

Intrusive and depositional constraints on the Cretaceous tectonic history of the southern Blue Mountains, eastern Oregon

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ABSTRACT

We present an integrated study of the postcollisional (post–Late Jurassic) history of the Blue Mountains province (Oregon and Idaho, USA) using constraints from Cretaceous igneous and sedimentary rocks. The Blue Mountains province consists of the Wallowa and Olds Ferry arcs, separated by forearc accretionary material of the Baker terrane. Four plutons (Lookout Mountain, Pedro Mountain, Amelia, Tureman Ranch) intrude along or near the Connor Creek fault, which separates the Izee and Baker terranes. High-precision U–Pb zircon ages indicate 129.4–123.8 Ma crystallization ages and exhibit a north-northeast–younging trend of the magmatism. The ⁴⁰Ar/³⁹Ar analyses on biotite and hornblende indicate very rapid (<1 m.y.) cooling below biotite closure temperature (~350 °C) for the plutons. The (U–Th)/He zircon analyses were done on a series of regional plutons, including the Lookout Mountain and Tureman Ranch plutons, and indicate a middle Cretaceous age of cooling through ~200 °C. Sr, Nd, and Pb isotope geochemistry on the four studied plutons confirms that the Izee terrane is on Olds Ferry terrane basement. We also present data from detrital zircons from Late Cretaceous sedimentary rocks at Dixie Butte, Oregon. These detrital zircons record only Paleozoic–Mesozoic ages with only juvenile Hf isotopic compositions, indicating derivation from juvenile accreted terrane lithosphere. Although the Blue Mountains province is juxtaposed against cratonic North America along the western Idaho shear zone, it shows trends in magmatism, cooling, and sediment deposition that differ from the adjacent part of North America and are consistent with a more southern position for terranes of this province at the time of their accretion. We therefore propose a tectonic history involving moderate northward translation of the Blue Mountains province along the western Idaho shear zone in the middle Cretaceous.

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INTRODUCTION

The western margin of the North American Cordillera contains abundant terranes of oceanic crustal affinity. In general, accretion of these exotic terranes has led to westward growth of Laurentia (e.g., Davis et al., 1978; Oldow et al., 1989; McClelland et al., 1992; Hacker et al., 1995; Moores et al., 2002; Hildebrand, 2013). A well-exposed example is the Blue Mountains province of Oregon and Idaho (USA) (Fig. 1). The Blue Mountains province consists of two island arcs (the offshore Wallowa arc and the continent-fringing Olds Ferry arc), the intervening Baker accretionary prism (i.e., Baker terrane), and the forearc to collisional successor basin (Izee terrane). The two magmatic arcs collided with each other offshore cratonic North America prior to docking against North America (e.g., Dickinson and

Thayer, 1978; Dickinson, 1979; Dorsey and LaMaskin, 2007; Schwartz et al., 2010), but there is some debate about whether collision of the Blue Mountains province with North America occurred during the Late Jurassic Epoch (e.g., Dickinson, 1979, 2004; Avé Lallemant, 1995; Schwartz et al., 2010, 2011b) or prior to that time (e.g., LaMaskin et al., 2015). There is general agreement, however, that the Blue Mountains province was accreted to western North America no later than ca. 130 Ma along the Salmon River suture zone (e.g., Selverstone et al., 1992; McClelland et al., 2000; Snee et al., 2007; LaMaskin et al., 2011). The exact location of arc-continent collision is not known because postcollisional dextral translation could be ~100 km (e.g., Dickinson, 2004; Gray and Oldow 2005), ~400 km (e.g., Oldow, 1984; Wyld and Wright, 2001; Wyld et al., 2003; LaMaskin et al., 2011), or >1000 km (e.g., Housen and Dorsey, 2005).

The postaccretion tectonic history of the Blue Mountains province is less well understood due to the lack of contractional deformation of rocks after the Early Cretaceous Epoch. The time between accretion (either ca. 128 Ma, Getty et al., 1993; or before 160 Ma, LaMaskin et al., 2015) and cessation of deformation in the western Idaho shear zone (ca. 90 Ma;

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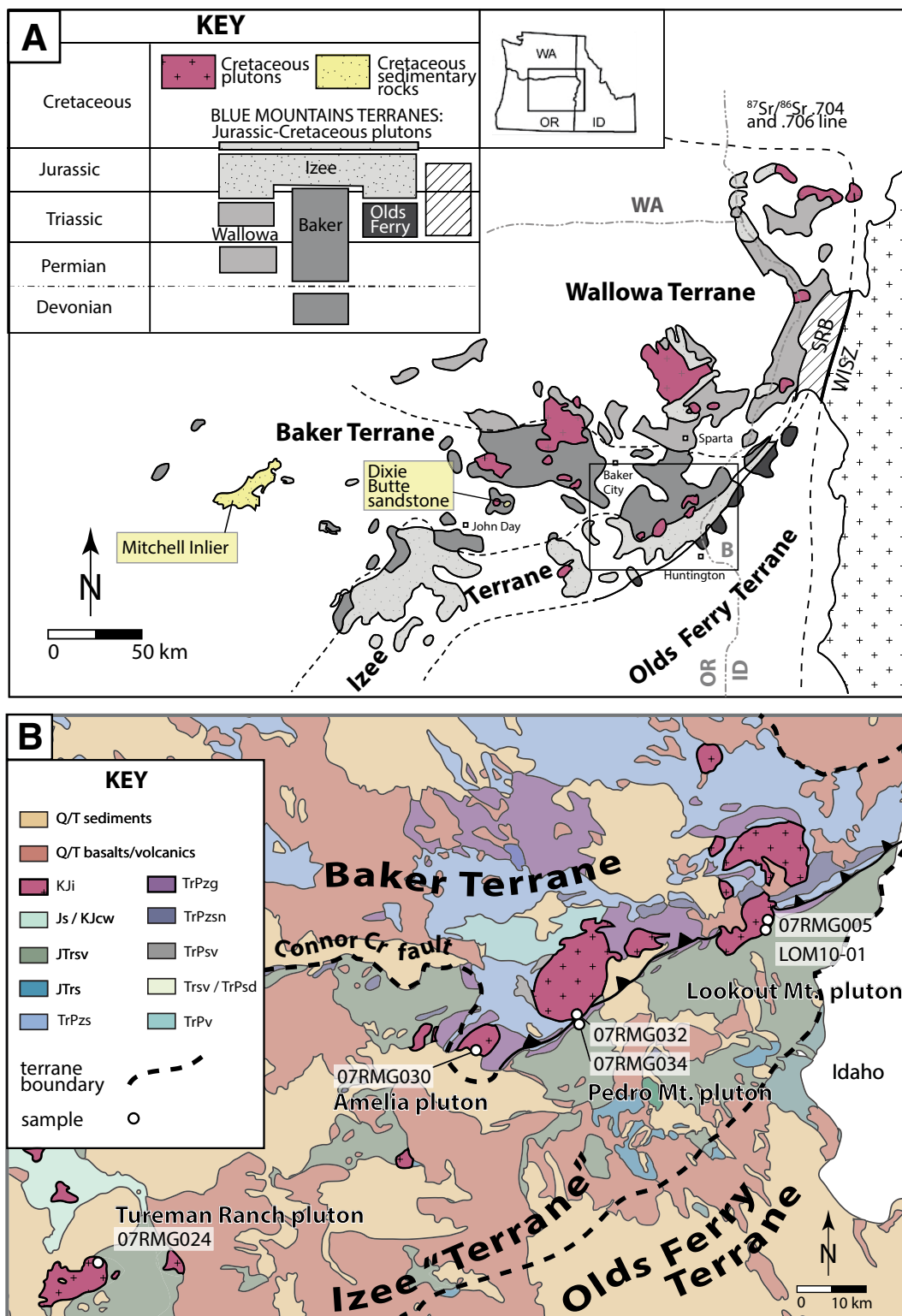


Figure 1. Geologic overview maps of the Blue Mountains province. (A) Simplified map of accreted terranes, with Cretaceous plutons and studied sediments in color (modified from Ware, 2013). (B) Overview of Blue Mountains plutons and surrounding area, modified from U.S. Geological Survey geologic map of Oregon. Sample locations within each studied pluton are shown. Q/T—Quaternary/Tertiary; KJi—Jurassic-Cretaceous intrusive rocks; Js/ KJcw—Cretaceous and Jurassic sedimentary rocks; JTrsv—Triassic-Jurassic sedimentary and volcanic rocks; JTrs—Triassic-Jurassic sedimentary rocks; TrPzs—Paleozoic-Triassic sedimentary rocks; TrPzg—Paleozoic-Triassic gabbroic rocks; TrPzsn—Paleozoic-Triassic marble; TrPsv—Triassic to Permian sedimentary and volcanic rocks; Trsv/TrPsd—Triassic sedimentary and volcanic rocks/Triassic-Permian sedimentary rocks; TrPv—Triassic-Permian volcanic rocks.

Giorgis et al., 2008) was a time of voluminous tonalite-trondhjemite-granodiorite magmatism, and these plutons record important information about the evolving postcollisional forearc region (Walker, 1986; Schwartz et al., 2011a). To date, important characteristics such as the magma source, precise ages, depth of emplacement, and the subsequent tectonic and erosional evolution of these intrusions remain unknown.

To better constrain the postcollisional history of the southern Blue Mountains province, we present new U-Pb zircon geochronology; major and trace element and Sr, Nd, and Pb isotopic geochemistry; plagioclase-hornblende thermobarometry; and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology for a suite of postaccretionary Early Cretaceous plutons that intruded near a terrane-bounding fault (the Connor Creek fault) of the Blue Mountains province (Fig. 1B; sample locations in Table 1). We also present the results of (U-Th)/He thermochronology for some of these plutons and other localities west of the western Idaho shear zone (0.706 Sr line). These new data indicate rapid shallow emplacement of Early Cretaceous plutons adjacent to an existing crustal-scale fault. We present detrital zircon analysis of a Late Cretaceous (late Cenomanian–Turonian) sandstone sample from shallow-marine sedimentary rocks of Dixie Butte, Oregon. The detrital zircon age distribution is consistent with derivation from the accreted oceanic terranes of the North America Cordillera, but not exclusively the Blue Mountains province. In addition, the near absence of zircons from rocks affected by the coeval transpression in the western Idaho shear zone, currently located east of Dixie Butte, suggests that the Blue Mountains province was translated into place during the last stages of, or after, western Idaho shear zone deformation.

GEOLOGIC BACKGROUND

In the Blue Mountains province, various interpretations of Triassic and Jurassic geochemical, isotopic, and structural data sets resulted in different interpretations of the early Mesozoic tectonic evolution of the region (e.g., Dickinson, 1979; Vallier, 1995, 1998; Avé Lallemant, 1995; Gray and Oldow, 2005; Dorsey and LaMaskin, 2007; Schwartz et al., 2011a; LaMaskin et al., 2015). Points of general agreement are that the Wallowa terrane is a distal arc, while the Olds Ferry arc was nearest to the cratonic North American continent and received continental-sourced sedimentation (Kurz et al., 2016).

The deformation history of the Blue Mountains province includes well-documented Late Triassic (228–219 Ma) left-lateral strike-slip deformation in the Wallowa terrane (D_1 ; Avé Lallemant et al., 1985; Avé Lallemant, 1995). This deformation, identified along the Oxbow and other regional shear zones, has been widely interpreted as subduction-related intraarc deformation during oblique plate convergence between the Wallowa and Baker terranes (i.e., noncollisional; Avé Lallemant et al., 1985; Follo, 1992; Avé Lallemant, 1995; Kurz and Northrup, 2008; Kurz et al., 2012). A subsequent Late Jurassic deformation event (D_2) predates intrusion of the Wallowa batholith (earliest phase ca. 140 Ma; Johnson et al., 2011),

which sutured the Wallowa and Baker terranes (Vallier, 1995; Dickinson, 1979). This second deformation has been interpreted as recording Late Jurassic collision between the Wallowa, Baker, and Olds Ferry–Izee composite terranes (Avé Lallemant et al., 1985; Avé Lallemant, 1995; Schwartz et al., 2011a).

Alternatively, a two-stage model for the early Mesozoic evolution of the Blue Mountains province includes: (1) Middle Jurassic accretion of the previously amalgamated Wallowa–Baker–Olds Ferry–Izee terranes to the western U.S. plate margin (LaMaskin et al., 2015); followed by (2) Late Jurassic regional shortening in the Blue Mountain province representing postaccretion outboard subduction (e.g., Dorsey and LaMaskin, 2007, 2008; LaMaskin et al., 2008, 2011, 2015; LaMaskin, 2012). This second model proposes that collisional tectonics played a significant role in the development of the Blue Mountains province, but that collision was complete by ca. 160 Ma (earliest Late Jurassic).

The terranes of the Blue Mountains province are intruded by plutons having four distinct age clusters: (1) Late Triassic (ca. 235–212 Ma); (2) late-Middle to Late Jurassic (ca. 162–154 Ma); (3) Late Jurassic to Early Cretaceous, including the Bald Mountain and Wallowa batholiths (ca. 148–122 Ma); and (4) Early Cretaceous (ca. 124–111 Ma; Walker, 1986; Johnson et al., 1997; Unruh et al., 2008; Kurz et al., 2012; Johnson et al., 2011; Schwartz et al., 2011a, 2011b; Fig. 1A). Some granitoids of the youngest phase of magmatism (e.g., Lookout Mountain pluton) intruded preexisting faults, such as the Connor Creek fault.

Following accretion, evidence for intraterrane deformation includes the northeast-southwest-oriented Connor Creek fault, which composes part of the border between the Baker and Olds Ferry terranes. This boundary is locally intruded by a series of Early Cretaceous plutons, which presumably exploit the fault as a magma conduit. In particular, the Lookout Mountain pluton acts as a stitching pluton intruding the terrane-bounding fault. Ware (2013) suggested, on the basis of U-Pb detrital zircon data from the nearby Weatherby Formation, that movement along the Connor Creek fault can be constrained between 170 and 129 Ma.

PLUTONS OF THE SOUTHERN BLUE MOUNTAINS

The four plutons of the southern Blue Mountains province are tonalitic and relatively similar in mineralogy. They intrude along a ~50 km corridor between the Burnt River Schist (Baker terrane) and Weatherby Formation (Izee terrane) that is locally subparallel to the southeast-vergent Connor Creek thrust fault (Fig. 1B). The two easternmost plutons (Lookout Mountain, Pedro Mountain) clearly crosscut this contact. The central Amelia stock is poorly exposed, but likely crosscuts the contact at depth given its proximity to Pedro Mountain and the inferred trace of the Connor Creek fault. The southwest Tureman Ranch stock is located within the Izee terrane, which locally covers the contact between the Baker and Olds Ferry terranes. Consequently, the exact position of the Tureman Ranch pluton relative to the contact at depth is unknown. However, the linear north-northeast alignment

TABLE 1. SAMPLE LOCATIONS

Sample	Latitude*	Longitude*	Lithology	Unit
LOM10-01	44.5231	-117.2852	biotite-hornblende tonalite	Lookout Mountain pluton
10RMG005	44.5297	-117.2854	biotite-hornblende tonalite/granodiorite	Lookout Mountain pluton
10RMG024	44.2139	-118.1317	biotite-hornblende tonalite	Turamen Ranch pluton
10RMG029	44.5360	-118.7132	sandstone	Cretaceous sandstone
10RMG030	44.4028	-117.6525	biotite-hornblende tonalite	Amelia pluton
10RMG032	44.4383	-117.5316	hornblende-biotite tonalite	Pedro Mountain pluton
10RMG034	44.4301	-117.5267	hornblende-biotite tonalite	Pedro Mountain pluton

*Coordinates given in North American Datum 1927.

of the four plutons suggests that they may all intrude the Baker–Olds Ferry boundary. Sample locations and coordinates are given in Table 1.

Lookout Mountain Pluton

The Lookout Mountain pluton is the largest and easternmost of the four plutons. Its exposure is discontinuous, but the southern portion of the pluton clearly cuts the Connor Creek fault. It is a medium gray phaneritic hornblende-biotite tonalite with quartz and plagioclase crystals ranging from 0.5 to 3 mm and biotite phenocrysts to 8 mm. Mafic minerals constitute ~20% of the rock (15% biotite and 5% hornblende). In thin section, plagioclase is subhedral to euhedral and exhibits albite twinning (Fig. 2A). Alkali feldspar (<5%) is distinguishable by tartan twinning. Hornblende is subhedral to anhedral with moderately developed cleavage and is weakly altered to epidote and chlorite around crystal edges. The rock also contains accessory igneous zircon, apatite, and magnetite. Quartz grains are broken up in linear alignment along with hornblende and biotite crystals, showing a high-temperature, solid-state deformation fabric.

Pedro Mountain Pluton

The ~60 km² Pedro Mountain pluton is exposed southwest of Lookout Mountain. The southeast corner of the pluton cuts the Connor Creek fault at the surface. Pedro Mountain is similar in mineralogy and microstructure to Lookout Mountain, but contains more hornblende and larger mafic phenocrysts. Quartz and plagioclase crystals range from 0.5 to 3 mm, biotite crystals range from 3 to 5 mm, and hornblende crystals range from 5 to 10 mm. In hand sample, hornblende crystals are either blocky or elongated. Mafic minerals constitute ~20% of the rock, with subequal amounts of biotite and hornblende. In thin section, subhedral to euhedral plagioclase exhibits albite twinning and zoning and quartz exhibits undulatory extinction. Quartz and plagioclase crystals are generally equigranular and smaller than the mafic minerals. Alkali feldspar is more prevalent (10%) than in Lookout Mountain. Anhedral to subhedral hornblende has poorly developed cleavage. Most hornblende crystals are found in aggregates and show alteration to epidote and chlorite. Biotite is present as isolated crystals as well as aggregates associated with magnetite and hornblende. Accessory zircon and apatite are also present.

Amelia Stock

The Amelia stock is much smaller (~3 km²) than the Lookout Mountain and Pedro Mountain plutons. It is mineralogically similar to, but finer grained than, the larger plutons, with 1–2 mm quartz and plagioclase crystals and 0.5–5 mm biotite and hornblende crystals. Mafic minerals constitute 20% of the rock, with roughly equal amounts of biotite and hornblende. In hand sample, hornblende is present as elongated crystals and as aggregates with biotite crystal fragments. Subhedral to euhedral plagioclase laths are twinned and zoned in thin section, quartz is undeformed, and alkali feldspar is scarce (5%). Quartz and plagioclase crystals appear generally equigranular in thin section (Fig. 2B). Biotite fragments are generally found in aggregates with hornblende, epidote, chlorite, and magnetite. The Amelia stock contains the most magnetite of any of the plutons. The magnetite appears very fresh and has ilmenite lamellae. The stock also contains accessory zircon and apatite.

Tureman Ranch Stock

The Tureman Ranch stock is fine grained and equigranular, with mafic minerals constituting ~20% of the rock, and has a weak fabric defined

by elongated hornblende crystals. Quartz, plagioclase, hornblende, and biotite crystals are mostly 1–3 mm, with a few larger (to 5 mm) mafic minerals. In thin section, anhedral plagioclase is twinned and zoned and quartz exhibits undulatory extinction (Fig. 2C). Alkali feldspar constitutes 5%–7% of the thin section. Hornblende is anhedral with poorly to moderately developed cleavage. Biotite and hornblende aggregates are associated with magnetite, chlorite, and epidote, as in the Amelia stock.

U-Pb GEOCHRONOLOGY

Methods

Zircon grains were separated from bulk samples via standard magnetic and heavy liquid separation techniques at the Department of Geosciences, Boise State University (BSU). Individual zircon crystals targeted through cathodoluminescence (CL) imaging were extracted from grain mounts, chemically abraded using a single aggressive abrasion step in concentrated HF at 180 °C for 12 h, and the residual crystals processed for isotope dilution thermal ionization mass spectrometry (ID-TIMS). Samples were spiked with the BSU-1B mixed U-Pb tracer, which has been calibrated against EARTHTIME gravimetric standards (Condon et al., 2015) and tested via both synthetic mixed U-Pb solutions and natural zircon standards. The details of ID-TIMS analysis were described by Kurz et al. (2012). U-Pb dates and uncertainties for each analysis were calculated using the algorithms of Schmitz and Schoene (2007) and the U decay constants of Jaffey et al. (1971). Other details of analytical parameters can be found in Appendix 1 in the Data Repository¹. The quoted uncertainties are based upon nonsystematic analytical errors, including counting statistics, instrumental fractionation, tracer subtraction, and blank subtraction. These error estimates should be considered when comparing our ²⁰⁶Pb/²³⁸U dates with those from other laboratories that used tracer solutions calibrated against the EARTHTIME gravimetric standards. When comparing our dates with those derived from other decay schemes (e.g., ⁴⁰Ar/³⁹Ar, ¹⁸⁷Re–¹⁸⁷Os), the uncertainties in tracer calibration (0.03%) and U decay constants (0.108%; Jaffey et al., 1971) should be quadratically added to the internal error.

Results

All of the plutonic samples yielded Early Cretaceous ages with a younging trend from west to east (Fig. 3). Sample 10RMG024 of granodiorite from the Tureman Ranch area yielded the oldest ages; five zircon crystals yielded equivalent ²⁰⁶Pb/²³⁸U dates and a weighted mean ²⁰⁶Pb/²³⁸U age of 129.36 ± 0.06 Ma. Sample 10RMG030 from the Amelia stock had 5 of 6 zircon grains yield equivalent ²⁰⁶Pb/²³⁸U dates with a weighted mean ²⁰⁶Pb/²³⁸U age of 125.50 ± 0.076 Ma; a single older analysis is interpreted as biased by inheritance. Sample 10RMG032 from the Pedro Mountain pluton had 4 of 6 zircons yield equivalent ²⁰⁶Pb/²³⁸U dates with a weighted mean ²⁰⁶Pb/²³⁸U age of 124.84 ± 0.073 Ma; a single older analysis was discarded as biased due to inheritance, and a single younger analysis was discarded as biased due to Pb loss. Sample LOM10–01 from the easternmost and youngest Lookout Mountain pluton yielded 8 single crystal analyses with equivalent ²⁰⁶Pb/²³⁸U dates and a weighted mean ²⁰⁶Pb/²³⁸U age of 123.84 ± 0.042 Ma.

¹GSA Data Repository Item 2017092, Appendix 1: Pages from Ware (2013) including calculated U-Pb ages of plutons; Table DR1: EMP Operating Conditions; Table DR2: Hornblende EMP and pressure-temperature; Table DR3: Detrital zircon U-Pb ages and Hf isotope data, is available at www.geosociety.org/datarepository/2017, or on request from editing@geosociety.org.

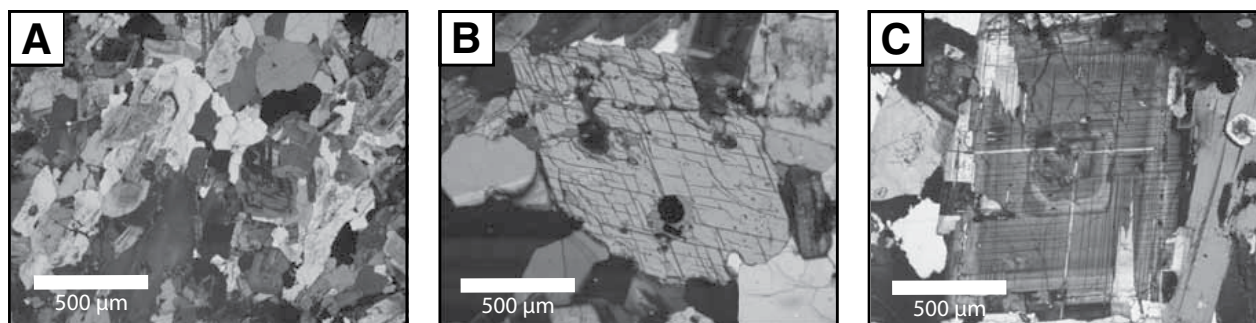


Figure 2. Photomicrographs in cross-polarized light. (A) Solid-state deformation fabric in Lookout Mountain pluton. (B) Hornblende in Amelia pluton. (C) Zoned feldspar in Tureman Ranch pluton.

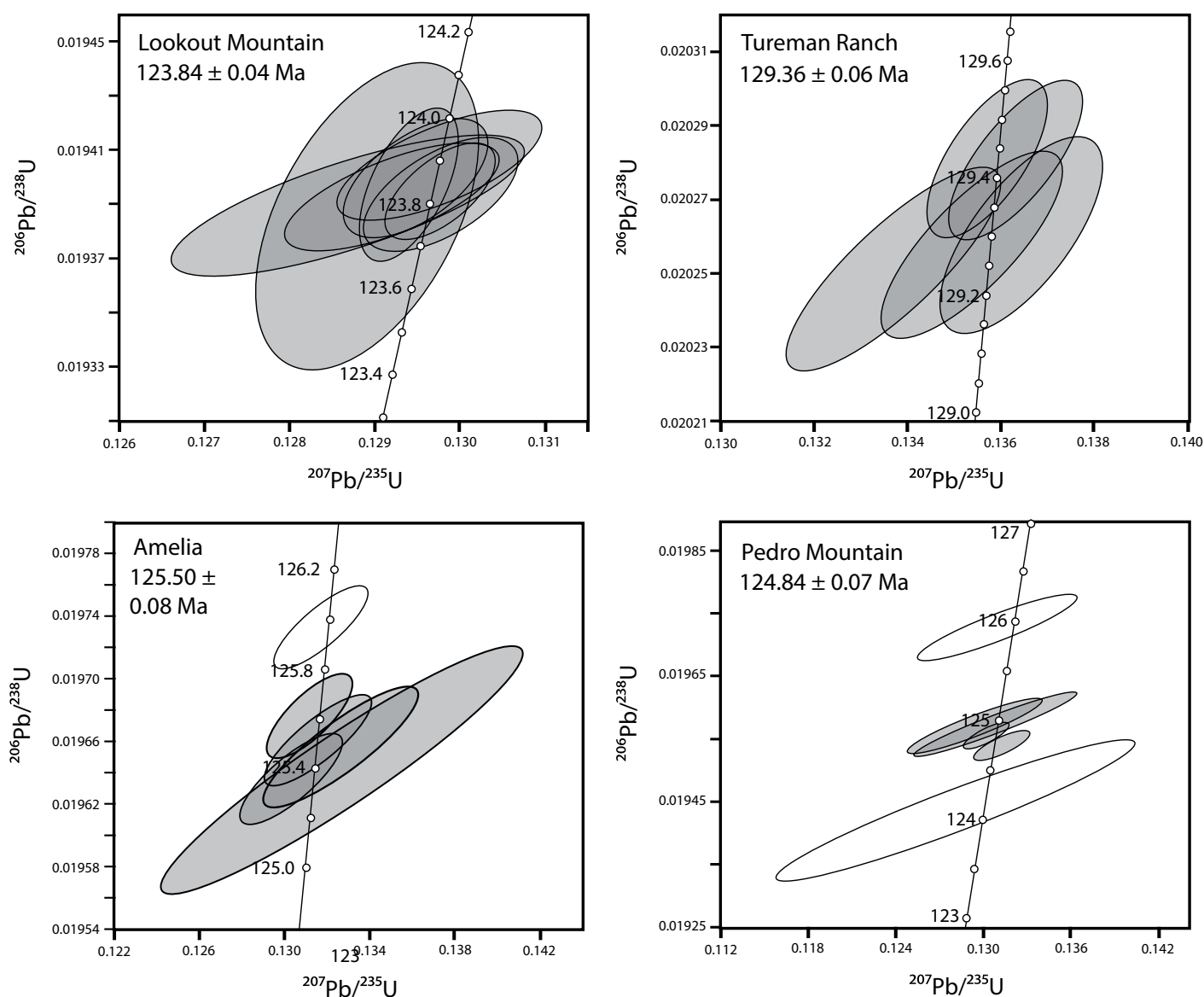


Figure 3. U-Pb concordia plots with 2σ data-point error ellipses. Weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages are calculated from shaded ellipses. Inherited zircon components were observed in the Amelia and Pedro Mountain samples, but not the Tureman Ranch or Lookout Mountain samples.

⁴⁰Ar/³⁹Ar GEOCHRONOLOGY**Methods**

The ⁴⁰Ar/³⁹Ar ages for the four plutons were determined through laser incremental heating of amphibole and biotite crystals at the WiscAr laboratory (University of Wisconsin-Madison). Large amphibole and biotite phenocrysts (500 μm to 2 mm) were separated from samples BT-23 (Pedro), BT-19 (Amelia), and BT-21 (Tureman Ranch) via crushing, hand-picking, and ultrasonic cleaning with acetone. Samples were then wrapped in aluminum packets, placed in aluminum disks, and irradiated along with the 28.201 Ma Fish Canyon sanidine (FCs) standard at the Oregon State University TRIGA reactor in the cadmium-lined in-core irradiation tube. Single amphibole and biotite crystals were fused or incrementally heated using a 25 W CO₂ laser. Gas cleanup and isotopic analysis using the MAP 215–50 mass spectrometer followed the methods of Jicha et al. (2006). The reported ages (Table 2; Fig. 4) are shown with 2σ analytical uncertainties (including J uncertainty) and were calculated using the decay constants of Min et al. (2000).

Results

The ⁴⁰Ar/³⁹Ar results (Fig. 4) are interpreted to represent the cooling ages of the plutons. The Pedro Mountain pluton records weighted mean plateau ages of 124.52 ± 0.42 and 124.85 ± 0.26 for hornblende and biotite, respectively (Table 2). Hornblende and biotite for the Amelia pluton yield plateau ages of 124.44 ± 0.47 and 124.89 ± 0.33. Hornblende from the Tureman Ranch pluton yields a plateau age of 124.47 ± 0.75. These results indicate that the Pedro Mountain and Amelia plutons cooled through hornblende and biotite closure temperatures (~550 °C and ~300 °C, respectively; e.g., Harrison, 1982; Grove and Harrison, 1996) rapidly, as these cooling ages are within analytical error. The cooling ages are also remarkably consistent with the U-Pb zircon ages, at 124.84 ± 0.07 Ma (Pedro Mountain) and 125.50 ± 0.08 Ma (Amelia). We interpret these results to indicate very rapid crystallization and cooling through ~350 °C, possibly due to shallow emplacement. The hornblende cooling age on the Tureman Ranch pluton is ~5 m.y. younger than the 129.36 ± 0.06 Ma U-Pb zircon age, suggesting that this pluton cooled more slowly, and thus might have intruded slightly deeper in the crust.

(U-Th)/He THERMOCHRONOLOGY**Methods**

Thermochronometry is used to constrain the cooling path of a rock, from which exhumation mechanisms can be inferred. In this study we apply (U-Th)/He zircon analysis to determine the time at which samples cooled below ~200 °C. This method is based on the accumulation and retention of He, a decay product of U and Th. As with other noble gas chronometers, the diffusion of He is a function of grain size and cooling rate. Other factors affecting the He closure temperature in zircon are crystallization age and U and Th concentrations, both contributing to the amount of radiation damage in the crystal (Guenther et al., 2013).

Three zircon grains per sample were selected for clarity and size, imaged, measured, and packed in Nb tubes for He extraction. All zircon imaging and analyses were conducted at the University of Arizona Radiogenic Helium Dating Laboratory according to procedures given by Reiners and Nicolescu (2006). The cooling age was given by the average of three analyses; the data are presented in Table 3. The methods are given in more detail in Fayon et al. (2017).

We conducted (U-Th)/He zircon analysis on three of the four plutons (Lookout Mountain, Amelia, and Tureman Ranch). In addition, to provide more regional coverage, we also included one analysis on the older Sparta complex, which is located west of Richland, Oregon (e.g., Prostka, 1967; Vallier, 1995). The Sparta complex contains latest Permian and Late Triassic components (Walker, 1995) and is part of the Wallowa–Seven Devils terrane (e.g., Vallier, 1995; Kurz et al., 2016), correlative to other inliers such as the Oxbow complex exposed along the Snake River near Oxbow, Oregon (e.g., Avé Lallemant et al., 1980, 1985; Avé Lallemant, 1995; Vallier, 1995).

Results

The results (Table 3) indicate that these samples from southern Blue Mountains province cooled through ~200 °C between ca. 120 and 80 Ma, during the Cretaceous Period. Three zircons from the Lookout Mountain pluton yield similar ages with an average age of 80.0 ± 8.6 Ma. Two zircons were analyzed from the Tureman Ranch pluton; the single grain ages are 132.1 ± 2.3 and 91.9 ± 1.5 Ma. The large difference between these two ages could be due to the size differences of the zircons analyzed. Regardless, the Lookout Mountain and younger of the two Tureman Ranch cooling ages are younger than the U-Pb zircon and ⁴⁰Ar/³⁹Ar ages for these plutons and indicate relatively rapid cooling through ~350 °C, with cooling rate slowing after biotite closure.

The Amelia pluton gave consistent ages of younger than 5 Ma. This same site was analyzed for paleomagnetic signature, which indicated high natural magnetic remanence with no consistent direction, suggesting lightning strikes. Given that the sample site is an isolated conical granite hill, lightning strikes are probably frequent, and we hypothesize that lightning strikes affected the (U-Th)/He in zircon (e.g., Mitchell and Reiners, 2003).

The Sparta complex consists of different components with U-Pb zircon ages of 253 and 215 Ma (Walker, 1995). Because the rest of the plutons are near the Conner Creek fault, ages from this complex constrain cooling away from an intra-Blue Mountains province terrane boundary. Three zircons from the Sparta intrusion record cooling ages of 66.5 ± 1.0, 109 ± 1.7, and 130 ± 2.0 Ma. The spread of single-grain ages can be explained by eU concentrations. Zircons yielding older ages have low eU concentrations (61 and 100 ppm) compared to the zircon yielding the youngest age. This grain has an eU concentration of 694 ppm. Recent advances in zircon (U-Th)/He dating have documented the effects of radiation damage and crystallization age. If an old zircon grain accumulates significant amounts of radiation damage, fast diffusion pathways allow for the rapid diffusion of He, thereby recording a young apparent cooling age. Thus, we interpret that this higher eU concentration results in the younger age. Consequently, this sample from the Sparta complex records cooling below 200 °C ca. 120 Ma.

GEOCHEMISTRY**Methods****Whole-Rock Geochemistry**

Samples of the four plutons were analyzed for major and trace elements by X-ray fluorescence and inductively coupled plasma–mass spectrometer (ICP-MS) at the Geoanalytical Laboratory at Washington State University following the methods of Johnson et al. (1999) and Knaack et al. (1994), respectively. Sr, Nd, and Pb isotope analyses were also conducted on these samples by multicollector-ICP-MS at Washington State University, following the methods in Gaschnig et al. (2011). Initial isotopic values are calculated from isotope dilution data for Sm–Nd and ICP-MS trace element data for Sr and Pb. Major and trace element and isotopic results are reported in Table 4.

TABLE 2. SUMMARY OF $^{40}\text{Ar}/^{39}\text{Ar}$ INCREMENTAL HEATING RESULTS FROM PLUTONS IN THE BLUE MOUNTAINS PROVINCE, OREGON

Sample	Material	K/Ca total	Number	^{39}Ar (%)	MSWD	$^{40}\text{Ar}/^{39}\text{Ar}_i$	$\pm 2\sigma$	Isochron age (Ma)	$\pm 2\sigma$ analytical uncertainty	Plateau age (Ma)	$\pm 2\sigma$ analytical uncertainty
Pedro Mountain											
11BT-23	biotite	22.562	15 of 18	89	0.60	234.5	± 53.3	125.279	± 0.459	124.854	± 0.263
	hornblende	0.048	6 of 14	74	0.47	299.1	± 73.6	124.471	± 1.048	124.519	± 0.410
Amelia											
BT-19	biotite	23.670	11 of 16	80	1.09	337.3	± 92.8	124.616	± 0.704	124.886	± 0.334
	hornblende	0.069	6 of 11	81	0.26	268.5	± 46.3	124.960	± 1.006	124.438	± 0.468
Tureman Ranch											
BT-21	hornblende	0.061	7 of 12	52	1.12	285.1	± 26.9	125.314	± 2.302	124.469	± 0.751

Note: Ages calculated relative to 28.201 Ma Fish Canyon sanidine (Kuiper et al., 2008) using decay constants of Min et al. (2000). MSWD—mean square of weighted deviates.

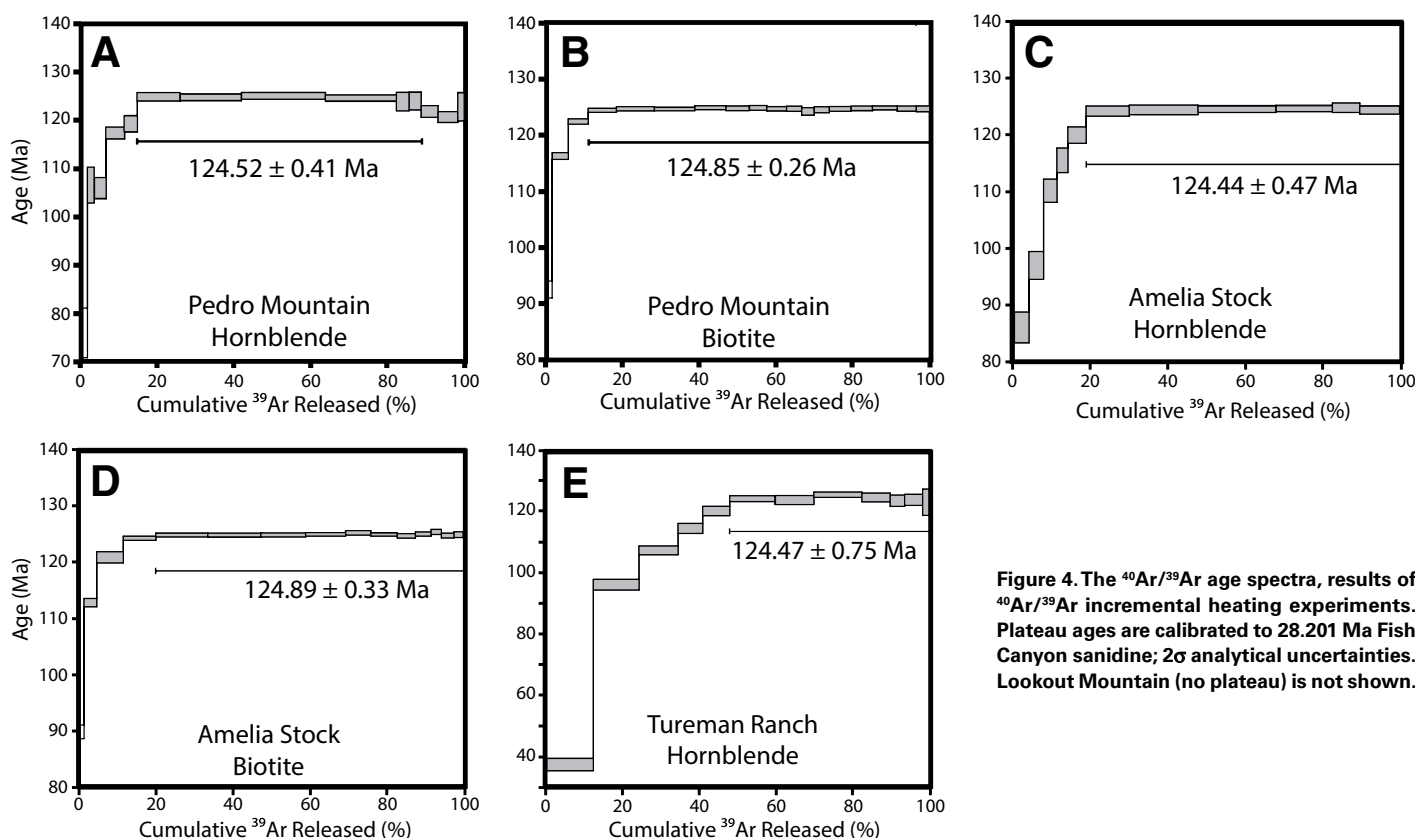


Figure 4. The $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra, results of $^{40}\text{Ar}/^{39}\text{Ar}$ incremental heating experiments. Plateau ages are calibrated to 28.201 Ma Fish Canyon sanidine; 2σ analytical uncertainties. Lookout Mountain (no plateau) is not shown.

TABLE 3. ZIRCON (U-Th)/He DATA FROM LOOKOUT MOUNTAIN PLUTON, AMELIA PLUTON, AND SPARTA COMPLEX

Sample	NAD27 (long)	NAD27 (lat)	Mass* (g)	r^{\dagger} (μm)	l^{\S} (μm)	eU (ppm)	U (ppm)	Th (ppm)	He (nmol/g)	Ft**	Raw date (Ma)	Corrected date (Ma)	Error (m.y.)	Mean age (Ma)	Standard deviation (m.y.)
LOM10_01_Zr1	-117.29	44.52	0.0000064	41.25	210.50	680.43	650.28	128.30	225.31	0.76	61.13	80.89	1.45		
LOM10_01_Zr2	-117.29	44.52	0.0000054	39.00	192.50	528.35	498.84	125.59	152.32	0.75	53.25	70.95	1.45		
LOM10_01_Zr3	-117.29	44.52	0.0000047	35.25	204.50	442.20	420.77	91.18	154.21	0.73	64.36	88.03	2.78	79.96	8.58
10RMG024_Zr2	-118.13	44.21	0.0000077	42.25	234.50	333.89	309.64	103.20	185.43	0.77	102.13	132.06	2.27		
10RMG024_Zr3	-118.13	44.21	0.0000545	87.50	388.00	231.80	213.90	76.14	101.51	0.88	80.69	91.85	1.54	111.95	28.44
13AF38_zr1	-117.33	44.88	0.0000092	45.25	246.00	693.85	641.59	222.34	195.84	0.79	52.14	66.52	0.96		
13AF38_zr2	-117.33	44.88	0.0000030	34.75	137.00	99.62	89.52	42.97	42.08	0.71	77.84	109.91	1.74		
13AF38_zr3	-117.33	44.88	0.0000031	32.00	165.50	61.07	56.13	21.03	30.41	0.70	91.65	130.42	2.08	102.28	32.62

Note: 1σ analytical uncertainty propagated from the U, Th, and He measurements and grain length uncertainties. NAD27—geodetic North American Datum 1927.

*Zr-based mass for zircon.

† Average radius.

§ Average length.

**Ft is alpha ejection correction of Hourigan et al. (2005).

TABLE 4. WHOLE-ROCK GEOCHEMISTRY

Sample ID	10RMG005	10RMG024	10RMG030	10RMG032	10RMG034
Unit	Lookout Mtn pluton	Turamen Ranch pluton	Amelia pluton	Pedro Mtn pluton	Pedro Mtn pluton
Lithology	Tonalite	Tonalite	Tonalite	Tonalite	Tonalite
XRF major elements (wt %)					
SiO ₂	65.72	65.69	65.37	64.95	59.94
TiO ₂	0.45	0.45	0.46	0.50	0.70
Al ₂ O ₃	16.99	16.61	17.34	16.81	17.93
FeO*	4.08	4.06	4.00	4.85	6.43
MnO	0.07	0.08	0.08	0.10	0.13
MgO	2.00	2.47	1.81	2.13	3.17
CaO	5.30	5.17	5.58	5.27	6.38
Na ₂ O	4.14	3.92	4.08	3.82	3.84
K ₂ O	0.94	1.21	1.01	1.27	1.17
P ₂ O ₅	0.14	0.14	0.12	0.11	0.14
XRF trace elements (ppm)					
Ni	10	16	10	8	8
Cr	18	24	18	19	19
Sc	10	12	9	12	19
V	86	104	71	99	146
Ba	345	504	470	552	500
Rb	19	19	22	30	29
Sr	491	646	377	359	387
Zr	93	69	92	102	102
Y	10	10	10	15	22
Nb	2	2	3	3	2
Ga	18	20	19	17	19
Cu	4	16	5	7	7
Zn	67	70	69	73	85
Pb	6	6	5	5	4
La	10	5	10	8	7
Ce	18	16	14	18	18
Th	2	1	1	2	1
Nd	12	10	10	10	11
U	2	2	1	1	1
ICP-MS trace elements (ppm)					
La	7.63	9.16	8.48		7.53
Ce	16.9	18.9	18.2		16.8
Pr	2.36	2.52	2.55		2.46
Nd	10.4	10.3	11.2		11.4
Sm	2.48	2.24	2.81		3.25
Eu	0.812	0.731	0.925		1.03
Gd	2.27	2.02	2.60		3.52
Tb	0.343	0.298	0.391		0.620
Dy	1.93	1.77	2.17		4.04
Ho	0.364	0.357	0.402		0.844
Er	0.90	0.93	1.01		2.35
Tm	0.131	0.135	0.147		0.347
Yb	0.819	0.893	0.899		2.23
Lu	0.137	0.141	0.145		0.354
Ba	346	499	470		496
Th	1.28	1.52	1.45		1.44
Nb	1.66	1.78	2.36		1.94
Y	9.75	9.26	10.8		21.7
Hf	2.41	1.86	2.11		2.67
Ta	0.131	0.112	0.176		0.134
U	0.475	0.515	0.513		0.530
Pb	4.67	4.62	3.76		3.98
Rb	17.3	17.7	21.5		27.6
Cs	0.769	0.498	0.877		3.15
Sr	482	661	372		379
Sc	8.92	11.2	8.61		18.1
Zr	76.5	62.0	73.2		93.7

(continued)

TABLE 4. WHOLE-ROCK GEOCHEMISTRY (*continued*)

Sample ID	10RMG005	10RMG024	10RMG030	10RMG032	10RMG034
Unit	Lookout Mtn pluton	Turamen Ranch pluton	Amelia pluton	Pedro Mtn pluton	Pedro Mtn pluton
Lithology	Tonalite	Tonalite	Tonalite	Tonalite	Tonalite
$^{87}\text{Rb}/^{86}\text{Sr}$	0.1097	0.0836	0.1691	0.2449	0.2188
$^{87}\text{Sr}/^{86}\text{Sr}$	0.70376	0.70360	0.70409	0.70455	0.70450
2 std error	± 0.00001	± 0.00001	± 0.00003	± 0.00001	± 0.00001
$^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$	0.70356	0.70345	0.70379	0.70411	0.70411
Sm-ID	2.31	2.10	2.51	2.45	2.97
Nd-ID	9.85	10.1	10.6	10.8	11.2
$^{147}\text{Sm}/^{144}\text{Nd}$	0.14164	0.12642	0.14290	0.13704	0.16082
$^{143}\text{Nd}/^{144}\text{Nd}$	0.512932	0.512879	0.512910	0.512865	0.512959
2 std error	± 0.000010	± 0.000010	± 0.000006	± 0.000006	± 0.000009
$^{143}\text{Nd}/^{144}\text{Nd}(\text{i})$	0.512816	0.512776	0.512793	0.512753	0.512827
ϵ_{Nd}	5.9	4.9	5.5	4.6	6.4
$\epsilon_{\text{Nd}(\text{i})}$	6.8	6.0	6.3	5.5	7.0
2 std error	± 0.2	± 0.2	± 0.1	± 0.1	± 0.2
$^{206}\text{Pb}/^{204}\text{Pb}$	18.7265	18.7653	18.7314	18.7865	18.7413
2 std error	± 0.0004	± 0.0005	± 0.0006	± 0.0005	± 0.0005
$^{207}\text{Pb}/^{204}\text{Pb}$	15.5889	15.5871	15.5891	15.6038	15.5978
2 std error	± 0.0003	± 0.0005	± 0.0005	± 0.0004	± 0.0004
$^{208}\text{Pb}/^{204}\text{Pb}$	38.3391	38.3489	38.3218	38.4373	38.3616
2 std error	± 0.0008	± 0.0013	± 0.0012	± 0.0010	± 0.0012
$^{206}\text{Pb}/^{204}\text{Pb}(\text{i})$	18.341	18.289	18.602	18.645	18.464
$^{207}\text{Pb}/^{204}\text{Pb}(\text{i})$	15.570	15.564	15.583	15.597	15.584
$^{208}\text{Pb}/^{204}\text{Pb}(\text{i})$	38.198	38.290	38.237	38.283	38.294

Hornblende-Plagioclase Thermobarometry

Pressure-temperature conditions of tonalite emplacement and crystallization were determined using the hornblende-plagioclase thermobarometer (after Anderson and Smith, 1995). Hornblende-plagioclase pairs were analyzed at the Washington State University Geoanalytical Lab using a JEOL JXA-8500F field emission electron microprobe. Operating conditions are given in Table DR1 and results are reported in Table DR2. Only analyses of unaltered hornblende rims and adjacent plagioclases were used. Hornblende formulas were calculated based on 13 cations (Cosca et al., 1991).

Results and Interpretation

Five samples were analyzed, one each from the Lookout Mountain, Turamen Ranch, and Amelia plutons. All samples are hornblende-biotite tonalite with similar major element compositions. Two samples from the Pedro Mountain pluton were analyzed; one was very similar to the tonalite samples of the other plutons, and the other was more mafic quartz diorite. All samples are calcic and magnesian (Fig. 5), using the classification system of Frost et al. (2001). The compositions of these plutons overlap with plutons of similar age in western Idaho (Hazard Creek complex; Manduca et al., 1992) and related plutons to the north (Lee, 2004; Lewis and Frost, 2005), northeastern Oregon (Johnson et al., 1997), and the western Sierra Nevada batholith of California (Truschel, 1996; Lackey et al., 2012), all of which were emplaced in oceanic crustal terranes.

Major aspects of the trace element chemistry are the Nb-Ta depletion relative to large ion lithophile elements and light rare earth elements (LREE), high Sr/Nd, moderate LREE/heavy (H) REE, and no Eu anomaly (Fig. 6). The Nb-Ta depletion and high Sr/Nd are commonly considered to be signposts of arc magmatism (e.g., Pearce and Peate, 1995). The enrichment of LREE over HREE is similar for all samples except the more mafic Pedro Mountain sample, which shows an even shallower slope in its REE pattern. In addition to these relative differences between groups of elements, the concentrations of many insoluble incompatible elements

(e.g., La, Ce, Nb, and Y) are considerably lower than average continental crustal values (Rudnick and Gao, 2003), consistent with ocean arc crustal heritage. Constraints on the thickness of the crust and the depth of melting are often inferred from Sr/Y and La/Yb ratios due to the sequestration of Y and Yb in residual garnet (e.g., Tulloch and Kimbrough, 2003; Schwartz et al., 2011b). Sr/Y values of four plutons we studied vary from 18 to 71, but La/Yb values remain modest (≤ 10) and HREE show little fractionation over middle REE. These results suggest that Sr/Y ratios reflect amphibole stabilization and perhaps suppression of plagioclase crystallization (consistent with the lack of negative Eu anomaly) during differentiation due to high H_2O activity (e.g., Moore and Carmichael, 1998; Davidson et al., 2007) and that the crust was not unusually thick.

The Sr and Nd isotopic compositions of the plutons are relatively primitive, with $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ ranging from 0.7034 to 0.7041 and $\epsilon_{\text{Nd}(\text{i})}$ ranging from +5.5 to +6.7 (Fig. 7). These values are in a zone of overlap between the isotopic compositions of the Wallowa and Olds Ferry arc terranes (Kurz et al., 2016). These two arc terranes have distinct common Pb isotopic compositions; however, the Olds Ferry exhibits higher $^{207}\text{Pb}/^{204}\text{Pb}$ for a given $^{206}\text{Pb}/^{204}\text{Pb}$ than the Wallowa arc (Kurz et al., 2016). The four ca. 125 Ma plutons of this study plot near to within the Olds Ferry arc field, which is consistent with their position along the presumed suture between the Olds Ferry arc and the Baker accretionary terrane (Fig. 8).

The primitive Sr-Nd isotopic signatures combined with more radiogenic $^{207}\text{Pb}/^{204}\text{Pb}$ ratios suggest that the petrogenesis of the four plutons involved some level of reworking of Olds Ferry island arc basement. Melting of the basement could be driven by crustal thickening associated with the cryptic metamorphic events recorded in the Salmon River suture zone (e.g., Getty et al., 1993; Snee et al., 2007; McKay, 2011) or could be caused by contemporaneous mantle input due to subduction outboard of the Blue Mountains province. The small nature of this data set limits our ability to distinguish between these scenarios, particularly since Sr-Nd isotopic compositions of the Blue Mountains province largely overlap with the expected compositions of any fresh arc basalts (see compilation of Kelemen et al., 2003).

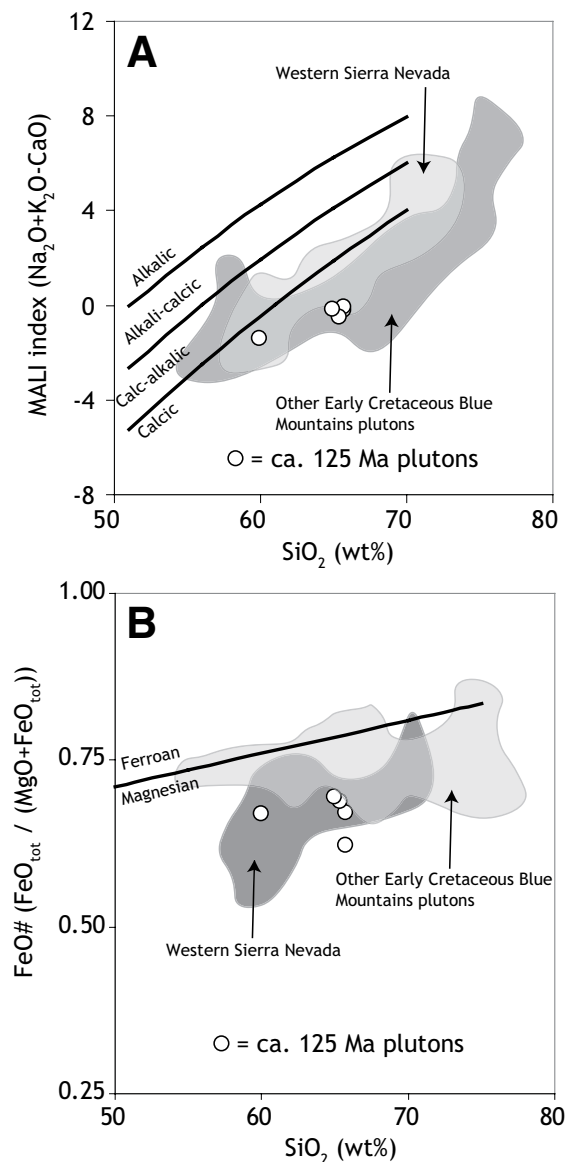


Figure 5. Major element-based classification of the four plutons based on Frost et al. (2001) (MALI—Modified alkali lime index). Shown for comparison are data for other Cordilleran plutons emplaced in accreted island arc terranes, including plutons of similar age elsewhere in the Blue Mountains province (Manduca et al., 1992; Lee, 2004; Johnson et al., 1997; Lewis and Frost, 2005) and the western Sierra Nevada (Truschel, 1996; Lackey et al., 2012). T—total.

Figure 7. Sr and Nd isotope characteristics of the stitching plutons. TR—Tureman Ranch pluton, LM—Lookout Mountain pluton, A—Amelia pluton, PM—Pedro Mountains pluton. Fields for the Wallowa, Olds Ferry, and Baker terranes are from Kurz et al. (2016), Tumpane (2010), and Schwartz et al. (2010), respectively. Average island arc basalt field is from Kelemen et al. (2003).

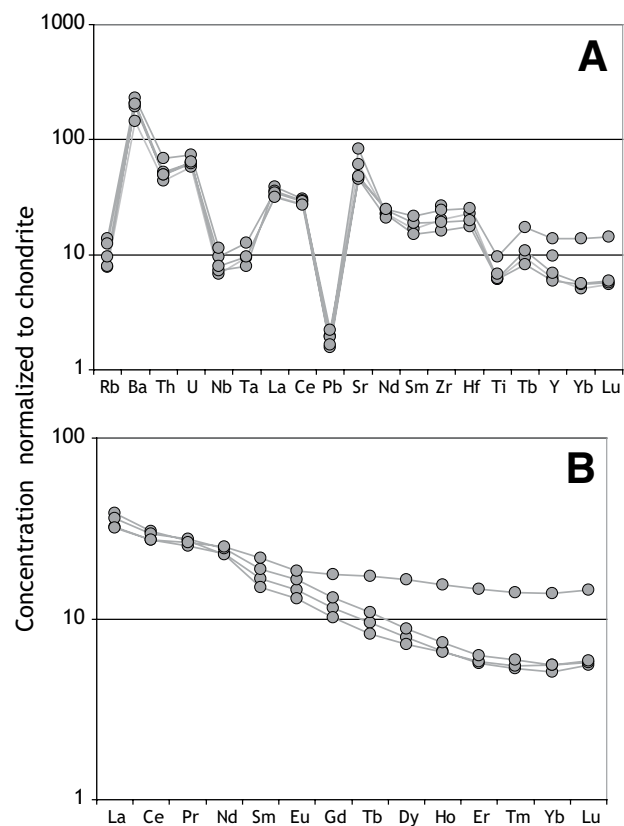
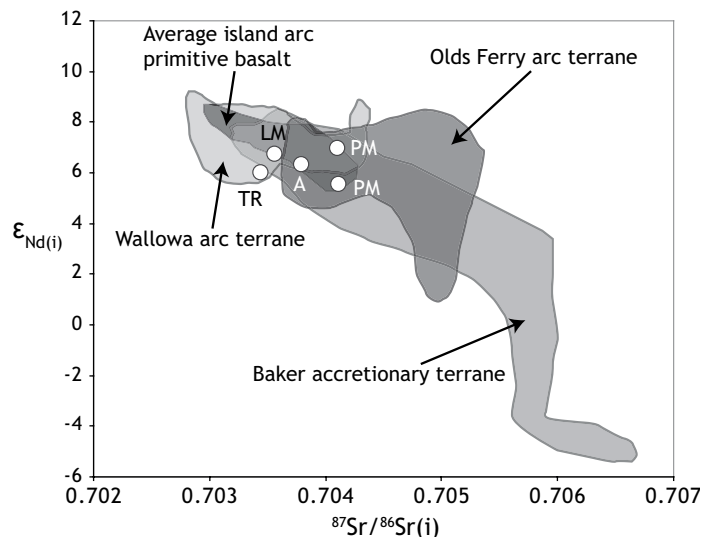


Figure 6. (A) General trace element variations, normalized to chondrite (McDonough and Sun, 1995). (B) Rare earth element (REE) variations, normalized to chondrite (McDonough and Sun, 1995). The stitching plutons have the Nb-Ta depletion and high Sr/Nd characteristic of arc magmas, suggesting an origin by recycling the Blue Mountains arc basement and/or renewed arc magmatism above a subduction zone outboard of the province. The moderate slope of the REE pattern and lack of strong fractionation between the middle and heavy REEs indicates that the magmas were formed and/or differentiated in the hornblende stability field (rather than garnet), suggesting that the crust had a normal thickness.



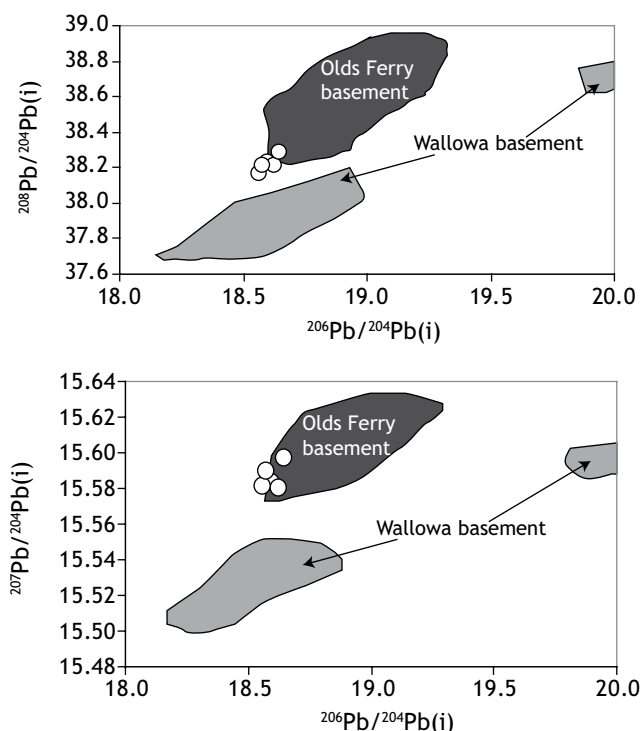


Figure 8. Pb isotope characteristics of the stitching plutons. Fields are based on data from Kurz et al. (2016). Pb isotopes are highly effective in distinguishing the Olds Ferry and Wallowa terranes, in contrast to Sr-Nd systematics. These results suggest that the stitching plutons were emplaced in and incorporated material from the Olds Ferry terrane.

Depth of Emplacement

Pressure-temperature conditions of crystallization for three of the four plutons are shown in Figure 9, based on the combined plagioclase-hornblende thermometer and Al-in-hornblende barometer (after Anderson and Smith, 1995). All hornblende analyses from the Lookout Mountain pluton and one from the Amelia pluton are unusually magnesian, falling below the $\text{Fe}_{\text{total}}/(\text{Fe}_{\text{total}} + \text{Mg})$ range recommended by Anderson and Smith (1995) for use of the thermobarometer, so they are not considered further. The remaining analyses from the Amelia and Pedro Mountain plutons yield a wide range of temperatures, spanning ~660 to ~740 °C (Fig. 9). Pressures derived for the Amelia pluton occupy a very narrow range, averaging ~2.9 kbar, whereas the Pedro Mountain yields more variable results, with a high-temperature group at ~2.5 kbar and a lower temperature group between 3.5 and 4.2 kbar. This variation is largely driven by differences in plagioclase composition, as most of the plagioclase crystals are zoned with more calcic cores, which results in the higher calculated temperatures and lower pressures seen in one of the two groups. Although those high-Ca plagioclase zones were in contact with hornblende, if we calculate pressure and temperature using the average plagioclase rim composition (An_{30}) for these hornblendes, pressure-temperature parameters are within the range of the other pairs.

DETRITAL ZIRCON ANALYSIS (DIXIE BUTTE)

Methods

Detrital zircons were separated from a Late Cretaceous (late Cenomanian–Turonian based on gastropod and pelecypod fossils, ca. 95–90 Ma;

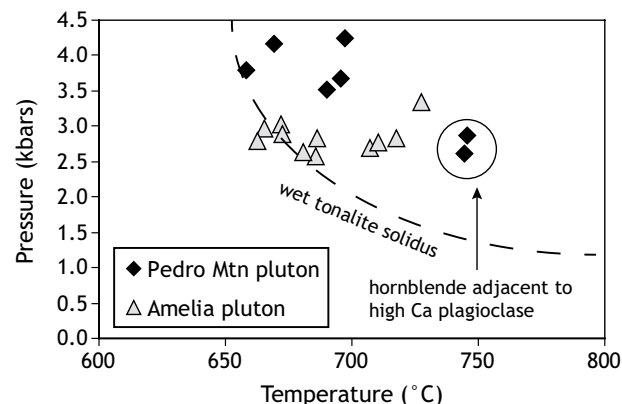


Figure 9. Results for plagioclase-hornblende thermobarometry using the formulation of Anderson and Smith (1995). Emplacement pressures of generally lower for the Amelia pluton. Two hornblende-plagioclase pair analyses (arrow) yield distinctly higher temperatures and lower pressures for the Pedro Mountain pluton than the majority of the other Pedro Mountain results. The former results are distinguished by unusually high Ca plagioclase, resulting in higher calculated temperatures, which drive down the calculated pressures.

Brooks et al., 1984) fossiliferous sandstone at Dixie Butte. Zircons were mounted by pouring en masse onto double-sided tape and grains were targeted for analysis randomly by circling different parts of the mount and analyzing every grain within the circles. Laser ablation-multicollector-ICP-MS Hf isotope geochemistry analyses were conducted at the Geoanalytical Laboratory at Washington State University following the methods in Gaschnig et al. (2013). Results are reported in Table DR3. Only U-Pb analyses <15% discordant are discussed in the following, but more discordant grains belong to identical age populations.

Results

Detrital zircons from the Late Cretaceous Dixie Butte sandstone are entirely Phanerozoic, and the majority are Cretaceous and Jurassic in age, with major age modes present at 109, 163, and 189 Ma (Fig. 10), which form 24%, 28%, and 30%, respectively, of the total number of <15% discordant analyses. The remaining 18% of analyses are Triassic and late Paleozoic (primarily Carboniferous). The youngest single age is 102 Ma, and using the approach of Dickinson and Gehrels (2009), the maximum depositional age constrained by the weighted mean of the youngest group of three or more analyses with overlapping 2σ errors is 105.1 ± 1.8 Ma (2σ errors), older than the fossil-based depositional age (95–90 Ma; Brooks et al., 1984). No ages are present between 123 and 147 Ma and there is a wider scarcity of ages between 117 and 154 Ma. The Hf isotope geochemistries of representative zircons analyzed from each major age distribution are entirely juvenile, with $\epsilon_{\text{Hf}(t)}$ values as high as +15 (Fig. 11). The late Paleozoic grains yield values consistently $>+10$, whereas the Mesozoic grains exhibit a greater range, extending to a minimum value of +6.5.

The lack of Precambrian (and hence Laurentian) detrital zircons and the strongly positive ϵ_{Hf} values of the observed Mesozoic and late Paleozoic zircons are consistent with derivation from the accreted oceanic terranes of the Cordillera, with no discernable influence from cratonic North America. The question of whether the zircons were supplied by local sources in the Blue Mountains province can be addressed by comparing

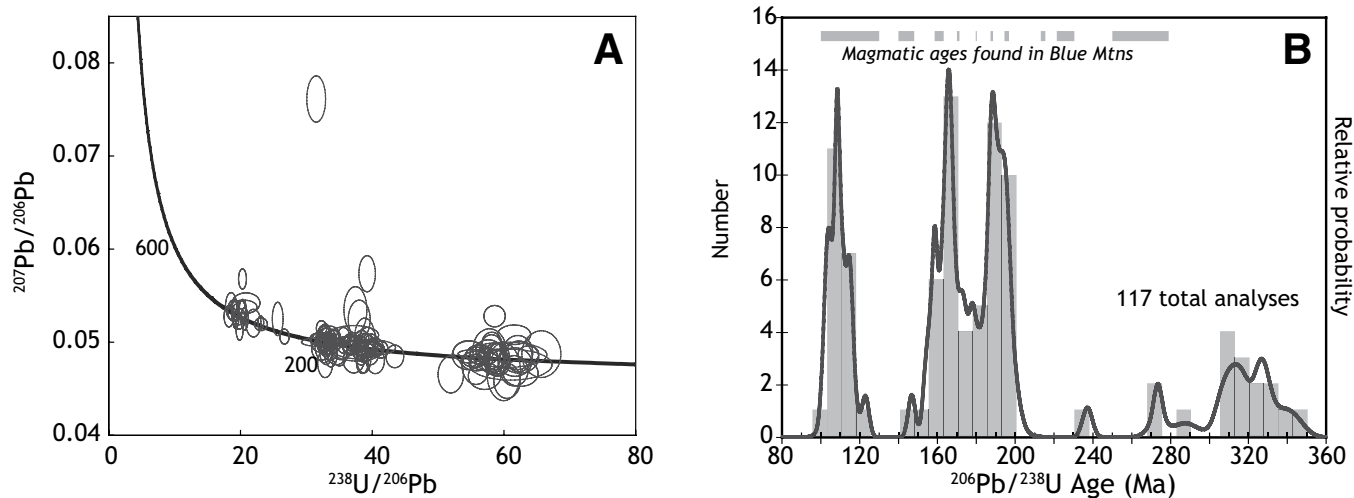


Figure 10. Detrital zircon U-Pb results. (A) Tera-Wasserburg diagram showing all U-Pb analyses. Ellipses represent total 2σ errors. **(B)** Histogram and probability density plot showing only $<15\%$ discordant analyses. (The excluded analyses do not alter the basic pattern.) Also shown (bar on top of figure) is the range of igneous ages reported for the Blue Mountains (Mtns) province in the literature (Manduca et al., 1993; Walker, 1995; Johnson et al., 1997, 2011; Unruh et al., 2008; Schwartz et al., 2010, 2011a, 2014; Tumpane, 2010; Kurz et al., 2012; LaMaskin et al., 2015).

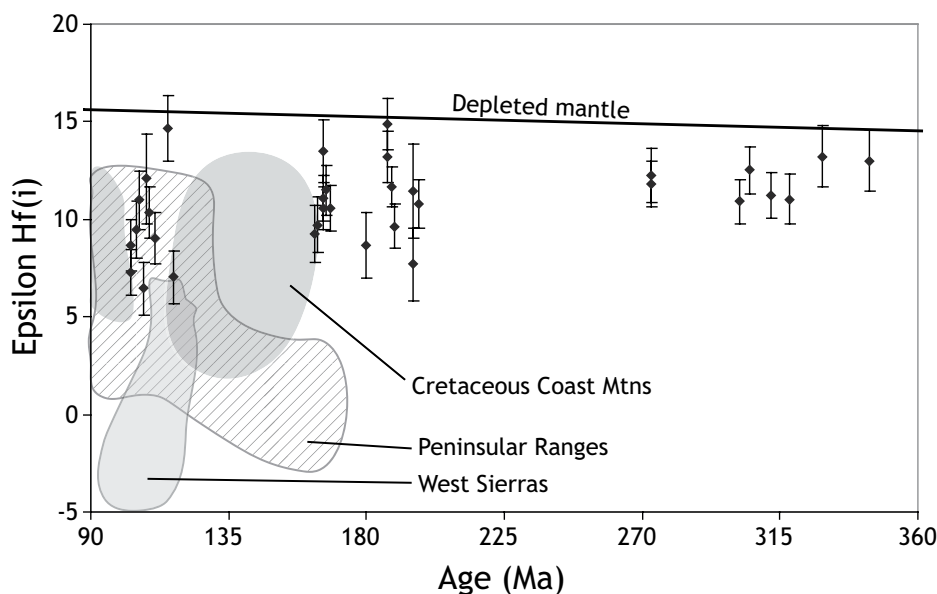


Figure 11. Hf isotope composition versus U-Pb age for detrital zircons. Depleted mantle trajectory from Vervoort and Blichert-Toft (1999). West Sierra, Peninsular Ranges, and Coast Mountains fields are from Lackey et al. (2012), Shaw et al. (2014), and Cecil et al. (2011), respectively.

the detrital zircon age distribution to the distribution of igneous ages in the Blue Mountains province (Fig. 10B). Igneous rocks between 120 and 100 Ma present in the Blue Mountains province and Salmon River suture belt adjacent to the western Idaho shear zone (Manduca et al., 1993; Unruh et al., 2008) and in the Blue Mountains interior (Johnson et al., 1997) could have supplied the youngest zircon in the Dixie Butte sandstone. Local Blue Mountains igneous rocks could have also supplied the Late Jurassic zircons (Schwartz et al., 2011b), and the Early Jurassic zircons could have been recycled from the Weatherby Formation (LaMaskin et al., 2011). However, the detrital zircon age gap between 154 and 117 Ma is problematic because abundant igneous rocks of this age are present in the Blue Mountains (e.g., this study; Johnson et al., 2011; Schwartz et al., 2011a, 2014). The Dixie Butte detrital zircons also do not record the major magmatic events of Late Triassic time that characterize the Blue

Mountains province (e.g., Tumpane, 2010; Kurz et al., 2012), although these source rocks also did not contribute to older Jurassic Blue Mountains sediments (LaMaskin et al., 2011) and may not have been exposed.

Assuming that the faunally based depositional age (95–90 Ma) is accurate, the Dixie Butte sediments should have been deposited during deformation and uplift in the western Idaho shear zone (which was active coincident with and/or slightly before deposition; Giorgis et al., 2008). If the Dixie Butte sediments were deposited nearby the active western Idaho shear zone, they should include detrital zircons grains from (1) Precambrian metasedimentary rocks in the western Idaho shear zone; and (2) 110–100 Ma igneous zircons with a mix of subchondritic and superchondritic Hf isotopic signatures (e.g., Braudy et al., 2016). However, no Precambrian zircons are observed in the Dixie Butte sediments and all of the Cretaceous detrital zircons have superchondritic Hf.

A final potential mismatch between the Dixie Butte sandstone and local Blue Mountains sources is the presence of the Paleozoic detrital zircons in the former and lack of any known igneous sources in the latter. Although zircons of similar age are found in the sedimentary rocks of the Izee and Baker terranes (e.g., LaMaskin et al., 2011), recycling of these older sedimentary rocks would likely introduce Precambrian grains that are not observed at Dixie Butte.

DISCUSSION

Tectonic Constraints from ca. 125 Ma Granitoids

Spatial Trends of Magmatism

Magmatism in the southern part of the Blue Mountains province occurred between 129.4 and 123.8 Ma, based on our new high-precision U-Pb zircon ages. The high precision of these ages allows us to resolve a younging trend from the southwest (Tureman Ranch pluton; 129.40 ± 0.04 Ma) to the northeast (Lookout Mountain pluton; 123.84 ± 0.04 Ma). Similar ages on intrusions with similar compositions have been reported regionally. For example, to the north of our field area, Johnson et al. (2011) documented an intrusion and a satellite body within the Wallowa batholith, emplaced at 125 Ma and 122 Ma, respectively.

Approximately 50° – 60° of clockwise post-Jurassic rotation of the Blue Mountains province is recorded by paleomagnetic analyses (Wilson and Cox, 1980; Heller et al., 1987; Dickinson, 2004). Restoring this rotation aligns the plutons along an approximately north-south orientation with a south to north progression of magmatism. This reconstruction also places the terrane boundaries into an approximately north-south-oriented, margin-parallel position.

The Blue Mountains province ca. 125 Ma likely occupied a forearc position in relation to slow, head-on eastward-dipping subduction under North America during the early stages of Sevier orogenesis (DeCelles and Coogan, 2006; Dumitru et al., 2010; LaMaskin et al., 2015). We infer this subduction geometry because of the presence of a nearly continuous magmatic arc in the U.S. Cordillera at the time that included the earliest Cretaceous components of the Peninsular and Sierra Nevada batholiths to the south, the youngest elements of the Wallowa batholith (Johnson et al., 2011), and the Blue Mountains plutons studied here. In this orientation, the along-strike directionality of magmatism could result from migration of a subducting spreading center (e.g., Kinoshita, 1999), a migrating slab window (e.g., Lomize and Luchitskaya, 2012), or change in slab subduction angle (e.g., Valencia-Moreno et al., 2006). At present, we have insufficient data to distinguish between these models.

Constraints on Movement of the Connor Creek Fault

The combination of the U-Pb zircon, $^{40}\text{Ar}/^{39}\text{Ar}$ analyses, and hornblende geobarometry constrains the movement of the Connor Creek fault. The Pedro Mountain and Lookout Mountain are relatively undeformed stitching plutons along the Connor Creek fault and therefore indicate that the fault ceased moving before ca. 125 Ma. The Al-in-hornblende geobarometry indicates that the plutons intruded at ~ 3 kbar, and the $^{40}\text{Ar}/^{39}\text{Ar}$ ages indicate cooling quickly after emplacement. These data are consistent with upper crustal depths of pluton intrusion.

The cessation of deposition within the Weatherby Formation constrains the timing of Connor Creek fault initiation (Ware, 2013). The Weatherby Formation has a cleavage that is subparallel to the Connor Creek fault, indicating that the sedimentary rocks were deposited prior to fault movement. The youngest sediments in the Weatherby Formation are Middle Jurassic (Bajocian; ca. 168 Ma). Consequently, the Connor Creek fault was active between 168 and 125 Ma. Faulting of other terrane boundaries

(e.g., Baker-Wallowa boundary; Bourne-Greenhorn subterranean boundary) in the Blue Mountains province also occurred during this time interval (Schwartz et al., 2011a). Recent geochronology in the Devils Canyon unit of the Burnt River schist (Baker terrane) from immediately north of the Connor Creek fault yields similar detrital zircon ages to the Weatherby Formation (Mailloux, 2011). The juxtaposition of metamorphosed rocks north of the fault against unmetamorphosed rocks to the south suggests a prolonged history of movement on the Connor Creek fault. Consequently, deformation likely ceased significantly after 168 Ma. At present, however, we cannot constrain the initiation of the Connor Creek fault.

Likely Sources for Dixie Butte Detrital Zircons

It is useful to consider possible sedimentary sources for the Dixie Butte sediments for two reasons. First, there is the likelihood of some amount of along-strike transport of the Blue Mountains province (e.g., Oldow, 1984; Wyld et al., 2003; Housen and Dorsey, 2005; LaMaskin et al., 2011), as with other outboard terranes in the Cordillera constrained by paleomagnetic data (e.g., Irving, 1985; Housen and Beck, 1999; Enkin et al., 2003). Second, the lack of an Idaho source for detrital zircons, despite the present position of Blue Mountains province, supports the contention that the terrane was translated north after deposition.

To the south, the terranes of the Klamath Mountains are largely oceanic and would likely yield zircons with sufficiently juvenile Hf isotope compositions. However, while the terranes of the Blue and Klamath Mountains both underwent abundant Jurassic magmatism overlapping in age with our detrital results for the Dixie Butte sandstone, no igneous rocks are present in the Klamath Mountains that could provide a source for the 120–100 Ma detrital age distribution (e.g., Hacker et al., 1995; Irwin and Wooden, 1999). While the data do not entirely eliminate the Klamath Mountains as a source of detrital zircon, they eliminate the possibility of that range being the sole source. Considering sources even further to the south, the requisite middle Cretaceous and Jurassic ages are present in the western Sierra Nevada and Peninsular Ranges batholiths. Hf isotope results are only available for mid-Cretaceous plutons in the Sierra Nevada batholith, which tend to be less juvenile (Lackey et al., 2012). However, sufficiently juvenile mid-Cretaceous plutons are present in the Peninsular Ranges (Shaw et al., 2014). Sources for the late Paleozoic detrital zircons exist in the Klamath Mountains (Miller, 1989), but are not known further south.

A potential source to the north is the Coast Mountains batholith. The Coast Mountains batholith underwent episodes of magmatism during Jurassic and Cretaceous time (e.g., Gehrels et al., 2009), at intervals that match the age distributions of the Dixie Butte detrital zircons. Hf isotope signatures for Cretaceous Coast Mountains plutons are sufficiently juvenile (e.g., Cecil et al., 2011) to match the Cretaceous detrital zircons. Jurassic Coast Mountains rocks have juvenile Nd isotopes (Girardi et al., 2012), suggesting that their Hf isotope composition would be sufficiently juvenile based on the close correlation between the Nd and Hf systems (e.g., Vervoort and Patchett, 1996). The Coast Mountains batholith may also provide a source for the late Paleozoic detrital zircons, as consistent ages have been reported for plutons in that region (e.g., Gardner et al., 1988).

If the Coast Mountains are a major source of detrital zircons to the Dixie Butte sandstone, this scenario implies that detrital zircons were either (1) carried longitudinally (southward) by a major north-south river; or (2) the Coast Mountains were closer to Oregon in the Late Cretaceous. A complication of the fluvial transport option is that a major contemporaneous depocenter, the Methow-Tyughton basin, was present to the north and might have captured any detritus traveling eastward from the Coast Mountains. However, it is also possible that some sediment was routed past this basin further south to the Blue Mountains province.

Significant paleomagnetic evidence exists for a more southern Late Cretaceous position of the Canadian Insular superterrane, which hosts the Coast Mountains batholith (e.g., Irving, 1985; Irving et al., 1996; Haggart et al., 2006; Umhoefer and Blakey, 2006). In this scenario, a portion of the Coast Mountains batholith would have been adjacent to the Blue Mountains, in an outboard position. A more southward position of the Coast Mountains is also supported by the fault-based reconstruction of Wyld et al. (2006). Consequently, we tentatively assign the source rock of these sediments to be the Coast Mountains batholith. If this interpretation is correct, we would expect similarly aged Cretaceous sedimentary rocks found in the Mitchell inlier to the west to show similar detrital zircon U-Pb and Hf systematics.

Tectonic Model for Easternmost Oregon in the Middle to Late Cretaceous

Our work has attempted to constrain the postaccretion tectonic history of the Blue Mountains province with cratonic North America. The accretion, recorded along the Salmon River suture zone, was certainly complete by 130 Ma (e.g., Selverstone et al., 1992; Getty et al., 1993; Vallier, 1995; Gray and Oldow, 2005; Snee et al., 2007; Schwartz et al., 2010), although it might have occurred much earlier (before 160 Ma; LaMaskin et al., 2011). One remaining question is what was the exact location of the Blue Mountains province prior to the activation of the western Idaho shear zone. In the following we consider the new data sets presented here and what bearing they have on the issue of whether the southern Blue Mountains were adjacent to western Idaho during the Early Cretaceous.

The Early Cretaceous igneous rocks in eastern Oregon have ages and compositions similar to the tonalite-trondhjemite-granodiorite magmatism in the Salmon River belt adjacent to the western Idaho shear zone (e.g., the 118 ± 5 Ma Hazard Creek complex of Manduca et al., 1993). However, the Early Cretaceous plutonic rocks of western Idaho intruded at significantly deeper crustal depths (~7 kbar; Zen, 1988; Manduca et al., 1993) relative to the eastern Oregon plutons (~2.5–4.5 kbar). The timing of cooling of the plutons below ~200 °C based on data from three locations in eastern Oregon is variable, ranging between 132 and 80 Ma, and is dependent on location. The older Sparta complex and the Tureman Ranch pluton appear to have cooled by ca. 120–110 Ma, whereas Lookout Mountain cooled below 200 °C by 80 Ma. The cooling age recorded by Lookout Mountain pluton is similar to cooling ages obtained from plutonic rocks exposed near the western boundary of the western Idaho shear zone (Hazard Creek complex of Manduca et al., 1993). Zircons from that region record cooling below ~200 °C ca. 76 Ma (Fayon et al., 2017). Thus, the Lookout Mountain pluton, the easternmost of the plutons investigated, shares a similar cooling history with rocks within the Salmon River suture zone. Collectively, these points are consistent with the interior Blue Mountains province and Salmon River belt being a coherent entity after the Early Cretaceous, but do not bear directly on the latitude at which the Blue Mountains initially docked with North America.

Sedimentation on the southern Blue Mountains province, recorded by the Dixie Butte sediments, suggests that the southern Blue Mountains were not adjacent to western Idaho in the middle Cretaceous. The western Idaho shear zone was active at 100–90 Ma, and deformed mostly orthogneisses aged 118–91 Ma (e.g., Manduca et al., 1993; Giorgis et al., 2008). The transpressional, high-strain nature of western Idaho shear zone would result in exhumation of zircon-rich orthogneisses (Giorgis and Tikoff, 2004; Giorgis et al., 2005). Therefore, the western Idaho shear zone should be a major source of detrital zircons. As noted herein, the complete lack of Precambrian detrital zircon and lack of middle Cretaceous detrital zircon with subchondritic Hf in the Dixie Butte strata indicate that western Idaho was not a provenance source. The same problem exists for other

Late Cretaceous sedimentary deposits in Blue Mountains province. The Gable Creek and Goose Rock conglomerates of central Oregon contain mostly clasts of chert, low-grade metamorphosed volcanic rocks, and plutonic rocks (Little, 1986). These lithologies are almost entirely missing from the western Idaho shear zone. Consequently, there is a significant mismatch between the orthogneisses being exhumed in the western Idaho shear zone and the middle Cretaceous sedimentary rocks deposited in the Blue Mountains province.

There is also a discrepancy in deformation histories in eastern Oregon relative to western Idaho. Contraction occurred throughout the Salmon River suture zone in the Early Cretaceous, on both the western (e.g., Salmon River belt; Getty et al., 1993) and eastern (e.g., Montz and Kruckenberg, 2017) sides of the western Idaho shear zone. This deformation is in addition to the transpressional deformation associated with the ca. 103–90 Ma western Idaho shear zone. Yet there is effectively no evidence for contractional deformation in the Blue Mountains province during this same time interval. There is not even reactivation of pre-existing terrane-boundary fault zones (e.g., Connor Creek fault), despite their presumed weakness and proximity (~100 km) to major geological structure (e.g., western Idaho shear zone).

The Blue Mountains province likely moved northward as a result of deformation along the dextral transpressional western Idaho shear zone (Tikoff et al., 2001; Giorgis et al., 2008). However, the western Idaho shear zone is only traceable southward to the Owyhee Mountains in southwestern Idaho (Benford et al., 2010); there is no obvious continuation of this structure southward. Strain analyses, which constrain only minimal displacement estimates, suggest 50–100 km of right-lateral motion (Giorgis et al., 2005; Benford et al., 2010).

One possibility is that the Blue Mountains province was located in northern Nevada prior to activation of the western Idaho shear zone. This hypothesis requires a minimum reconstruction of ~400 km of dextral motion, similar to that proposed by Wyld and Wright (2001) and LaMaskin et al. (2011). Specifically, a ~400 km reconstruction would restore the Blue Mountains to northern Nevada (Black Rock Desert region; Fig. 12). As summarized in LaMaskin et al. (2011), the Black Rock terrane of western Nevada and the Olds Ferry terrane of eastern Oregon are likely dismembered fragments of the same arc (Wyld and Wright, 2001). If so, volcanic centers in the Black Rock region were the source of the Late Triassic–Middle Jurassic sedimentary rocks of the Blue Mountains province. Furthermore, collision of the Blue Mountains province could be responsible for the Luning–Fencemaker fold-thrust belt, which initiated ca. 190 Ma (Wyld, 2002; Wyld et al., 2003). The coincidence of Late Triassic–Early Jurassic deformation in the Black Rock region (Jackson Mountains and the Pine Forest Range; ca. 201–185; Wyld et al., 1996; Wyld et al., 2003) and central Oregon (ca. 215–190; Dickinson and Thayer, 1978) supports this reconstruction.

An alternative hypothesis is that the Blue Mountains province could be much further traveled. Well-constrained paleomagnetic studies from the Mitchell inlier in the Blue Mountains province suggests 1200 ± 460 km of right-lateral offset since 93 Ma (Housen and Dorsey, 2005). Similar amounts of offset are inferred from paleomagnetic data for much of the Intermontane terrane in Canada (i.e., Stikinia–Cache Creek–Quesnellia; e.g., Irving et al., 1995, 1996; Haskin et al., 2003; Housen and Dorsey, 2005). The Intermontane terrane and the Blue Mountains province share compositional similarities, including the presence of a two island arc terranes separated by an argillite–matrix mélange (Stikinia–Cache Creek–Quesnellia versus Wallowa–Baker–Olds Ferry; Schwartz et al., 2011a). As such, it is possible that the Blue Mountains province is part of a much larger terrane that underwent large-scale dextral motion along the western edge of North America.

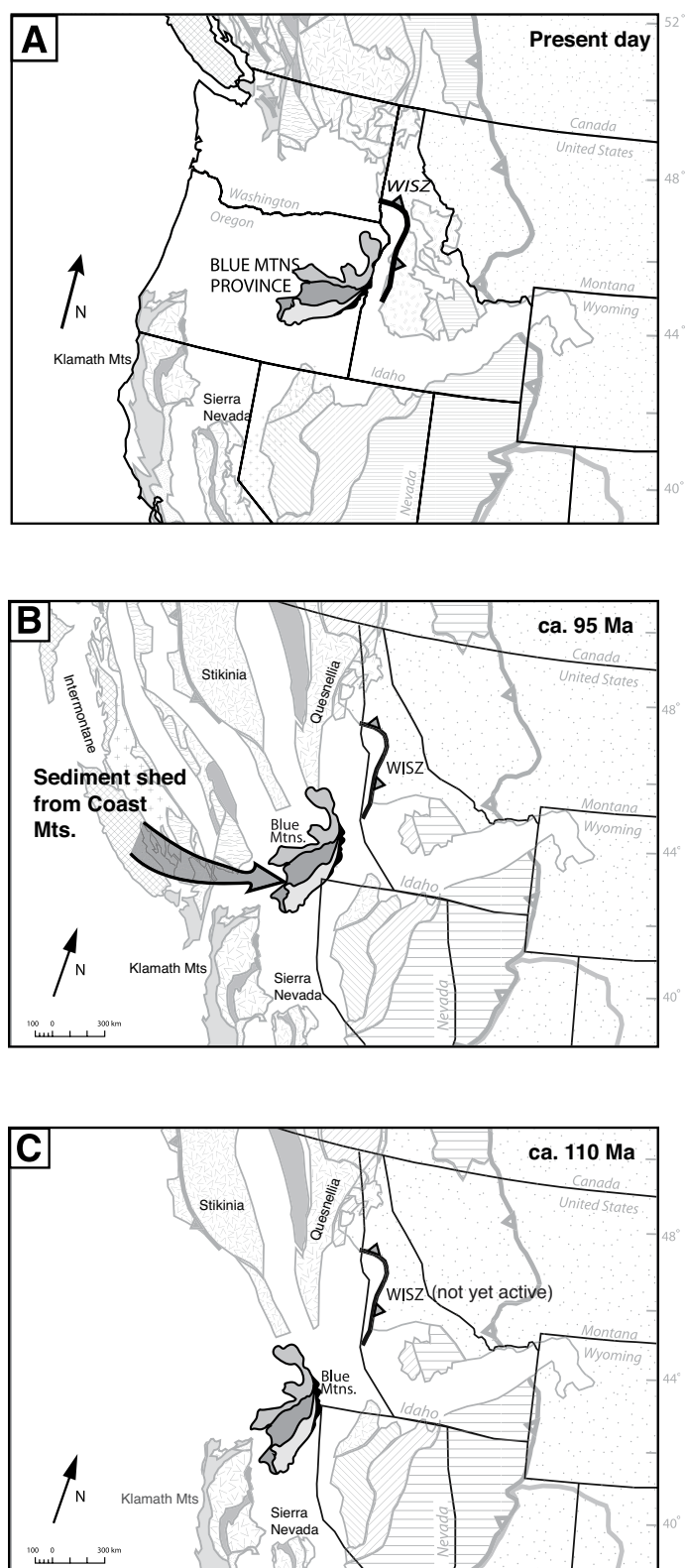


Figure 12. Schematic maps of the basement geology in the northwestern United States. (A) Present day. (B) 95 Ma. (C) 110 Ma. Sediment shed off the Coast Mountains batholith is possibly deposited on the southern Blue Mountains province ca. 95 Ma, as indicated by the arrow. Tectonic reconstructions are modified from Wyld et al. (2006). WISZ—western Idaho shear zone.

Is a southern location of the Blue Mountains province in the Early Cretaceous consistent with our data? If the collision that resulted in the deformation of the western Idaho shear zone (e.g., Giorgis et al., 2008) was limited to terranes outboard of western Idaho, the Blue Mountains province would have been unaffected if it was south of the Owyhee Mountains. Therefore, the Blue Mountains province and western Idaho would not share the same deformation history, consistent with our data. Furthermore, if the Blue Mountains province was far enough away from western Idaho, the Late Cretaceous sedimentation could have been unaffected by exhumation along the western Idaho shear zone. This inference is also consistent with our data from Dixie Buttes. Note that it is also unlikely that the Intermontane terrane was immediately westward of the Blue Mountains, as it would require two Intermontane-type terranes to be outboard cratonic North America during middle Cretaceous sedimentary deposition.

A southern location for the Blue Mountains province, however, raises the question of what material was outboard of the Salmon River suture zone in western Idaho during contractional deformation. Although significant contraction deformation is recorded in the Salmon River belt (e.g., Getty et al., 1993; Gray and Oldow, 2005), these rocks are located west of the western Idaho shear zone, and thus were also translated northward by that structure. However, collision must have occurred on the cratonic side of western Idaho, prior to the deformation in the western Idaho shear zone, as evidenced by deformation, melt generation, and assimilation of oceanic material on the eastern (North American) side of the western Idaho shear zone in the Early Cretaceous (Braudy et al., 2016; Montz and Kruckenberg, 2017). Thus, we postulate that a northward extension of the Blue Mountains province (which was located in northern Nevada) existed in western Idaho in the Early Cretaceous.

A potentially larger issue is to recognize the structures that accommodated the final northward movement of the Blue Mountains province. The western Idaho shear zone could accommodate significant offset, as the displacement offset estimates of 50–100 km assume homogeneous transpressional deformation throughout the shear zone (e.g., Giorgis and Tikoff, 2004). We know of no constraint that would not allow ~400 km of dextral translation on the western Idaho shear zone, but the temporal constraint is that deformation ceased by 90 Ma (Giorgis et al., 2008). More significant (~1200 km) amounts of dextral translation would require the presence of another strike-slip and/or transpressional fault zone system. The paleomagnetic data of Housen and Dorsey (2005) from the Mitchell inlier suggest that movement occurred after 93 Ma, yet the western Idaho shear zone ceased motion at 90 Ma (Giorgis et al., 2008). If 1200 km of motion occurred over 3 m.y., it would require displacement rates (~400 mm/yr) that are significantly larger than plate motions even in the Cretaceous Period. Consequently, any large-scale translation must have occurred on another dextral fault or shear zone in addition to the western Idaho shear zone. We know of no structure that can accommodate this displacement. Although we cannot resolve between moderate (~400 km) and more substantial (~1200 km) dextral translation with our data, we generally support a minimum reconstruction of ~400 km because it satisfies the regional geological constraints from the Blue Mountains province and northern Nevada.

CONCLUSIONS

This study focuses on the Cretaceous history of deformation in the southern Blue Mountains province, and its relation to the Salmon River suture zone and western Idaho shear zone. Four Early Cretaceous (ca. 125 Ma) plutons intrude along or near the Connor Creek fault, placing a minimum age on the formation of this structure. The $^{40}\text{Ar}/^{39}\text{Ar}$ analyses

on biotite and hornblende indicate very rapid (<1 m.y.) cooling below biotite closure temperature (~350 °C) and Al-in-hornblende geobarometry indicates moderate (~3 kbar) emplacement depths. Cooling through ~200 °C (U-Th)/He zircon data) of two of these plutons, and another intrusion near Sparta, Oregon, occurred in the middle Cretaceous.

The Late Cretaceous sedimentary sequence at Dixie Buttes provides a different type of constraint on middle Cretaceous tectonism. Detrital zircons in these sediments record Paleozoic–Mesozoic ages, indicating derivation from juvenile accreted terrane lithosphere. We suggest that the Insular terrane (Coast Mountains batholith) is the source, based on both U-Pb zircon and Hf isotope geochemistry analyses. We conclude that the southern Blue Mountains province was located south (400 km or more) of its present position during suturing and likely moved into place during transpressional deformation on the western Idaho shear zone.

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