------------|
| Magma liquidus temperature (T_m) | 1050 °C | Crystalization enthalpy of magma (J/kg) | 396000 |
| Magma initial temperature (T_m) | 1050 °C | Isobaric specific heat of magma (J/kg per K) | 1484 |
| Assimilant liquidus temperature | 800 °C | Fusion enthalpy (J/kg) | 270000 |
| Assimilant initial temperature | 400 °C | Isobaric specific heat of assimilant (J/kg per K) | 1370 |
| Solidus temperature | 650 °C | Crystalization enthalpy of recharge magma (J/kg) | 396000 |
| Recharge magma liquidus temperature | 1150 °C | Isobaric specific heat of recharge magma (J/kg per K) | 1484 |
| Recharge magma initial temperature (T_m) | 1150 °C |                  |
| Equilibration temperature (T_e) | 800 °C |                  |

| Compositional parameters | Sr | δ¹⁸O | Hf |
|--------------------------|----|------|----|
| Magma initial concentration | 800 ppm | 0.7045 | 5.3 | 15 |
| Magma isotope ratio | 0.7045 | 5.3 | 15 |
| Magma trace element distribution coefficient | 1.5 | 0.2 |
| Enthalpy of trace element distribution reaction | – | – |
| Assimilant initial concentration | 75 ppm | 0.7100 | 25 |
| Assimilant isotope ratio | 0.7100 | 25 | 0.8–1.2 ppm |
| Assimilant trace element distribution coefficient | 0.05 | 0.2 |
| Enthalpy of trace element distribution reaction | – | – |
| Recharge magma initial concentration | 600 ppm | 0.7035 | 5.3 | 15 |
| Recharge magma isotope ratio | 0.7035 | 5.3 | 15 |
| Recharge magma trace element distribution coefficient | 1.5 | 0.2 |
| Enthalpy of trace element distribution reaction | – | – |

**Note:** EC-RAFC—energy-constrained, recharge-assimilation-fractional crystallization. Dashes indicate no input data.
dissolution of zircons into the magma prior to zircon saturation could account for the varying Hf concentrations of the assimilant required to describe the data. Detrital zircon cores were not directly targeted for analysis in this study; however, cathodoluminescence imaging reveals that distinct cores are present as minor components in zircons in most plutonic rocks of the batholith, indicating that incomplete dissolution of preexisting zircon was a likely process during magmatic evolution. Although the EC-RAFC models simulate magma evolution after emplacement, we note that assimilation of wall rock may also occur at depth during magma ascent. Thus, results of the whole-rock and zircon models underscore the importance of supracrustal (wall rock) contamination in the evolution of the Bald Mountain batholith.

Figure 14. Results of energy-constrained, recharge–assimilation–fractional crystallization (EC-RAFC) models. (A) Initial $^{87}\text{Sr}/^{86}\text{Sr}$ versus Sr for whole-rock samples (data from Armstrong et al., 1977). (B) Measured and calculated $\delta^{18}\text{O}$ (WR—whole rock) versus Sr. VSMOW—Vienna standard mean ocean water. Calculated $\delta^{18}\text{O}$ (WR) were determined from $\delta^{18}\text{O}$ (Zrn) values using the Lackey et al. (2008) equation. Data for Elkhorn Ridge Argillite and metaigneous wall rocks are from Schwartz et al. (2010) and Schwartz and Johnson (our data). Teq, $T_m$, and $T_m^*$ refer to temperature of equilibration (or final magma temperature in the model), magma temperature, and initial magma temperature, respectively. Parameters for EC-RAFC are provided in Table 4.

Figure 15. $\varepsilon\text{Hf}(\text{Zrn})$ versus $\delta^{18}\text{O}$ (Zrn) with results of energy-constrained, recharge–assimilation–fractional crystallization (EC-RAFC) models for the high and low-Sr/Y suites. VSMOW—Vienna standard mean ocean water; $\varepsilon\text{Hf}$ and $\delta^{18}\text{O}$ mantle zircon compositions are after Vervoort et al. (1999) and Valley (2003). The variation in O and Hf isotope ratios can be reproduced by slight variations in the Hf concentration of the assimilant (ERA—Elkhorn Ridge Argillite). See text for details of the model. Teq, $T_m$, and $T_m^*$ refer to temperature of equilibration, magma temperature, and initial magma temperature, respectively. Parameters for EC-RAFC are provided in Table 4.
High-Sr/Y Magmas as Recycled Continental Crust

Geochemical modeling indicates that the type 1 high-Sr/Y magmas are largely derived from partial melting of preexisting, likely Triassic mafic arc crust and assimilation of metasedimentary wall rock either at depth or at the present level of emplacement. The high-Sr/Y magmatic rocks primarily represent recycling of isotopically juvenile, Triassic arc crust of the underthrust Wallowa arc, rather than new Cretaceous additions to continental crust. However, the presence of mafic enclaves presents convincing evidence that mantle-derived basaltic magmas were emplaced prior to or contemporaneously with the high-Sr/Y suite, and these basaltic melts likely provided thermal energy to partially melt the lower crust. Furthermore, type 2 low-Sr/Y tonalites extend to more mafic and juvenile isotopic compositions; this indicates that they were derived from or mixed to a larger degree with mantle-derived magmas (cf. Fig. 13D). Deep-crustal magma mixing as an origin for the type 2 low-Sr/Y tonalites is also supported by numerical simulations of basalt diking that demonstrate the inefficiency of voluminous partial melting outside the lower crust (Dufek and Bergantz, 2005).

Studies of collisional orogenic belts commonly invoke erosion-driven upward rebound of depressed geothermal gradients and/or radioactive self-heating to partially melt the middle to lower crust (England and Thompson, 1984; Patiño Douce et al., 1990; Gerdes et al., 2000). Time scales for partial melting by these mechanisms vary, but are typically tens of millions of years (Beaumont et al., 2004; Jamieson et al., 2004). The 7 m.y. time interval between collisional orogenesis and partial melting in the Blue Mountains province (154–147 Ma) is short and probably required advection of heat from mantle-derived melts in addition to heating from relaxation of geotherms to internally generate the temperatures required for partial melting (>900 °C), assuming equilibrium geothermal conditions prior to collision. One possibility is that mantle heat was supplied by mafic underplating generated by renewed subduction-related magmatism associated with reorganization of plate boundaries following arc-arc collision (cf. model in Schwartz et al., 2011b; Figs. 2A–2C). In this scenario, increased mantle convective power input during subduction resulted in the development of a MASH zone (melting, assimilation, storage, homogenization; Hildreth and Moorbath, 1988) at the lower crust–mantle transition, where underplated basalts mixed with lower crustal (Wallowa arc) partial melts. Figure 16 shows our conceptual view for the generation of the tonalite-granodiorite suite whereby the high-Sr/Y type 1 magmas are chiefly lower crustal partial melts with limited influence from basalt-crustal melt mixing. By contrast, low-Sr/Y type 2 magmas reflect greater mixing and homogenization with basaltic melts. Both type 1 and 2 magmas assimilated arc-related wall rock at depth, during ascent or at the level of emplacement. Enclaves present in both type 1 and 2 magmas likely represent injections of a distinct mantle-derived low-Sr/Y magma, the source of which may have driven deep-crustal anatexis beneath the Bald Mountain batholith.

CONCLUSIONS

Maggmatic construction of the Bald Mountain batholith occurred over ~15 m.y., commencing with the synollisional emplacement of the low-Sr/Y (<40) norite-granite suite. This event included emplacement of the norite of Badger Butte (156.9 ± 1.4 Ma) and the granite of Anthony Butte (154.7 ± 1.3 Ma). Plutons of similar age occur throughout the Baker terrane and signify the waning stages of subduction-related magmatism associated with terminal arc-arc collision (Schwartz et al., 2011b) between the Wallowa and Olds Ferry island-arc terranes.

A second phase of postcollisional magmatism is characterized by the emplacement of tonalitic to granodioritic magmas from 147 to 141 Ma. The majority of these magmas (type 1) are high-Sr/Y (>40) tonalites and granodiorites that are postcollisional and have geochemical signatures consistent with dehydration–partial melting of garnet-bearing amphibolites, leaving behind a plagioclase-poor residue of garnet + amphibole + clinopyroxene. A second suite of lower Sr/Y (<40), augite-bearing tonalites (type 2) in the northernmost portion of the batholith has distinct geochemical characteristics and represents (1) mixing between a high-Sr/Y felsic magma and low-Sr/Y mafic magma, (2) mid-crustal (<1.0 GPa) partial melting of mafic crust leaving behind an amphibolite +

Figure 16. Detailed model for the generation of the tonalite-granodiorite suite of Bald Mountain batholith. High-Sr/Y rocks were generated by dehydration–partial melting of mafic arc crust in a lower crustal MASH zone (melting, assimilation, storage, homogenization; Hildreth and Moorbath, 1988) at ~1.0 GPa pressure. Heat was supplied by mafic underplating of subduction-related magmas. During ascent through the Baker terrane, high-Sr/Y magmas assimilated high-δ18O Elkhorn Ridge Argillite (ERA). Low-Sr/Y tonalites of the northernmost pluton represent mixing and homogenization with crustal and basaltic melts at depth or partial melts of Wallowa arc crust at intermediate depths.
that was triggered by the addition of heat from largely represents recycling of existing crust the observed pulse of type 1 high-Sr/Y magmas Argillite) either at depth and/or during ascent from those exposed in other arc sections (e.g., diorite suite, and therefore are not considered plutons, such as the norite of Badger Butte, can-16). We also conclude that older Jurassic mafi c orogenically thickened Wallowa arc crust (Fig. 8). We speculate that these bodies may exist at depth and may have provided a heat source for lower crustal anatexis. The ubiquitous occurrence of mafi c enclaves that represent injections of mantle-derived basalts into tonalitic to granodioritic magma chambers. We suggest that increased mantle power associated with renewed subduction-related magmatism beginning ca. 147 Ma (Schwartz et al., 2011b) generated mafi c enclaves and putative deep-crustal mafi c magmas. This influx of basalt and heat triggered lower crustal partial melting of orogenically thickened Wallowa arc crust (Fig. 16).

We also conclude that older Jurassic mafi c plutons, such as the norite of Badger Butte, cannot be chemically related to the tonalite-granodiorite suite, and therefore are not considered an important component of arc construction from 147 to 141 Ma. This observation distinguishes norites in the Bald Mountain batholith from those exposed in other arc sections (e.g., Kohistan and Talkeetna; Garrido et al., 2006; Kelemen et al., 2003) where they are commonly interpreted as important cumulate components of subduction-related arc magmatism. We also note that all plutonic rocks in the Bald Mountain batholith, including the norite-granite suite and both type 1 and type 2 tonalites and granodiorites, show evidence for significant assimilation of metasedimentary wall rock (Elkhorn Ridge Argillite) either at depth and/or during ascent to shallow crustal pressures. We conclude that the observed pulse of type 1 high-Sr/Y magmas largely represents recycling of existing crust that was triggered by the addition of heat from underplated, subduction-related mafi c magmas.

ACKNOWLEDGMENTS

We acknowledge discussions and comments by Mark L. Ferns, Art Snoke, and Cal Barnes. We thank Craig Grimes for assistance with sample preparation and for discussions in situ analysis of zircons for δ18O. We also thank Brad Ito for keeping the SHRIMP-RG (sensitive high-resolution ion microprobe-reverse geometry) working so well and efficiently, and George Kamenov for assistance with Lu-Hf analyses. Noriko Kita and Jim Kern assisted in the Wisconsin Secondary Ion Mass Spectrometer Laboratory (WiscSIMS). We thank Mike Spicuzza for assistance with laser fluorination of analyses of δ18O. We thank Howard Stowell for assistance with pseudosection modeling of the Elkhorn Ridge Argillite, and Jonathan Rivas and Brian Clements for assistance in the California State University Northridge LA-SF-ICPMS laboratory (laser ablation–sector field–inductively coupled plasma–mass spectrometry). The manuscript benefited greatly from reviews by Jonathan Miller, Diane Clemens-Knot, Associate Editor Rita Economos, and Science Editor Shanaika de Silva. Partial financial support for this work was provided by National Science Foundation (NSF) grant EAR-0911681 (to Schwartz), NSF grant EAR-0911735 (to Johnson), and a University of Houston–Downtown Organized Research Committee grant (to Johnson). WiscSIMS is partially supported by NSF grants EAR-0319230, EAR-0744079, and EAR-1053466.

REFERENCES CITED

Alonso-Perez, R., Muntener, O., and Ulmer, P., 2009. Igneous garnet and amphibole fractionation in the roots of island arcs: Experimental constraints on andesitic liquids: Contributions to Mineralogy and Petrology, v. 157, p. 541–558, doi:10.1007/s00410-008-0353-8.
Anderson, J.L., and Smith, D.R., 1995, The effect of temperature and oxygen fugacity on Al-in-hornblende rock fractionation of a basaltic magma.
Ashley, R.P., 1995. Petrology and deformation history of the Burnt River Schist and associated plutonic rocks in the Pilot Range, southwestern Idaho, northeastern Oregon, in Pallier, T.L., and Brooks, H.C., eds., Geology of the Blue Mountains region, Idaho and Washington: Geological Society of America Bulletin, v. 88, p. 379–411, doi:10.1130/0016-7606(1995)88<379:PADHOT>2.3.CO;2.
Arth, J.G., Barker, F., Peterman, Z.E., and Friedman, I., 1980, Geochemistry of the gabbronorite-tonalite-trondhjemite suite of southwest Finland and its implications for the origin of tonalite and trondhjemite magmas: Journal of Petrology, v. 20, p. 299–316, doi:10.1093/ptel/20.2.289.
Ashey, R.P., 1995, Petrology and deformation history of the Burnt River Schist and associated plutonic rocks in the Pilot Range, southwestern Idaho, northeastern Oregon, in Pallier, T.L., and Brooks, H.C., eds., Geology of the Blue Mountains region, Idaho and Washington: Geological Society of America Bulletin, v. 88, p. 379–411, doi:10.1130/0016-7606(1995)88<379:PADHOT>2.3.CO;2.
Brown, S.J.A., and Fletcher, I.R., 1999, SHRIMP U-Pb dating of the pre-eruption growth history of zircons from the 340 kA Whakamaru Ignimbrite, New Zealand: Evidence for >250 kA magma residence times: Geology, v. 27, p. 1035–1038, doi:10.1130/0091-7613(1999)027<1035:SPIDOT>2.3.CO;2.
Bryan, W.B., Finger, L.W., and Chayes, F., 1969, Estimating proportions in petrogenetic models by least squares approximation: Science, v. 163, p. 926–927, doi:10.1126/science.163.3870.926.
Cecil, M.R., Rotberg, G., Ducea, M.N., Saleeby, J.B., and Gehrels, G.E., 2012, Magmatic growth and batholithic root development in the northern Sierra Nevada, California: Geosphere, v. 8, p. 592–606, doi:10.1130/GEOS0729.1.
Charlier, H.L., Wilson, C.J.N., Lowenstern, J.B., Blake, S., van Calsteren, P.W., and Davidson, J.P., 2005, Magma generation at a large, hyperarcic silicic volcano (Taupo, New Zealand) revealed by U-Th and U-Pb systemsatics in zircons: Journal of Petrology, v. 46, p. 3–32, doi:10.1144/0022-1526(2005)046<0003:MGGALT>2.0.CO;2.
Chung, S.L., Liu, D.Y., Ji, J.Q., Chu, M.F., Lee, H.Y., Wen, D.J.O., Lo, C.H., Lee, T.Y., Qian, Q., and Zhang, Q., 2003, Adakites from continental collision zones: Melt-18O. We thank Harold Stowell for provision of oxygen isotope data from the Burnt River Schist: Geology, v. 31, p. 719–722, doi:10.1130/0091-7613(2003)031<0719:ADFTCC>2.0.CO;2.
Chung, S.L., Liu, D.Y., Ji, J.Q., Chu, M.F., Lee, H.Y., Wen, D.J.O., Lo, C.H., Lee, T.Y., Qian, Q., and Zhang, Q., 2003, Adakites from continental collision zones: Melt-18O. We thank Harold Stowell for provision of oxygen isotope data from the Burnt River Schist: Geology, v. 31, p. 719–722, doi:10.1130/0091-7613(2003)031<0719:ADFTCC>2.0.CO;2.
Chung, S.L., Liu, D.Y., Ji, J.Q., Chu, M.F., Lee, H.Y., Wen, D.J.O., Lo, C.H., Lee, T.Y., Qian, Q., and Zhang, Q., 2003, Adakites from continental collision zones: Melt-18O. We thank Harold Stowell for provision of oxygen isotope data from the Burnt River Schist: Geology, v. 31, p. 719–722, doi:10.1130/0091-7613(2003)031<0719:ADFTCC>2.0.CO;2.
Examples from the Mount Stuart and Tenpeak intrusions, North Cascades, Washington: Geological Society of America Bulletin, v. 118, p. 1412–1430, doi: 10.1130/B25923.1.

McKay, M., 2011, Pressure-temperature-time paths, prograde garnet growth, and protolith of teconites from a polyphase metamorphic aureole: Salmon River suture zone, west-central Idaho [M.S. thesis]: Tuscaloosa, University of Alabama, 135 p.

Mennet, V., Paterson, S., Matzel, J., Mundil, R., and Okaya, D., 2010, Magmatic lobes as “snapshots” of magma chamber growth and evolution in large, composite batholiths: An example from the Tuolumne intrusion, Sierra Nevada, California: Geology of America Bulletin, v. 122, p. 1912–1931, doi: 10.1130/0016-7606(2010)122[1912:MACLAC]2.0.CO;2.

Michel, J., Baumgartner, L., Putlitz, B., and Albarède, F., 2007, In situ 143Nd/144Nd and 87Sr/86Sr in zircons from the Tuolumne granite, Sierra Nevada, California: Earth and Planetary Science Letters, v. 258, p. 27–39, doi: 10.1016/j.epsl.2007.02.007.

Miller, J.S., Miller, C.F., Burgess, S.D., and Wooden, J.L., 2004, Residence, resorption and slow diffusion in zircon: American Mineralogist, v. 89, p. 2145–2161, doi: 10.2113/GSABull.89.12.2145.

Miller, R.B., and Paterson, S.R., 2001, Construction of the Cordilleran batholith: “Snapshots” of incrementally constructed magma chambers in a thickened continental crust exemplified by the Sevier terrane, northeastern Oregon; in Vervoort, J.D., Patchett, P.J., Blenkinsop, T., and Albarède, F., eds., Geology of the Sevier terrane, northeastern Oregon; Bald Mountain batholith, Elkhorn Mountains, and some comparisons with the Wallowa batholith, Wallowa Mountains, northeastern Oregon, in Vallier, T.L., and Brooks, H.C., eds., Geology of the Blue Mountains region of Oregon, Idaho, and Washington: petrology and tectonic evolution of pre-Tertiary rocks of the Blue Mountains region: U.S. Geological Survey Professional Paper 1438, p. 45–123.

Tulloch, A.J., and Kimbrough, D.L., 2003, Pluton saltine belts in convergent margins and the development of high Sr/Y magmatism: Peninsular Ranges batholith of Baja California and Median batholith of New Zealand, in Johnson, S.E., et al., eds., Tectonic evolution of northern Mexico and the southwestern USA: Geological Society of America Special Paper 374, p. 275–295, doi: 10.1130/0016-7714(1990)374<0275:ETRNMR>2.0.CO;2.

Valley, J.W., 2003, Oxygen isotopes in zircon, in Hanchar, J.M., and Hoskin, P.W.O., eds., Zircon: Reviews in Mineralogy and Petrology Volume 53, p. 343–385, doi: 10.2110/53.030343.

Vallier, T.L., 1995, Petrology of pre-Tertiary igneous rocks in the Blue Mountains region of Oregon, Idaho, and Washington: Contributions to Mineralogy and Petrology, v. 123, p. 205–221, doi: 10.1007/s004100050260.

Wood, M.B., and Wylie, P.J., 1993, Garnet growth during amphibolite anatexis: Implications of a garnet-rutile reequilibration: Journal of Geology, v. 101, p. 375–373, doi: 10.1086/243030.

Tulloch, A.J., and Kimbrough, D.L., 2003, Pluton saltine belts in convergent margins and the development of high Sr/Y magmatism: Peninsular Ranges batholith of Baja California and Median batholith of New Zealand, in Johnson, S.E., et al., eds., Tectonic evolution of northern Mexico and the southwestern USA: Geological Society of America Special Paper 374, p. 275–295, doi: 10.1130/0016-7714(1990)374<0275:ETRNMR>2.0.CO;2.