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Construction and preservation of batholiths in the northern U.S. Cordillera

R.M. Gaschnig[1]*, J.D. Vervoort[2], B. Tikoff[3], and R.S. Lewis[4]

[1]SCHOOL OF EARTH AND ATMOSPHERIC SCIENCES, GEORGIA INSTITUTE OF TECHNOLOGY, 311 FERST DRIVE, ATLANTA, GEORGIA 30332, USA
[2]SCHOOL OF THE ENVIRONMENT, WASHINGTON STATE UNIVERSITY, PO BOX 642812, PULLMAN, WASHINGTON 99164, USA
[3]DEPARTMENT OF GEOSCIENCES, UNIVERSITY OF WISCONSIN–MADISON, 1215 W DAYTON STREET, MADISON, WISCONSIN 53703, USA
[4]IDAHO GEOLOGICAL SURVEY, 875 PERIMETER DRIVE, MS 3014, MOSCOW, IDAHO 83844, USA

ABSTRACT

There is a nearly continuous record of magmatism through the Late Cretaceous–early Paleogene in Idaho and adjacent areas of Oregon and Montana, including the various phases of the Idaho batholith. We suggest that much of this magmatic record, however, has been obscured by subsequent tectonic deformation, erosion, and magmatic disruption and cannibalization, the latter of which can be tracked by zircon inheritance. Specifically, a mid-Cretaceous magmatic arc was significantly deformed by the western Idaho shear zone and intruded by the 83–67 Ma Atlanta peraluminous suite of the Idaho batholith. The northern part of the Atlanta peraluminous suite was, in turn, intruded by the 65–55 Ma Bitterroot lobe of the Idaho batholith. Consequently, the present age distribution of magmatism is strongly biased toward the youngest phases of plutonism; much of the older phases were destroyed by tectonic, magmatic, and erosional processes. The destruction of granitic batholiths may characterize Cordilleran-style orogens worldwide, which can lead to significant underestimates of magmatic fluxes.

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INTRODUCTION

Mesozoic–Paleogene granitic coastal batholiths characterize the North American Cordillera. They are thought to be a hallmark of Andean-style subduction of oceanic lithosphere under the western edge of North America (Dickinson, 2004). There are, however, fundamental along-strike differences in the timing and longevity of magmatism along the North American Cordillera. The southern Cordillera is typified by the Sierra Nevada batholith in California and Peninsular Ranges batholith further south. These Cretaceous, subduction-related magmatic arcs were emplaced within the transition between continental and oceanic crust, and they ceased activity by ca. 85 Ma (Bateman, 1992). In contrast, the magmatic record of the northern North American Cordillera in Canada is complicated by episodes of terrane accretion and probable translation, with the active magmatic arc occurring on the outboard oceanic Insular terrane (Monger et al., 1982; Butler et al., 2001). In this northern section of the North American Cordillera, there is a large mid-Cretaceous pulse of magmatism, but it is important that subduction-related magmatism continued until at least ca. 50 Ma (Gehrels et al., 2009).

The transition between northern and southern magmatic patterns occurs in Idaho, and, although it has similarities to both, it also has important differences. The Idaho batholith is a massive ~23,500 km^2 magmatic center that was entirely emplaced in Precambrian continental crust, unlike the other large coastal batholiths. The precise chronology of the Idaho batholith, which is geographically divided into a northern Bitterroot and a southern Atlanta lobe (Fig. 1), was unclear for many years because of the large amount of Precambrian zircon inheritance. When finally dated, it was discovered that the timing of Idaho batholith magmatism is distinct from that of other coastal Cordilleran batholiths. In terms of exposed granites, there was apparently little granitic magmatism in Idaho during the key interval of 110–85 Ma, which is a time of voluminous magmatism in all other coastal batholiths. Rather, most of the exposed portions of the Idaho batholith are younger than 80 Ma (e.g., Foster and Fanning, 1997; Unruh et al., 2008; Gaschnig et al., 2010). Why does the Idaho segment appear so different from the other parts of the North American Cordillera?

In this contribution we argue that magmatism in Idaho was relatively continuous from ca. 110 to 43 Ma and that the Idaho batholith underwent the same Early to Late Cretaceous flare-up as the other coastal batholiths. The record of this flare-up has been lost to a combination of tectonic shortening, magmatic disruption and cannibalization, and erosion. The former has been discussed (Giorgis et al., 2005), in which transpressional deformation associated with the western Idaho shear zone significantly shortened an existing magmatic arc. Evidence for the loss of other major elements of the earlier plutonic record through a combination of magmatic disruption and cannibalization and erosion is the focus of this manuscript. The tendency for specific plutons to contain mixed crystal populations, including crystals from earlier magmatic pulses, is well established (e.g., Miller et al., 2007; Claiborne et al., 2010). The record of crystal recycling has been particularly well documented in recent years and the detailed geochronological and geochemical studies that show inheritance in zircon populations have provided important insights into the how individual volcanic and plutonic systems are constructed (Reid et al., 1997; Miller et al., 2007; Bryan et al., 2008; Stelten and Cooper, 2012; Zimmerer and McIntosh, 2012; Barboni et al., 2013). We

*Now at the Department of Environmental, Earth, and Atmospheric Sciences, University of Massachusetts Lowell, Lowell, Massachusetts 01854.

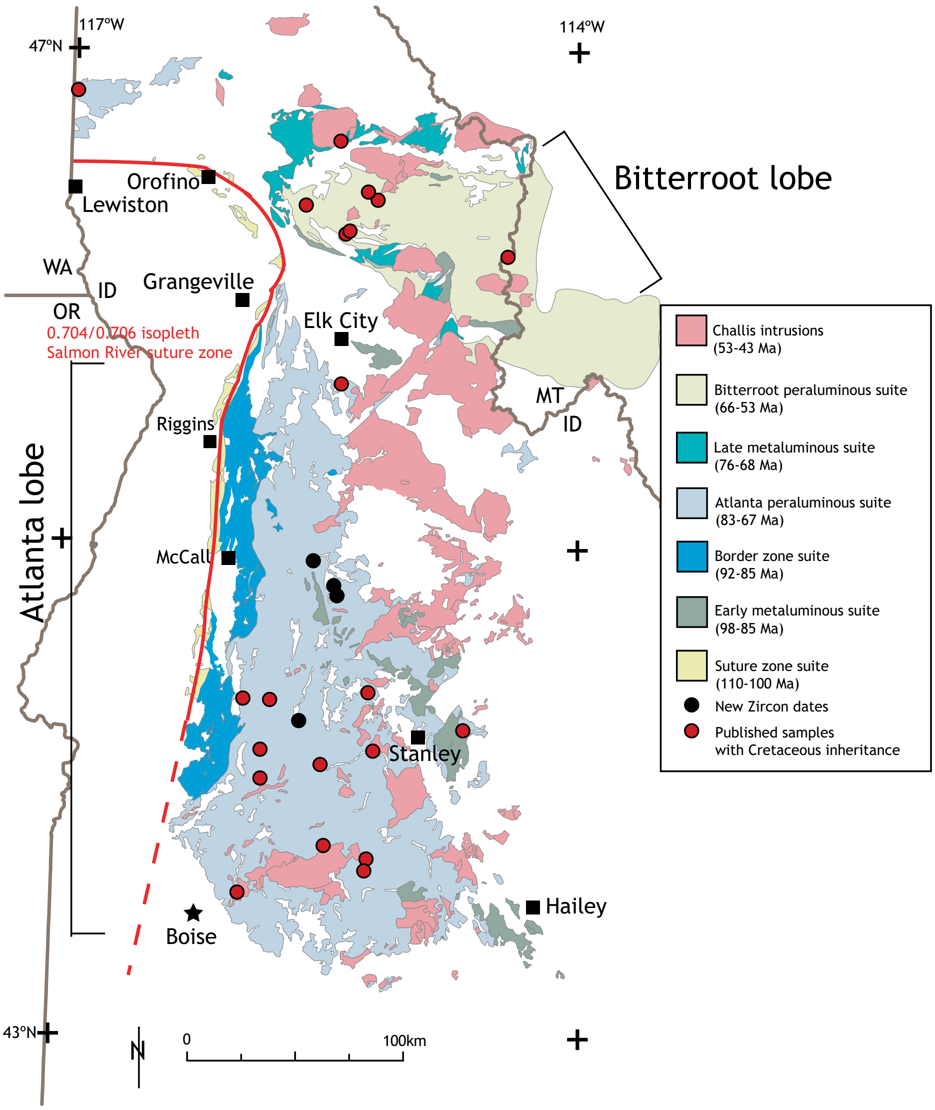

Figure 1. Simplified geologic map (after Gaschnig et al., 2010) showing major phases of the batholith and locations of new zircon samples (black dots), along with previously published zircons samples (red dots; from Gaschnig et al., 2010) that showed Cretaceous inheritance.

argue that the same process can occur on the scale of an entire batholith and its importance in the evolution of batholiths is often underestimated. We use information gathered from the zircon U-Pb record to provide new and important insights into the construction and destruction of granitic batholiths in Idaho and place this information within the context of the broader Cordilleran magmatic arc.

Throughout this paper we use the magmatic suite classification as described in Gaschnig et al. (2010) for identifying different units of the Idaho batholith (see Fig. 1 for the geographic distribution). In brief, the suture zone suite is a narrow (~10 km wide or less) band of strongly deformed and compositionally diverse plutons coincident with the western Idaho shear zone (WISZ), ranging from ca. 110 to 100 Ma. The border zone suite is a belt of mostly ca. 92 Ma tonalite plutons immediately east of the WISZ. The ca. 98–87 Ma early metaluminous suite is composed of hornblende granodiorite and tonalite and occurs primarily on the east side of, and as roof pendants within, the Atlanta lobe. The Atlanta peraluminous suite is compositionally restricted biotite granodiorite and muscovite-bearing granite and makes up the bulk of the Atlanta lobe. The 76–68 Ma late metaluminous suite is a belt of quartz diorite, tonalite, and hornblende granodiorite stocks forming a perimeter around the Bitterroot lobe. The ca. 66–53 Ma Bitterroot peraluminous suite is compositionally restricted biotite granodiorite and muscovite-bearing granite forming the bulk of the Bitterroot lobe. The 53–43 Ma Challis intrusive province is a belt of compositionally diverse plutons and dikes widely distributed throughout, and to the east of, the Idaho batholith, with contemporaneous volcanics further east.

METHODS

Geochronology

New U-Pb ages for samples from the central portion of the Idaho batholith are presented here. Sample locations are shown in Figure 1 and results are plotted in Figure 2. Example cathodoluminescence images of zircons are shown in Figure 3. Samples were analyzed by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) at Washington State University, using a New Wave UV Nd:YAG 213 nm laser coupled to a Thermo-Finnigan Element2 single collector high-resolution ICP-MS. Methods are identical to those described in Gaschnig et al. (2010). Weighted mean $^{206}Pb/^{238}U$ ages, mean square of weighted deviates, and the probabilities of fit are calculated based on internal measurement errors only. The error from the weighted mean calculation was then combined quadratically with the standard deviation derived from the reproducibility of the zircon standard. The given error following the weighted mean in text is this total uncertainty at the 2σ level. Tabulated results are reported in the Data Repository[1] along with sample locations.

Compilation of Geochronological Results from Idaho

In addition to the new U-Pb results presented here, we also compile the large number of instances of earlier Cretaceous inheritance in younger samples of the Idaho batholith, as reported in the literature (Gaschnig et al., 2010, 2013; Braudy et al., 2016). These are cases where zircon populations in the latest Cretaceous and Paleocene peraluminous units of the batholith contain components that are 5–20 m.y. older than the dominant zircon rim age. These instances are listed in Table 1 and their spatial distributions are shown in Figures 1, 4B, and 4C.

Magmatic Flux and Areal Addition Rate

Knowledge of the age distributions and areas of different suites of the Idaho batholith allows for the calculation of the apparent areal rate of magmatic addition at different times during

[1]GSA Data Repository Item 2016265, New U-Pb zircon results and sample locations, is available at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org.

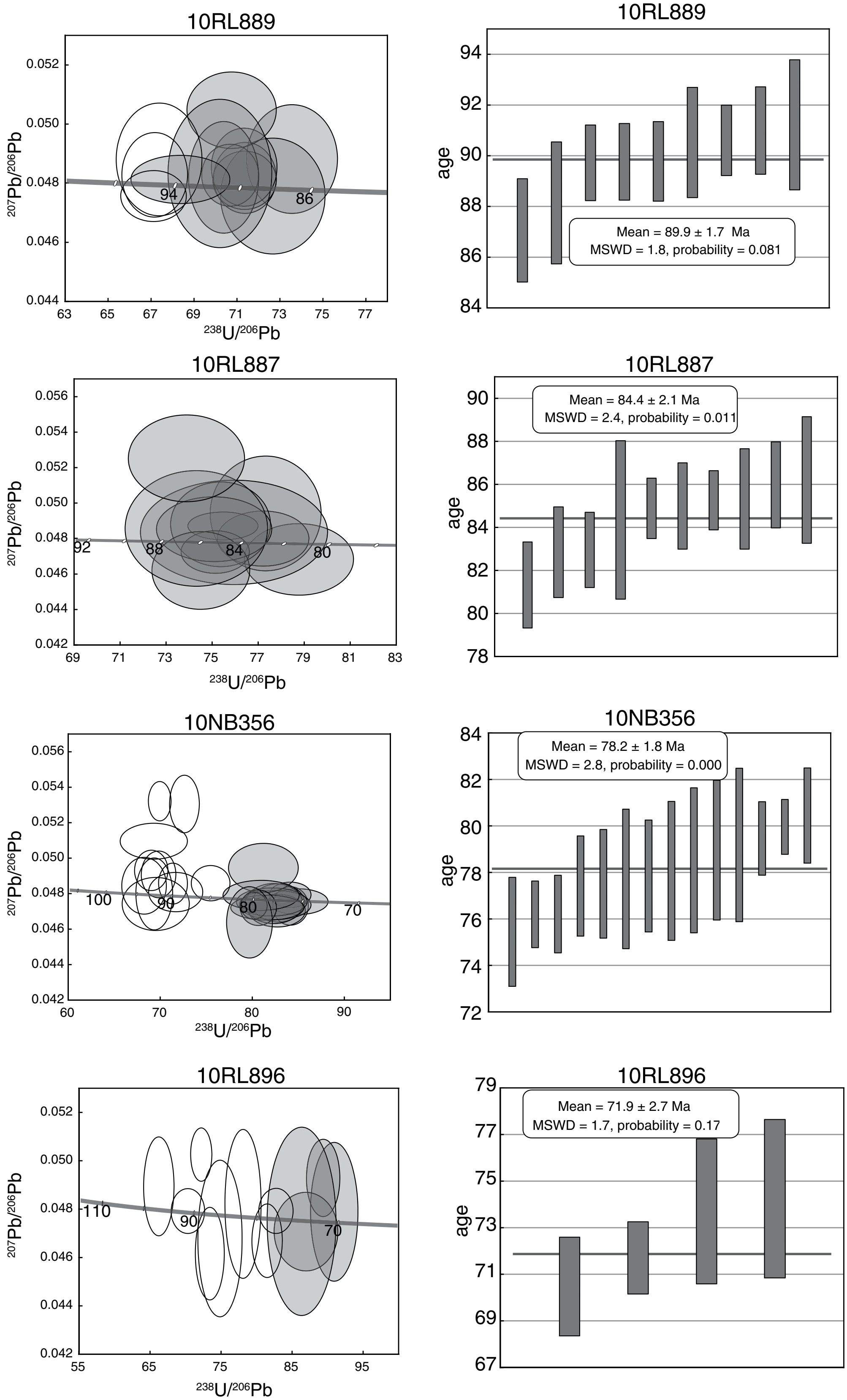

Figure 2. Tera-Wasserburg (left) and weighted mean $^{206}Pb/^{238}U$ age diagrams (right) for new zircon U-Pb geochronology results. Shaded ellipses in the Tera-Wasserburg diagrams represent analyses used to calculate weighted mean ages. All but one sample shows earlier Cretaceous inheritance, most notably between 100 and 90 Ma. All errors (on both individual analyses and final calculated ages) are 2σ. MSWD—mean square of weighted deviates.

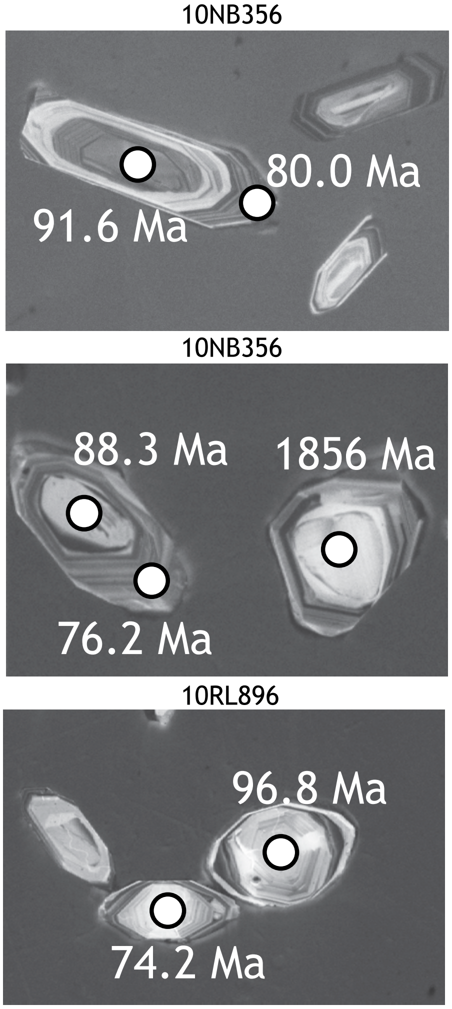

Figure 3. Cathodoluminescence images of zircons from sample 10NB356 and 10RL896 showing inherited zircon cores with both older Cretaceous and Precambrian ages surrounded by Late Cretaceous magmatic rims. Circles representing analytical spots are 30 μm in diameter.

TABLE 1. CASES OF CRETACEOUS INHERITANCE IN IDAHO BATHOLITH AND CHALLIS ZIRCON SAMPLES IN RECENT LITERATURE

Sample	Latitude§	Longitude§	^{206}Pb/^{238}U crystallization age (Ma)	Cretaceous inherited ages observed (Ma)
Atlanta peraluminous suite				
07RMG13*	45.5398	–115.4624	ca. 80	100
07RMG25	43.7805	–115.4927	74	81, 85, 87, 95 (2)
07RMG28	43.7525	–115.2442	70	77 (2), 78, 82, 86, 88, and 95
07RMG29	43.6840	–115.2787	67	74, 75, 80
07RMG43	44.1722	–115.2441	71	76, 81
07RMG45	44.0708	–115.5381	77	83, 84, 87, 88, 89, 98, 100
07RMG46	44.0504	–115.8909	77	87, 97, 99
07RMG56	44.3576	–115.2356	76	83, 86, 89
09RMG01	46.8097	–117.0070	ca. 78	90, 99
10RMG042†	44.3715	–115.7673	82	97
10RMG044†	44.3744	–115.9521	83	86, 88, 89, 99, 102
98IB53	44.2189	–115.9161	75	81, 83, 86, 87, 92, 99
98IB68	44.2678	–114.7561	83	94, 103
Bitterroot peraluminous suite				
06RMG02	46.3793	–115.7130	61	79 and 83
06RMG03	46.2865	–115.3839	66	71 (2), 72
07RMG66	46.4269	–115.2899	59	66, 69
98IB12	46.2842	–115.3881	55	66, 70, 76, 77
98IB13	46.1469	–114.5011	53	68, 70 (2), 78 (3)
Challis intrusives				
06RMG04	46.3315	–115.3457	ca. 50	67, 76, 77
07RMG23	43.5929	–115.9545	48	91
98IB24	46.6861	–115.3625	46	70

*Published in Gaschnig et al. (2013)
†Published in Braudy et al. (2016).
§North American Datum 1927.
Note: All other results are from Gaschnig et al. (2010). Numbers in parentheses after certain inherited ages are the number of individual grains observed containing those particular ages. Individual uncertainties on ages are typically ~2% (2σ) and can be found in the above references.

batholith construction (Paterson and Ducea, 2015). These results are combined with recently published areal addition curves (DeCelles et al., 2009; Gehrels et al., 2009; Miller et al., 2009; Paterson et al., 2011) for other Cordilleran batholiths. To calculate areal addition rates, we assume that each magmatic suite was constructed by a constant rate of magmatic addition during its magmatic lifetime. For example, the Atlanta peraluminous suite occupies an area of ~16,000 km^2 and formed over a 16 m.y. interval between 83 and 67 Ma (Gaschnig et al., 2010). The apparent or areal addition rate in this case would therefore be ~1000 km^2/m.y. over the course of those 16 m.y. Several of the magmatic suites overlap in time so their individual area addition rates during these overlaps must be summed in order to determine the total batholithic magmatic addition rate.

We can also make estimates about the volume of the intrusion phases by using recent geophysical information associated with the IDOR (Idaho-Oregon) EarthScope project. Davenport et al. (2015) show the results of an active source seismology study across the Atlanta lobe of the Idaho batholith. Their results indicate low seismic velocities (<6.4 km/s) down to at least 12 km, consistent with the presence of felsic intrusions. Assuming that the Idaho batholith everywhere continues to 12 km depth, the three-dimensional flux estimate for the Atlanta peraluminous suite is 12,000 km^3/m.y. The modern vertical dimensions of the other suites, along with their original thickness (prior to erosion), are largely unknown, with the exception of the apparently thin and sill-like Bitterroot peraluminous suite (Wiswall and Hyndman, 1987). Given these uncertainties in the vertical dimensions of units of the Idaho batholith and similar uncertainties in other Cordilleran batholiths, we choose to use the areal addition rate, rather than volumetric addition rate, as the measure of comparison.

RESULTS

New Geochronology

Samples 10RL887 and 10RL889 are biotite granodiorite and leucogranodiorite, respectively, collected from the Stibnite mining district near the eastern edge of the central Atlanta lobe. Sample 10RL889 yields a weighted mean ^{206}Pb/^{238}U age of 89.9 ± 1.7 Ma and contains four older grains interpreted as inherited with ages of ca. 95 Ma (Fig. 2). Both the crystallization age and inherited age of 10RL889 are well within the established age range of the early metaluminous suite (i.e., 98–87 Ma; Gaschnig et al., 2010). Sample 10RL887 yields an age of 84.4 ± 2.1 Ma and shows no inheritance. While the leucocratic lithology is consistent with its placement within the Atlanta peraluminous suite, it is the oldest age so far determined for this suite.

Samples 10NB356 and 10RL896 are biotite granodiorite samples taken from the interior of the north and central Atlanta lobe and they yield crystallization ages of 78.2 ± 1.8 and 71.9 ± 2.7 Ma, respectively (Fig. 2). Both samples contain

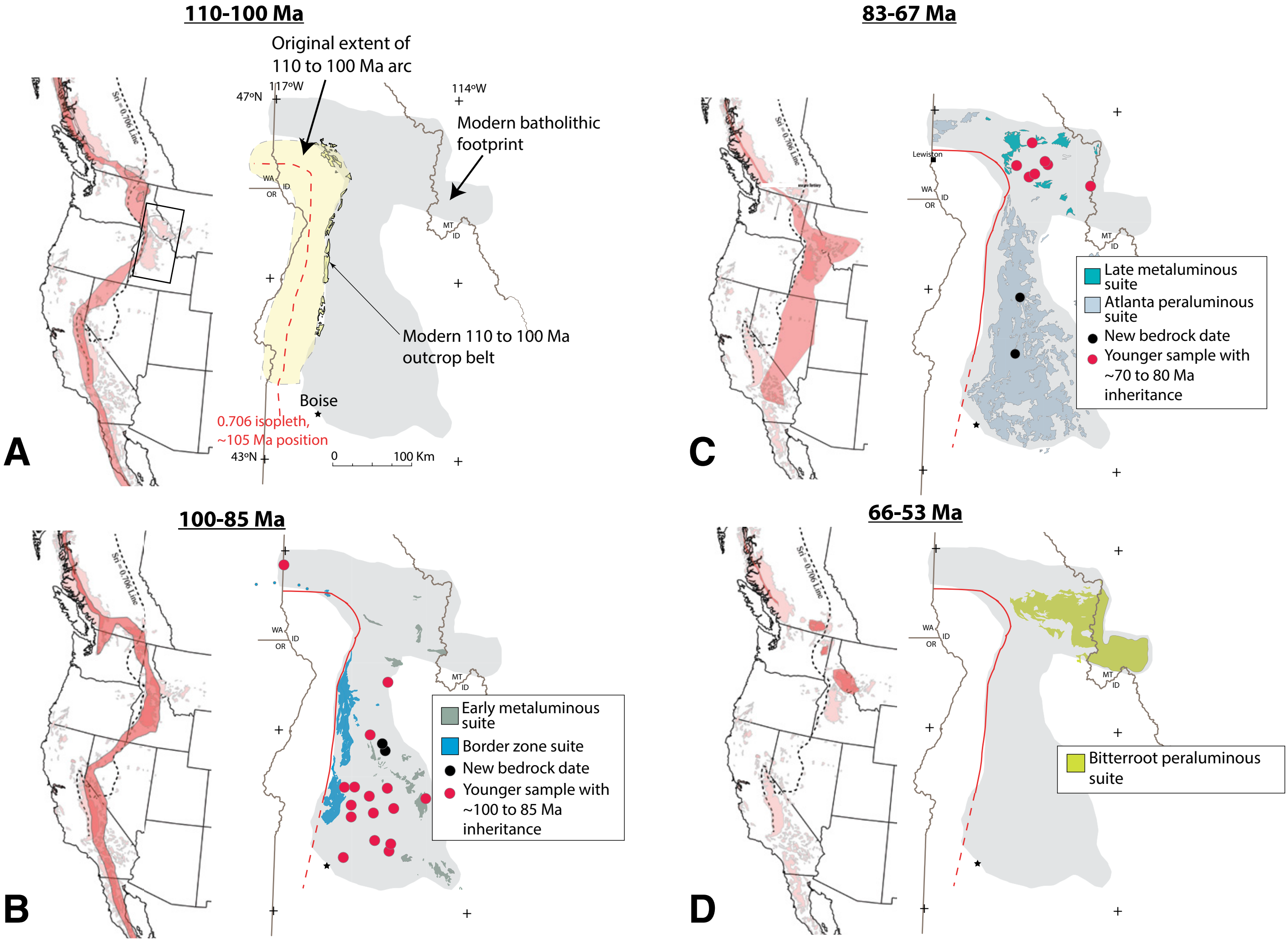

Figure 4. Active magmatism in the Cordillera (left panels) and Idaho batholith region (right panels) at different times. The faintly shaded area in the right panels represents the total geological footprint of the Idaho batholith today. (A) 110–100 Ma magmatism. The map shows the suture zone suite with subsequent shortening removed, using a moderate shortening estimate from the range given by Giorgis et al. (2005). (B) 100–85 Ma magmatism. During and after the shortening of the western Idaho shear zone, the border zone and early metaluminous suites were emplaced. The pervasive nature of ca. 90 Ma inheritance in samples from younger intrusions (marked as red dots, including results from Gaschnig et al., 2010, and this paper) implies that the scattered outcrops of ca. 90 Ma plutons were once connected and occupied most of the modern Idaho batholith footprint. (C) 83–67 Ma magmatism. Much of the 100–85 Ma Idaho arc was disrupted by the formation of the Atlanta peraluminous suite. The presence of ca. 66–83 Ma inheritance (red dots) to the north of the Atlanta lobe proper and presence of a 78 Ma outlying pluton north of Lewiston suggest that the Atlanta peraluminous suite originally occupied most of the batholitic footprint. (D) 66–53 Ma. Bitterroot lobe. The Bitterroot peraluminous suite was emplaced at this time and further disrupted the preexisting batholithic rocks.

many inherited age components ranging to as much as 15 m.y. older than the crystallization ages and overlapping with the age range of the early metaluminous suite (Fig. 3). Sample 10NB356 also contains one inherited Late Jurassic age. Precambrian ages found as inherited cores in all four samples were presented in Gaschnig et al. (2013).

Areal Addition Rate Pattern

The Idaho batholith areal addition rate pattern based on modern outcrop areas shows a main peak at 75 Ma (Fig. 5). This is distinct from the other Cordilleran batholiths. The other Cordilleran batholiths all underwent a period of peak flux between 100 and 80 Ma, centered on 90 Ma, and the Sierra Nevada, Peninsular Ranges, and North Cascades underwent an abrupt magmatic shutdown between 85 and 80 Ma. The later Challis peak in Idaho is completely absent in the southern batholiths, but is comparable to, if slightly younger than, the early Cenozoic peak in the Coast Mountains batholith and the North Cascades.

DISCUSSION

Five Phases of Cretaceous–Paleogene Magmatism in Idaho

The Idaho batholith (sensu lato) formed as a result of continuous magmatism lasting ~60 m.y. and was marked by a series of magmatic phases, each with distinct composition, inferred tectonic regime, and geographic locus. In the following we outline these five phases of batholith development. We utilize insights provided by

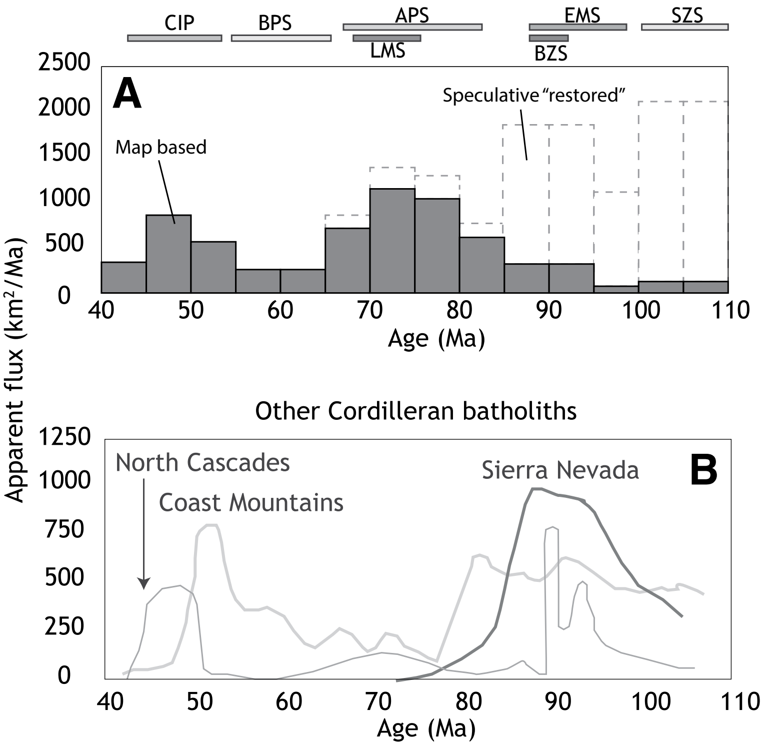

Figure 5. Apparent magmatic flux pattern, also called areal addition rates (Paterson and Ducea, 2015), shown as a bar graph with 5 m.y. bin sizes (in km^2/m.y.) for the Idaho batholith, compared to those for other Cordilleran batholiths. (A) Idaho batholith and subsequent Challis addition rates based on present-day map patterns (shaded). The areal addition pattern is likely biased toward higher flux values at younger ages due to the obfuscation of older batholith phases by tectonic, magmatic, and erosional processes. If we remove these biasing effects (see text), we can obtain a speculative addition rate pattern (dashed bars) showing a much higher flux from 110 to 85 Ma, comparable to the flare-up undergone by the other Cordilleran batholiths. The age range for each magmatic suite is shown as a series of horizontal bars at the top of the plot (CIP—Challis intrusive province, BPS—Bitterroot peraluminous suite, APS—Atlanta peraluminous suite, LMS—late metaluminous suite, BZS—border zone suite, EMS—early metaluminous suite, SZS—suture zone suite). (B) Areal addition rate curves for other Cordilleran batholiths (DeCelles et al., 2009; Miller et al., 2009; Gehrels et al., 2009; Paterson et al., 2011).

recently published (Gaschnig et al., 2010) and new data for inherited antecrystic zircons from throughout the Atlanta and Bitterroot lobes to help elucidate an earlier, and now largely erased, history and to constrain the evolution of this large Cordilleran magmatic system. Figure 4 shows the present-day outcrop extent of the different magmatic suites and provides clues to their original extent through the presence of xenocrystic zircon in younger phases.

Construction and Disruption of an Arc, 110–100 Ma

The Idaho batholith is bound on the west side by the collisional Salmon River suture zone (Lund and Snee, 1988; Tikoff et al., 2001) and the younger and overprinting transpressional western Idaho shear zone (WISZ; e.g., McClelland et al., 2000; Giorgis et al., 2008). The WISZ is currently the north-northeast–trending, lithospheric-scale structure that separates Precambrian continental crust of North America on the east from accreted Paleozoic and Mesozoic island arc crust of the Blue Mountains on the west (Manduca et al., 1992; McClelland et al., 2000). From ca. 110 to 100 Ma, magmatism within the Salmon River suture zone led to the production of intrusions ranging from gabbro to granite with a crude west to east, mafic to felsic compositional zoning and isotope characteristics suggesting a mix of mantle and crustal sources (e.g., the Little Goose Creek Complex of Manduca et al., 1992). Granitic rocks of this age (Manduca et al., 1992) extend most of the length of the WISZ. Transpressional deformation in the WISZ, between 105 and 92 Ma (Giorgis et al., 2005), transformed this plutonic suite into a series of orthogneisses. While the extreme (5%–10% of original width) shortening estimates proposed by Giorgis et al. (2005) are subject to many assumptions, the granitic suite was clearly once considerably wider than the current ~5 km. Thus, the pre–100 Ma granites from this phase were significantly reduced in their outcrop area, in this case due to deformation.

Construction and Destruction of an Arc, 100–85 Ma

While the ca. 110–100 Ma Idaho arc was being collapsed by tectonic activity, a new episode of magmatism began to the east and continued well past the ca. 92 Ma termination of WISZ deformation (Giorgis et al., 2008). Plutons of this ca. 92 Ma episode in the Idaho batholith fall into two general groups, termed the border zone and early metaluminous suites (Gaschnig et al., 2010). The border zone suite consists of a weakly deformed to undeformed tonalite sill (Payette River tonalite; Manduca et al., 1993) emplaced on the east side of the WISZ along its entire north-south length (Benford et al., 2010). Plutons of this age are also found further to the east. The early metaluminous suite consists primarily of tonalite and hornblende-bearing granodiorite present as pendants within the Atlanta lobe, as isolated stocks between the Atlanta and Bitterroot lobes (Gaschnig et al., 2010), and as isolated stocks in the southeastern corner of the Idaho batholith. Both suites have overlapping compositional and isotopic characteristics, suggesting an origin by mixing between mantle and Precambrian crustal components (Gaschnig et al., 2011). Taking known outcrops together, the two ca. 92 Ma Idaho batholith suites cover an area slightly <3500 km^2 of a total batholith area of 23,500 km^2.

New geochronology and existing data compiled from the literature indicate that the modern outcrop-based area is likely a significant underestimate of the area affected by 92 Ma plutonism. Recent U-Pb zircon results have shown that the border zone suite extends around the bend in the Salmon River suture zone at Orofino and continues to the west into Washington (Murphy, 2007; Schmidt et al., 2009; Byerly et al., 2013). Additional outcrops of similarly aged plutons are also identified in the Atlanta lobe, including the example provided by sample 10RL889, and septa of granodiorite orthogneiss in the Bitterroot lobe have overlapping ages (Lund et al., 2008). Most significant, however, is that ca. 92 Ma zircon xenocrysts (both whole grains and core or mantles with younger rims) are pervasive in the younger phases of the southern and central Atlanta lobe, as exemplified in samples 10NB356 and 10RL896 (see preceding) and many other cases (Table 1; Gaschnig et al., 2010). An outlying ca. 78 Ma pluton northwest of the main batholith near Moscow also contains similar zircon xenocryst ages (Gaschnig et al., 2010). All of these observations suggest that the border zone and early metaluminous suite once formed a larger and more continuous magmatic system. We speculate that it may have occupied a large percentage of the existing Idaho batholith footprint (today dominated by post–83 Ma igneous ages). If true, the ca. 92 Ma batholith may have been similar in areal extent (and possibly volume) to the other Late Cretaceous Cordilleran batholiths.

What happened to this ca. 92 Ma batholith? The zircon xenocrysts of this age in the younger phases of the batholith can only be acquired by the remelting and/or assimilation of those older phases. However, major differences between the Nd and Hf isotope compositions of the ca. 92 Ma granitoids and the younger Atlanta peraluminous suite preclude that the former cannot be a primary ingredient in the latter (Gaschnig et al., 2011). Likewise, assimilation of large amounts of crust, especially by a relatively evolved magma, is thermally difficult (e.g., Glazner, 2007). Therefore, while limited assimilation or remelting undoubtedly occurred in order to supply the xenocrysts to the younger magmas, these processes cannot have resulted in the complete destruction of the ca. 92 Ma arc. Instead, we speculate that much of the volume of the 92 Ma arc existed at a higher level of exposure and was largely eroded away. Some support for this hypothesis is provided by the upper to middle crustal hornblende geobarometer emplacement pressures (~3–4 kbar) observed in many of the outlying stocks of the early metaluminous suite (Jordan, 1994) and the occurrence of early metaluminous plutons as roof pendants within the central Atlanta peraluminous suite. Evidence for erosive removal of the ca. 92 Ma arc is also present in the detrital age zircon populations in Cretaceous and Paleogene basins in southwest Montana (Stroup et al., 2008; Fuentes et al., 2011; Laskowski et al., 2013) and coastal Oregon (Heller et al., 1985; Dumitru et al., 2013), all of which have 100–85 Ma age populations and are inferred to have come, at least in part, from the Idaho region.

Atlanta "Arc," 83–67 Ma

From 83 to 67 Ma, the lower crust of the Idaho batholith region underwent significant partial melting, resulting in the Atlanta peraluminous suite (Gaschnig et al., 2010), and obscuring much of the earlier ca. 92 Ma batholith. The Atlanta peraluminous suite, a relatively homogeneous mass of granite and granodiorite, currently occupies an outcrop area of 16,000 km^2, making up the bulk of the Atlanta lobe of the Idaho batholith. Just as we find evidence for ca. 92 Ma magmatism in xenocrystic zircon of the Atlanta peraluminous suite, evidence for even more widespread ca. 75 Ma Atlanta magmatism is also present in the form of similar zircon inheritance in the Paleocene Bitterroot peraluminous suite of the northern Idaho batholith. Based on this evidence from xenocrysts in the Bitterroot peraluminous suite, coupled with the presence of ca. 78 Ma granite outliers similar in composition west of Orofino, we speculate that the Atlanta peraluminous suite may have originally had a larger footprint than it does today.

Bitterroot, 66–53 Ma

During the Paleocene, the Idaho batholith underwent a second pulse of crustal melting. In this case, magmatism was focused in a much smaller area (3000 km^2), leading to the formation of the Bitterroot peraluminous suite, the main component of the Bitterroot lobe of the batholith. In addition to its relatively small area compared to the older Atlanta peraluminous suite, some evidence suggests that the Bitterroot lobe has limited vertical dimensions, forming a sill-like structure only a few kilometers thick (Wiswall and Hyndman, 1987; Foster et al., 2001). Ultimately, Bitterroot magmatism continued until ca. 53 Ma and was followed by the Eocene Challis magmatic event, reflecting a switch to an extensional tectonic environment.

Eocene Postscript: Challis Magmatism (Post–53 Ma)

Following the formation of the Bitterroot peraluminous suite, and starting ca. 53 Ma, the Idaho batholith region underwent a new episode of magmatism. The Challis intrusive province consists of epizonal plutons emplaced into the Cretaceous–Paleocene Idaho batholith and the Challis volcanic field, located east of the south and central batholith (e.g., Gaschnig et al., 2010). Challis magmatism was part of a widespread igneous pulse that extended from Oregon to South Dakota and northward into British Columbia (Morris et al., 2000; Feeley, 2003; Duke, 2009; Bordet et al., 2014). Much of this magmatism is associated with a tectonic switch from contraction to extension in the northern Cordillera, and most areas show geochemical evidence of some level of mantle input. Slab rollback (Humphreys, 1995; Schmandt and Humphreys, 2011) or the formation of slab windows due to ridge subduction (Thorkelson and Taylor, 1989; Breitsprecher et al., 2003; Madsen et al., 2006) are commonly cited explanations for this widespread Eocene magmatism.

Areal Addition Rate Estimates

Recent studies of magmatic fluxes in different localities have shown that magmatic addition in continental arc settings is a non–steady-state process, characterized by high-volume flare-ups separated by magmatic lulls (Ducea, 2001; DeCelles et al., 2009; Gehrels et al., 2009; Paterson et al., 2011). This is a paradoxical observation because subduction continues at a relatively constant rate and so magmatic pulses have been linked to tectonic cycles such as periodic underthrusting of backarc material beneath the arc (DeCelles et al., 2009) or changes in the rate and angle of convergence (e.g., Page and Engebretson, 1984). In the North American Cordillera, studies have shown that the Sierra Nevada batholith (and by extension the Peninsular Ranges batholith) underwent an intrusive flare-up from 105 to 85 Ma (Ducea, 2001). The Coast Mountains batholith underwent a broader middle to Late Cretaceous flare-up that began earlier and ended slightly later than the Sierra Nevada, followed by a second flare-up around the Paleocene-Eocene boundary (Gehrels et al., 2009).

Based on modern map patterns, a large part of the Idaho batholith was formed by a magmatic flare-up between 80 and 70 Ma, significantly later than the other Cordilleran batholiths, which were mostly formed during a flare-up ca. 90 Ma. While the Idaho batholith was active during this earlier interval, the apparent areal addition rate was relatively low. The Eocene Challis event was also a period of high areal addition rates in the Idaho batholith region. This period of activity was shared with the North Cascades and Coast Mountains to the north, but contrasts with the time of quiescence in the Sierra Nevada and Peninsular Ranges, which were extinguished before the end of the Cretaceous.

Our estimate of the areal addition rate pattern for the Idaho batholith is based on the area of the present-day outcrops of the different lithological suites. However, it is clear from the evidence presented here that the earlier phases of the batholith occupied a greater area than their present-day footprint. The oldest plutons (ca. 110–100 Ma) were tectonically shortened within the WISZ. The presence of xenocrystic ca. 90 Ma zircons in much of the younger Atlanta peraluminous suite (Fig. 4B) provides evidence for the greater extent of the early metaluminous and border zone suites. This 92 Ma suite was largely removed by a combination of erosion and assimilation or remelting. The removal of much of the original areal extent of these units biases the areal addition rate toward younger ages.

If we take into account the evidence, as given here, for the shortening of earliest intrusive phases and the magmatic disruption and/or erosion of the 100–85 Ma batholith components, it is possible to construct a hypothetical areal addition rate curve (Fig. 5) that estimates the amount of the earlier phases of the batholith that have been removed. We do this by speculating on the original areal extent of the earlier phases of the batholith using the following assumptions: (1) the 110–100 Ma intrusive suite was originally 70 km wide, which is roughly midway between the 28 and 112 km range given by Giorgis et al. (2005); (2) the 98–85 Ma early metaluminous suite and border zone suite once occupied the full modern footprint of the Idaho batholith, based on the pervasive nature of 98–85 Ma inherited zircon components in younger batholith phases and the scattered but widely distributed nature of outcrops along strike; and (3) the 83–67 Ma Atlanta peraluminous suite originally continued north and occupied the area now containing the Bitterroot lobe of the batholith, based on the presence of 83–67 Ma inherited zircon components in younger batholith phases and the presence of a 78 Ma granitic mass west of Orofino. All of these restorations are speculative; the first requires that a significant amount of shortening occurred within the WISZ, while the latter two require a combination of remelting and magmatic recycling and erosional removal of large sections of an earlier formed batholith. While there is unambiguously abundant and widespread inheritance of earlier batholithic components, the true amount of removed material is admittedly speculative. The reconstruction, however, provides an end-member case of the maximum areal extent of magmatism in the Idaho batholith region.

The assumptions and resulting restored areal addition rate pattern display a shift in the timing of peak magmatism from ca. 90 to ca. 75 Ma. If true, the Idaho batholith had the same high magmatic flux episode that occurred in the other Cordilleran batholiths and a single arc extending from Baja California to Alaska underwent a magmatic flare-up during this interval. Nonetheless, the continuation of voluminous magmatism to the end of the Cretaceous remains a unique aspect of Idaho magmatism in comparison to the other Cordilleran batholiths.

The biasing of the geologic record toward younger ages is especially strong in the Idaho batholith compared to the other Cordilleran batholiths. This is due to the relatively nonmigratory nature of post–100 Ma magmatism in the Idaho batholith. Both the Peninsular Ranges and Sierra Nevada batholiths showed a steady and well-documented eastward migration in the axis of magmatism in the Cretaceous that helped preserve the older phases of those batholiths (e.g., Bateman, 1992; Premo et al., 2014), and this is also true of the western half of the Coast Mountains batholith (Gehrels et al., 2009). In contrast, after the shortening of the earlier phases in the WISZ, the axis of Cretaceous Idaho batholith magmatism was relatively static from ca. 100 to 70 Ma, leading to the disruption of the early metaluminous and border zone suites by the Atlanta peraluminous suite. Following this long period of a relatively fixed magmatic axis, magmatism in the Atlanta lobe ceased, but magmatism to the north in the Bitterroot lobe continued through the Paleocene.

Intense horizontal shortening of the earlier magmatic phases in the WISZ would have led to vertical stretching, resulting in uplift and erosion. Erosion is also likely to have been a major contributor to the removal of the large portions of the 100–85 Ma Idaho arc. As a result, the eroded batholithic material would have accumulated in adjacent basins to the east and west. Confirmation of this is found in numerous recent detrital zircon studies (Stroup et al., 2008; Fuentes et al., 2011; Dumitru et al., 2013; Laskowski et al., 2013), emphasizing the important role that provenance and basin analysis studies may have in reconstructing heavily modified and overprinted arcs. This may be particularly relevant for arcs with less pervasive zircon inheritance, such as the Sierra Nevada.

Idaho in Cordilleran Context

The magmatic evolution of the Idaho batholith in relation to the rest of the Cordillera is explored in Figure 4. The deformed and scattered field remnants and zircon xenocrysts indicate that the Idaho batholith underwent a flare-up of calc-alkaline arc magmatism from ca. 110 to 85 Ma. This interval coincides with the Cretaceous flare-up that affected the rest of the Cordilleran arc. Both the Peninsular Ranges and Sierra Nevada batholith were undergoing magmatism that began in their more mafic western parts (e.g., Ortega-Rivera, 2003; Lackey et al., 2012; Holland et al., 2013) and shifted to the east, leading to the formation of the iconic zoned La Posta and Tuolumne intrusive suites (e.g., Coleman and Glazner, 1997; Ortega-Rivera, 2003; Saleeby et al., 2008; Premo et al., 2014). Isolated ranges in northwest Nevada and southwest Idaho contain plutonic rocks with similar ages and compositions and provide a connection between the California and Idaho arcs (Benford et al., 2010; Van Buer and Miller, 2010; Brown et al., 2011). The Coast Mountains batholith in British Columbia and adjacent Washington also underwent a major episode of magmatism at that time (Matzel et al., 2006; Gehrels et al., 2009).

The Idaho batholith underwent a large pulse of crustal melting after 85 Ma. In contrast, the Sierra Nevada and Peninsular Ranges batholiths underwent an abrupt shutoff of magmatism ca. 85 Ma, most commonly attributed to shallowing of the subduction angle of the Farallon slab (Dumitru et al., 1991). By 75 Ma, magmatism in the Cordillera south of the Idaho batholith was limited to a diffuse belt of metaluminous to peraluminous granitoids extending from the Mojave region to the eastern Great Basin. These dominantly peraluminous granites have been referred to as the Cordilleran interior belt or Cordilleran muscovite granite belt, which includes the main phase (Atlanta lobe) of the Idaho batholith (e.g., Miller and Bradfish, 1980; Miller and Barton, 1990). In addition, a group of smaller batholiths and stocks, such as the Boulder batholith, formed simultaneously to the east in western Montana (Lund et al., 2002; du Bray et al., 2012). These magmatic bodies are distinct from the Atlanta peraluminous suite in that they are more compositionally diverse and show variable input from mantle sources (Mueller et al., 1996; du Bray et al., 2012). Further north, the Coast Mountains batholith magmatism continued, but at a reduced flux (Gehrels et al., 2009; Mahoney et al., 2009).

In the Paleocene, crustal melting in Idaho continued but was more localized and far less voluminous. The southern Cordillera was largely amagmatic. To the north of the Idaho batholith, magmatism in the Coast Mountains batholith continued at low flux levels (Gehrels et al., 2009). Crustal melting associated with metamorphic core complexes also occurred at the southern end of the Coast Mountains batholith (Gordon et al., 2010) and to the southeast (Carr, 1992; Gordon et al., 2008; Kruckenberg et al., 2008).

In summary, the history of the Idaho region closely parallels that of the rest of the western margin of the North American Cordillera until ca. 85 Ma (immediately after cessation of the western Idaho shear zone). After that time, the magmatism in the Idaho batholith appears to have a distinctive history, recording a significant amount of remelting, magmatic recycling, and erosional removal of earlier-formed batholithic rocks.

CONCLUSIONS

The present-day Idaho batholith is dominated by latest Cretaceous (after 80 Ma) and Paleocene intrusive rocks, but this may not provide a complete record of its magmatic history. We speculate that much of the earlier formed parts of the batholith were removed by a range of geologic processes. Large-scale obfuscation of the earlier magmatic record may have resulted from the shortening of a ca. 110–100 Ma intrusive suite, followed by a combination of magmatic disruption and assimilation and erosion, which may have removed much of the record of ca. 100–85 Ma magmatism. More localized Paleocene magmatism may have likewise removed a portion of the ca. 80–70 Ma magmatic system.

When the resulting bias toward younger ages is taken into account, we infer that the largest intrusive volume of the Idaho batholith may have been formed by the same Cretaceous magmatic flare-ups that contributed to the Sierra Nevada and Peninsular Ranges batholiths. In contrast, the continuation of high-flux magmatism in the Idaho batholith after 85 Ma has no analog in the other U.S. Cordilleran batholiths to the south, but is consistent in timing with the formation of the Cordilleran muscovite granite belt (Miller and Bradfish, 1980).

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