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Provenance analysis of the Ochoco basin, central Oregon: A window into the Late Cretaceous paleogeography of the northern U.S. Cordillera

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ABSTRACT

Cretaceous forearc strata of the Ochoco basin in central Oregon may preserve a record of regional transpression, magmatism, and mountain building within the Late Cretaceous Cordillera. Given the volume of material that must have been eroded from the Sierra Nevada and Idaho batholith to result in modern exposures of mid- and deep-crustal rocks, Cretaceous forearc basins have the potential to preserve a record of arc magmatism no longer preserved within the arc, if forearc sediment can be confidently linked to sources. Paleogeographic models for mid-Cretaceous time indicate that the Blue Mountains and the Ochoco sedimentary overlap succession experienced postdepositional, coast-parallel, dextral translation of less than 400 km or as much as 1700 km. Our detailed provenance study of the Ochoco basin and comparison of Ochoco basin provenance with that of the Hornbrook Formation, Great Valley Group, and Methow basin test paleogeographic models and the potential extent of Cretaceous forearc deposition. Deposition of Ochoco strata was largely Late Cretaceous, from Albian through at least Santonian time (ca. 113–86 Ma and younger), rather than Albian–Cenomanian (ca. 113–94 Ma). Provenance characteristics of the Ochoco basin are consistent with northern U.S. Cordilleran sources, and Ochoco strata may represent the destination of much of the mid- to Late Cretaceous Idaho arc that was intruded and eroded during and following rapid transpression along the western Idaho shear zone. Our provenance results suggest that the Hornbrook Formation and Ochoco basin formed two sides of the same depositional system, which may have been linked to the Great Valley Group to the south by Coniacian time, but was not connected to the Methow basin. These results limit northward displacement of the Ochoco basin to less than 400 km relative to the North American craton, and

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suggest that the anomalously shallow paleomagnetic inclinations may result from significant inclination error, rather than deposition at low latitudes. Our results demonstrate that detailed provenance analysis of forearc strata complements the incomplete record of arc magmatism and tectonics preserved in bedrock exposures, and permits improved understanding of Late Cretaceous Cordilleran paleogeography.

INTRODUCTION

Numerous studies of the North American Cordillera have greatly improved our understanding of its complex tectonic history of subduction and arc magmatism, terrane accretion, and coast-parallel strike-slip motion (e.g., Monger et al., 1982; Oldow et al., 1989; Dickinson, 2004, 2008; Wyld et al., 2006; Gehrels et al., 2009; DeCelles and Graham, 2015). However, details regarding the latitude of accretion and distance of subsequent coast-parallel translation of many Cordilleran terranes continue to be debated, as exemplified by the Baja–British Columbia controversy (Irving, 1985; Umhoefer, 1987; Cowan et al., 1997; Mahoney et al., 1999; Haggart et al., 2006; Wyld et al., 2006; Rusmore et al., 2013; Garver and Davidson, 2015). Furthermore, potential links between changes in Farallon and Pacific plate convergence beginning ca. 100 Ma (e.g., Page and Engebretson, 1984; Engebretson et al., 1985; Liu et al., 2008), widespread Late Cretaceous Cordilleran magmatic flare-ups (e.g., Ducea, 2001; Ducea and Barton, 2007; Gehrels et al., 2009; Ducea et al., 2015; Paterson and Ducea, 2015), and dextral transpression throughout the Cordillera (e.g., Tobisch et al., 1995; Tikoff and Greene, 1997; Wakabayashi, 1992; Wyld et al., 2006; Wright and Wyld, 2007) are not yet clear.

Present-day exposures of mid- and deep-crustal arc rocks in the Sierra Nevada and Idaho batholith preserve an impressive but incomplete record of Cretaceous tectonics and magmatism in the western United States. Given the volume of material that must have been eroded from these arcs, Cretaceous forearc basins in the western U.S. Cordillera may preserve a record of arc magmatism no longer present in the arc itself. The Ochoco basin of central Oregon may have been part of a large, Cretaceous forearc system in which the strata record details of regional transpression, magmatism, and mountain building in the U.S. Cordillera (Kleinhans et al., 1984; Nilsen, 1986; Miller et al., 1992; Dorsey and Lenegan, 2007). Alternatively, the Ochoco basin may have been distinct from other Cretaceous forearc basins in the U.S. Cordillera, and deposited as much as 1700 km south of its modern-day location (Housen and Dorsey, 2005).

Although Cenozoic flood basalts blanket much of the central Oregon region, several mid- to Late Cretaceous inliers deposited on Permian–Triassic rocks of the Blue Mountains Province comprise the surface exposures of the Ochoco basin (Dickinson and Vigrass, 1965; Oles and Enlows, 1971; Dickinson, 1979; Kleinhans et al., 1984; Dorsey and Lenegan, 2007). The Mitchell inlier in central Oregon is spatially and stratigraphically the largest exposure in the Ochoco basin (Figs. 1 and 2). East of the Mitchell inlier, several smaller inliers of Cretaceous sedimentary rocks at Antone Ranch, Bernard Ranch, and along the John Day River have been correlated with Mitchell inlier strata (Fig. 2; e.g., Dickinson and Thayer, 1978; Little, 1986). In addition, Late Cretaceous sedimentary rocks documented in the subsurface of central Oregon (Thompson et al., 1984) and small Cretaceous sedimentary exposures near Dayville and Dixie Butte are potential remnants of the Ochoco basin (Fig. 2).

Various paleogeographic models for mid-Cretaceous time suggest that the Blue Mountains and Klamath terranes, along with the potential Hornbrook-Ochoco sedimentary overlap succession, experienced either no postdepositional, coast-parallel, dextral translation (Dickinson and Thayer, 1978; Miller et al., 1992; Dickinson, 2004, 2008), moderate translation of ~400 km (Wyld and Wright, 2001; Wyld et al., 2006; LaMaskin et al., 2011), or significant displacement (1200–1700 km; Housen and Dorsey, 2005, their model 1). Moderate to no translation models suggest Cretaceous basin sediment sources in the southern Canadian terranes and North Cascades, Blue Mountains, western Idaho, and early stages of the Idaho batholith and interior regions of the continent. Large-scale displacement suggests sediment sources in the southern Sierra Nevada, the Peninsular Ranges, and/or the Sonora Mountains of Mexico. In addition, the Blue Mountains and perhaps western Idaho rocks could also be sediment sources in the large-scale displacement model, if these were accreted together far to the south (Housen and Dorsey, 2005). A third paleogeographic model posits that the Mitchell inlier is distinct from the rest of the Ochoco basin rocks to the east and represents a forearc sliver deposited on a crustal block separate from the more easterly Blue Mountains Province. This model suggests that a major fault boundary separates the Mitchell inlier rocks from the easternmost Cretaceous inliers (Housen and Dorsey, 2005, their model 2). If the Mitchell inlier is indeed part of a separate forearc sliver that underwent large-scale displacement (Housen and Dorsey, 2005; Dorsey and Lenegan, 2007), then provenance data from the Mitchell inlier should indicate southern sources distinct from those of the smaller inliers to the east.

In this study, we integrated new and published sandstone petrography, conglomerate clast composition, paleocurrent data, and detrital-zircon age and Hf isotopic analysis for samples from the Mitchell, Antone Ranch, Goose Rock Conglomerate, Dayville, and Dixie Butte inliers to test whether rocks of the Mitchell inlier and all of the smaller inliers are part of one large Ochoco basin (Dickinson and Vigrass, 1965; Oles and Enlows, 1971; Dickinson, 1979; Kleinhans et al., 1984; Dorsey and Lenegan, 2007), which was deposited on terranes of the Blue Mountains

Province. Our detailed provenance data are consistent with a single Ochoco basin, and our detrital-zircon age data suggest deposition occurred largely during Late Cretaceous time, from Albian through at least Santonian time (ca. 113–86 Ma and younger), rather than Albian–Cenomanian (ca. 113–94 Ma) deposition (Jones et al., 1965; Wilkinson and Oles, 1968; Kleinhans et al., 1984). Provenance characteristics of the Ochoco basin are consistent with northern sources in the U.S. and southern Canadian Cordillera, and Ochoco strata may represent the destination of much of the "missing" Idaho arc (cf. Giorgis et al., 2005; Gaschnig et al., 2016) that was intruded and eroded during and following rapid transpression along the western Idaho shear zone from 105 to 90 Ma.

Our new provenance and depositional age data allow better comparison with coeval strata in other potentially related Cordilleran forearc basins. Our provenance results suggest that the Hornbrook Formation and Ochoco basin formed two sides of the same depositional system, as has been previously suggested (e.g., Miller et al., 1992; Nilsen, 1993; Wyld et al., 2006). Our results indicate that the combined Hornbrook-Ochoco basin may have been linked to the Great Valley Group to the south, but not to the Methow basin to the north. These results suggest a limit to northward displacement of the Ochoco basin of ~400 km.

GEOLOGIC SETTING

Cretaceous strata of the Ochoco basin rest nonconformably on accreted terranes of the Blue Mountains Province in eastern Oregon (Fig. 2; Dickinson and Vigrass, 1965; Oles and Enlows, 1971; Dickinson et al., 1979; Kleinhans et al., 1984). The Blue Mountains Province includes late Paleozoic to early Mesozoic volcanic island-arc assemblages of the Wallowa and Olds Ferry terranes, a Paleozoic to early Mesozoic subduction-accretionary complex of the Baker terrane, and a Triassic–Jurassic clastic sedimentary succession called the Izee terrane (Fig. 2; e.g., Dickinson and Thayer, 1978; Silberling et al., 1984; LaMaskin et al., 2011; Northrup et al., 2011). Plutons intruding the Blue Mountains Province fall mainly into three age ranges: ca. 235–212 Ma,

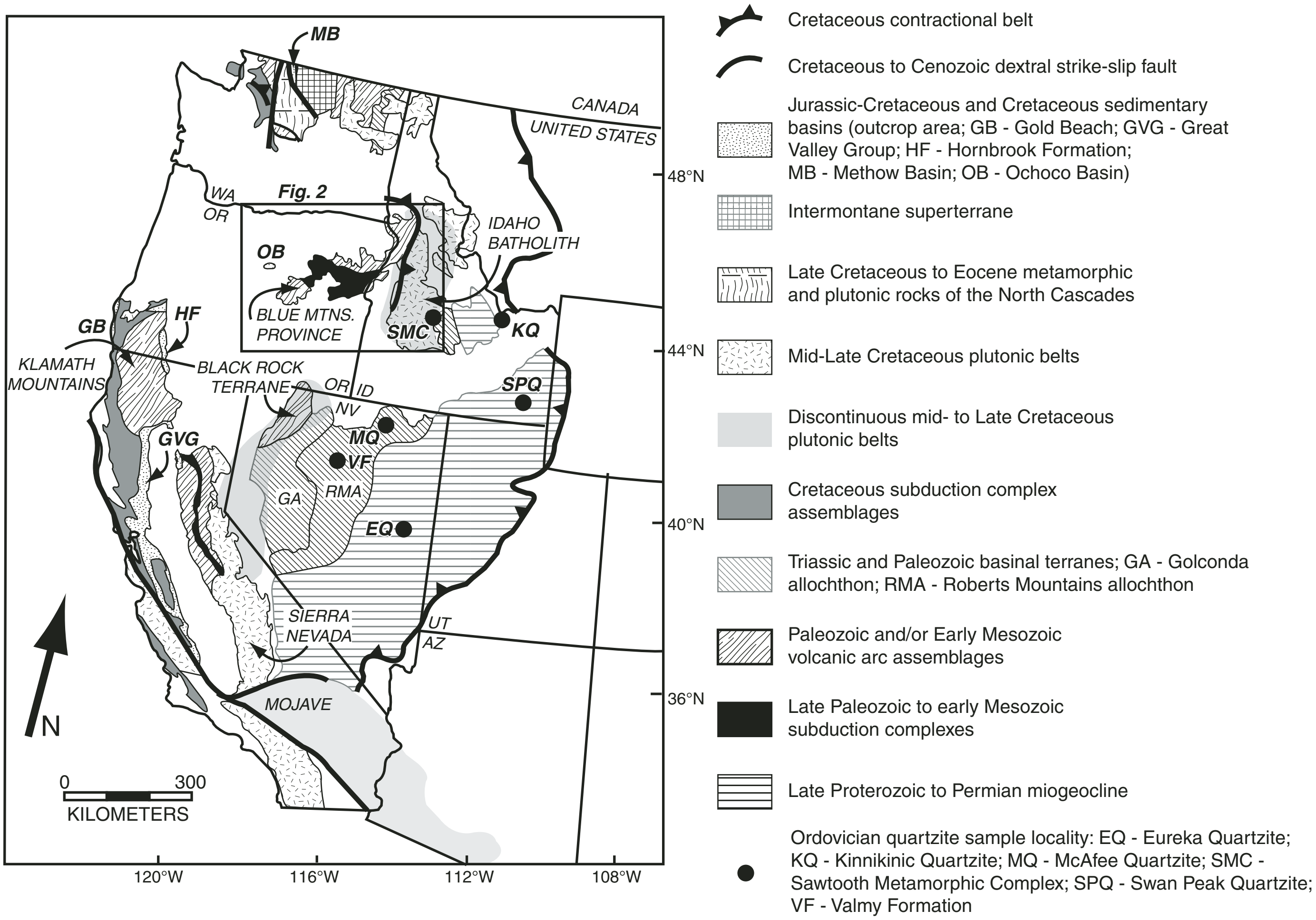

Figure 1. Generalized map of the U.S. Cordillera (modified from Wyld et al., 2006). Box shows location of Figure 2. State abbreviations: UT—Utah; AZ—Arizona; ID—Idaho; NV—Nevada; OR—Oregon; WA—Washington.

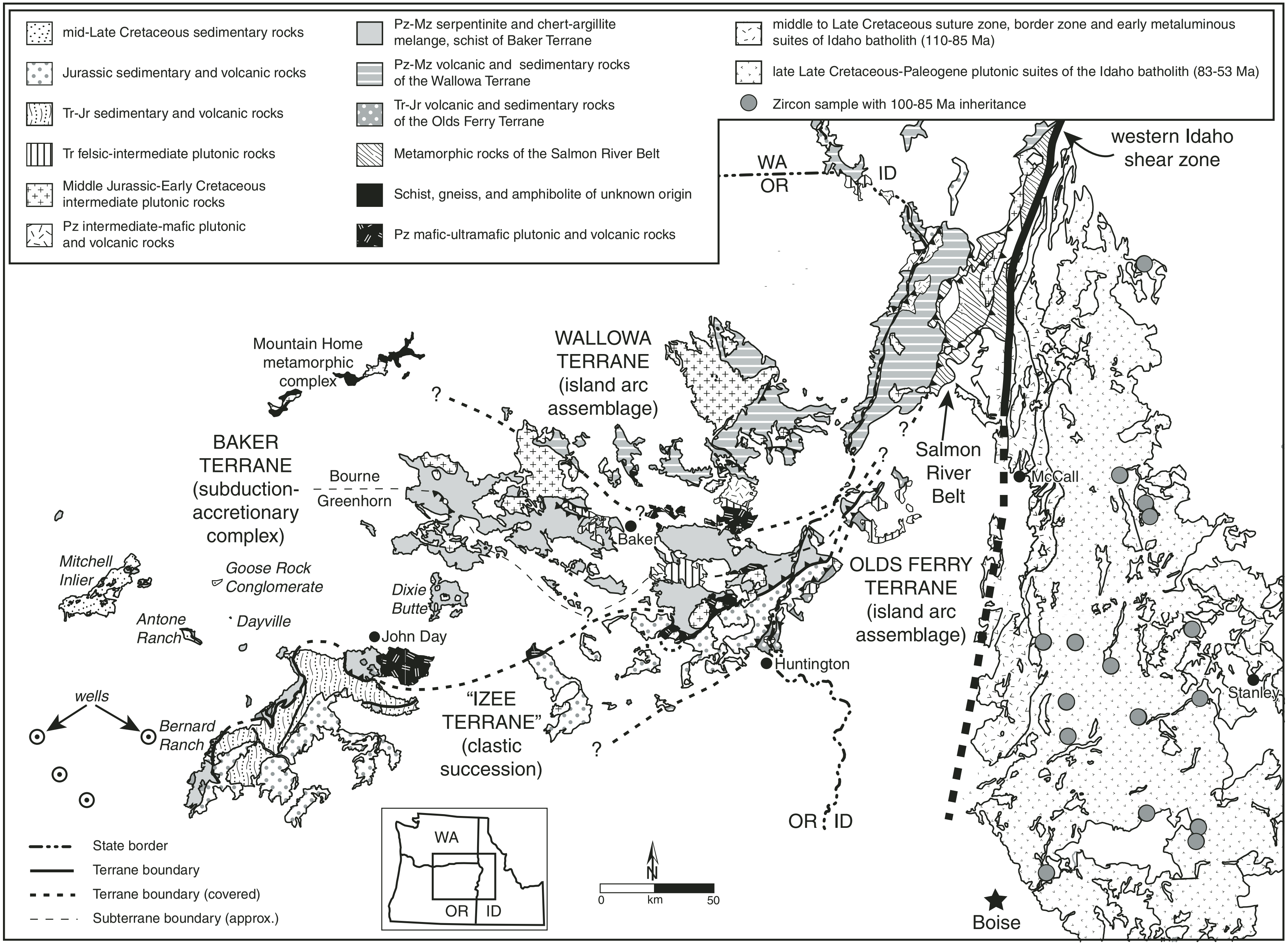

Figure 2. Map showing geology of the Blue Mountains and Idaho batholith regions and locations of Cretaceous sedimentary inliers (adapted from Dorsey and Lenegan, 2007; LaMaskin et al., 2015; Gaschnig et al., 2016). Tr—Triassic; Jr—Jurassic; Pz—Paleozoic; Mz—Mesozoic. State abbreviations: ID—Idaho; OR—Oregon; WA—Washington.

162–154 Ma, and 148–122 Ma (Walker, 1986, 1995; Unruh et al., 2008; Johnson et al., 2011; Northrup et al., 2011; Schwartz et al., 2011a, 2011b; Kurz et al., 2012). These terranes are believed to have accreted to North America during Jurassic (Brooks and Vallier, 1978; Selverstone et el., 1992; Kurz et al., 2012, 2016; LaMaskin et al., 2011, 2015; LaMaskin and Dorsey, 2016) or Early Cretaceous (Lund and Snee, 1988; Getty et al., 1993; Snee et al., 1995, 2007; Schwartz et al., 2010, 2011a, 2011b; Gray and Oldow, 2005; Gray et al., 2012; Žák et al., 2015) time. Wilson and Cox's (1980) paleomagnetic study indicated no northward translation of the Blue Mountains and as much as 60° ± 29° of clockwise rotation since Early Cretaceous time; using stratified rocks in the Mitchell inlier, Housen and Dorsey (2005) revised this to 37° ± 7° of clockwise rotation and as much as 1700 km of northward translation since mid-Cretaceous time.

Early Cretaceous thrusting and metamorphism (ca. 130 Ma; Lund and Snee, 1988; Selverstone et al., 1992; Getty et al., 1993; Snee et al., 1995, 2007) and mid-Cretaceous (ca. 105–90 Ma) magmatism and transpression associated with the western Idaho shear zone (e.g., Manduca et al., 1992, 1993; Tikoff et al., 2001; Giorgis et al., 2005; Benford et al., 2010; Braudy et al., 2016) significantly modified the original suture zone. Mid-Cretaceous transpression along the western Idaho shear zone resulted in subvertical fabrics and a steep $^{87}Sr/^{86}Sr$ isotopic gradient, marking a sharp boundary between rocks of oceanic origin to the west and continental rocks to the east (Fleck and Criss, 1985; Manduca et al., 1993). This transpression is believed to have resulted in rapid uplift, exhumation, and erosion of metamorphic and plutonic rocks within the shear zone (McClelland et al., 2000; Giorgis et al., 2005, 2008), but it may have produced only limited dextral translation (15–90 km; Giorgis et al., 2005, 2016).

Ochoco Basin

Ochoco basin strata overlap the westernmost Baker and Izee terranes (Fig. 2). In the Mitchell inlier (Figs. 2 and 3), Albian

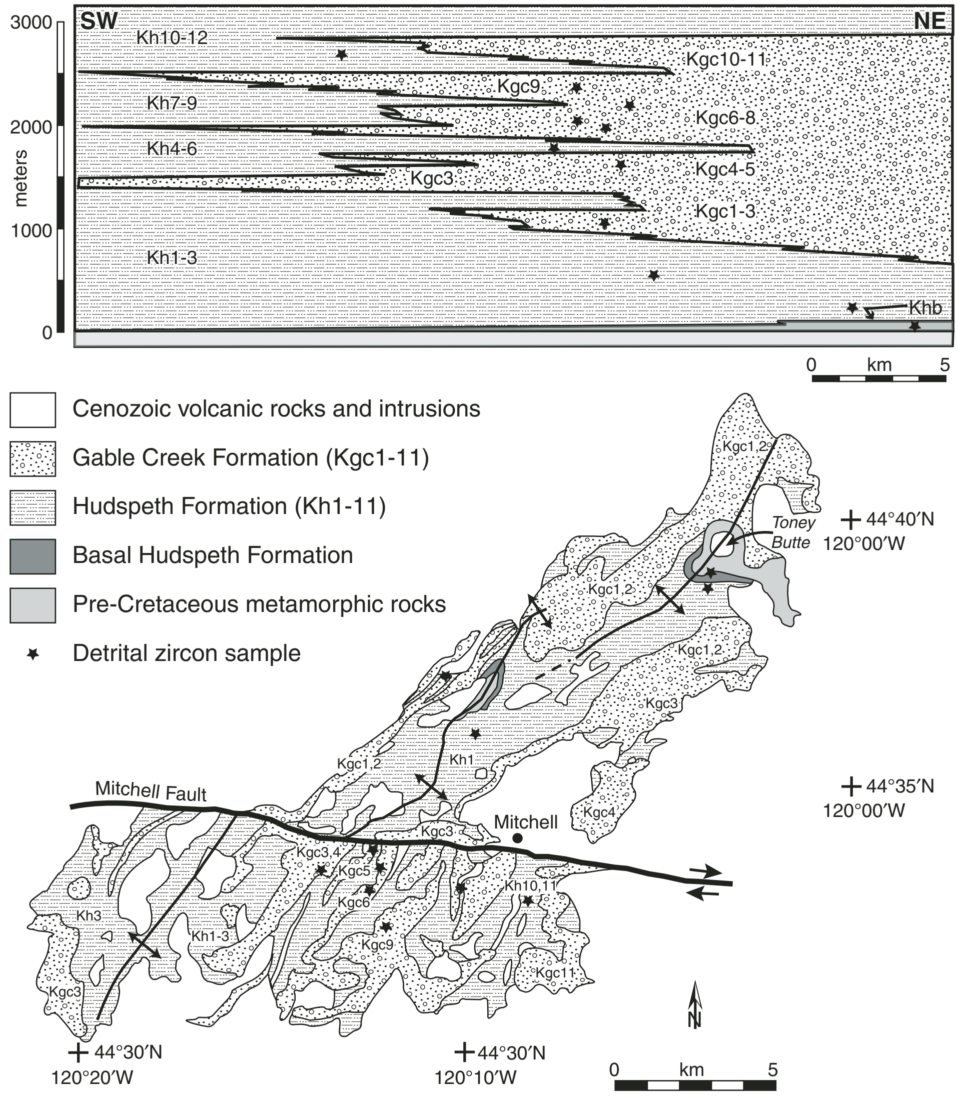

Figure 3. Schematic stratigraphy and simplified geologic map of the Mitchell inlier, near Mitchell, Oregon (circle). Original stratigraphy and map are from Oles and Enlows (1971); map is modified from Kleinhans et al. (1984). Stars indicate approximate locations of detrital-zircon samples.

and younger Ochoco strata are more than 2700 m thick (Kleinhans et al., 1984). Several other, smaller exposures of Cretaceous sedimentary rocks occur east of the Mitchell inlier, and Albian–Campanian strata are documented in wells south of the city of Mitchell, Oregon (Fig. 2; Thompson et al., 1984).

Mitchell inlier. The Mitchell inlier forms a northeast-trending belt of Cretaceous strata deformed by the northeast-trending Mitchell anticline and the east-west Mitchell fault (Fig. 3). Wilkinson and Oles (1968) mapped an intertonguing of Hudspeth and Gable Creek Formation strata in the Mitchell inlier (Fig. 3) and interpreted the Hudspeth Formation as deep-marine mudstone with subordinate siltstone and sandstone, and the Gable Creek Formation as fluvial-deltaic deposits. Subsequent studies (Kleinhans et al., 1984; Little, 1986; Dorsey and Lenegan, 2007) demonstrated that the Hudspeth and Gable Creek Formations were deposited in a submarine fan environment.

Wilkinson and Oles (1968) subdivided the Hudspeth Formation into a basal member (Khb), the Main Mudstone member (Kh1), and numbered mudstone units (Kh2 through Kh12) that are interbedded with numbered units of the Gable Creek Formation (Kgc1–Kgc11; Fig. 3). Khb includes locally derived green sandstone, mudstone, and a pebble-cobble conglomerate with abundant chert, volcanic, and plutonic clasts, and tan sandstone (Dorsey and Lenegan, 2007). Mudstone units of the Hudspeth Formation are typically dark gray to black and appear lithologically similar throughout the Mitchell inlier (Wilkinson and Oles, 1968; Jarman, 1973; Kleinhans et al., 1984; Dorsey and Lenegan, 2007). Ammonites found in calcite-cemented concretions in the Main Mudstone member (Kh1) of the Hudspeth Formation are Albian age (McKnight, 1964; Jones et al., 1965; Kleinhans et al., 1984; P. Rodda, personal commun. reported *in* Dorsey and Lenegan, 2007). Deposition of the Hudspeth Formation mudstone likely occurred by suspension settling or as dilute, distal turbidity currents in a basin-plain setting at outer neritic to bathyal depths (Kleinhans et al., 1984; Dorsey and Lenegan, 2007). Rare paleocurrent indicators in the basal Hudspeth Formation suggest northwest- to southeast-directed flow (Lenegan, 2001), and paleocurrent indicators in the upper main mudstone member of the Hudspeth Formation suggest north-northwest to northwesterly flow (McKnight, 1964; Little, 1986).

The Gable Creek Formation consists of interbedded units of conglomerate and sandstone that are numbered 1–11 (Fig. 3; Wilkinson and Oles, 1968). Conglomerate units are thick, massive, and clast-supported, with pebble to cobble clast sizes, and these are interbedded with medium- to coarse-grained sandstone. Paleocurrent data from clast imbrications within the lower Gable Creek Formation near Toney Butte indicate a clear southwesterly flow direction (Dorsey and Lenegan, 2007). Likewise, tool marks and flute casts on sandstone beds and imbricated conglomerate clasts yield a dominant, well-defined paleoflow direction to the southwest in the middle and upper Gable Creek Formation (Little, 1986), and east-directed flow at the top of the exposed Cretaceous section in the Mitchell inlier (Little, 1986).

Little's (1986) study of conglomerate clast compositions in the Gable Creek Formation revealed two compositional facies (Fig. 4A): Facies 1 is characterized by abundant plutonic and mafic volcanic clasts, and few chert clasts, and it is characteristic of most of the Gable Creek Formation; facies 2 is characterized by abundant chert and intermediate to felsic volcanic clasts with few plutonic clasts, and it is limited to strata in the northeastern map region near Toney Butte. Little (1986) demonstrated that conglomerate compositions south of the Mitchell fault (facies 1) do not vary systematically with stratigraphic position, suggesting consistent source compositions beginning with the deposition of Kgc3. Little (1986) could not confidently place facies 2 within the Mitchell stratigraphy because of his interpretation that these rocks occur only on the downthrown side of a high-angle fault at Toney Butte. However, more recent studies interpreted a nonconformable depositional contact of Kgc1 on basement rock (Lenegan, 2001; Dorsey and Lenegan, 2007), which places facies 2 in the lowermost Mitchell inlier stratigraphy.

Deposition of Gable Creek Formation conglomerate and sand units is interpreted to have occurred by sediment-gravity flows in a submarine fan system (Kleinhans et al., 1984). Interfingering of coarse-grained Gable Creek Formation sandstone and conglomerate with fine-grained Hudspeth Formation mudstone and siltstone may be allogenic, reflecting changing sediment supply and/or changing subsidence rates, and/or it may be autogenic, resulting from intrabasinal processes such as channel switching in the submarine fan (Kleinhans et al., 1984; Dorsey and Lenegan, 2007).

Goose Rock Conglomerate. The Goose Rock Conglomerate crops out along the John Day River east of the Mitchell inlier (Fig. 2) and was deposited nonconformably on metasedimentary rocks of the Baker terrane (Little, 1986). An ~90 m thickness of Goose Rock Conglomerate strata occurs in the Sheep Rock unit within the John Day Fossil Beds National Monument. These strata consist of thick conglomerate beds with lenses and thin beds of trough cross-stratified sandstone with minor mudstone (Kleinhans et al., 1984). No fossils have been found in the Goose Rock Conglomerate, although the rocks are inferred to be correlative with mid- to Late Cretaceous strata of the Mitchell inlier (Kleinhans et al., 1984; Little, 1986). The absence of dark mudstone and marine fossils, abundance of well-developed trough cross-stratification in the sandstone, and presence of large, woody fragments in the conglomerate suggest a fluvial depositional environment (Little, 1986). Foreset measurements in the lower Goose Rock Conglomerate localities indicate northwest- to southwest-directed flow, with a dominant southwesterly direction (Little, 1986; Hopson et al., 2013). The Goose Rock Conglomerate composition is similar to facies 2 of the Mitchell inlier, but with only moderate chert abundance and greater abundance of trachyte and rhyolite clasts than is typical of facies 2 (Little, 1986).

Antone Ranch inlier. Cretaceous sedimentary rocks at Antone Ranch, east-southeast of the Mitchell inlier (Fig. 2), include up to 730 m of pebbly conglomerate, sandstone, and

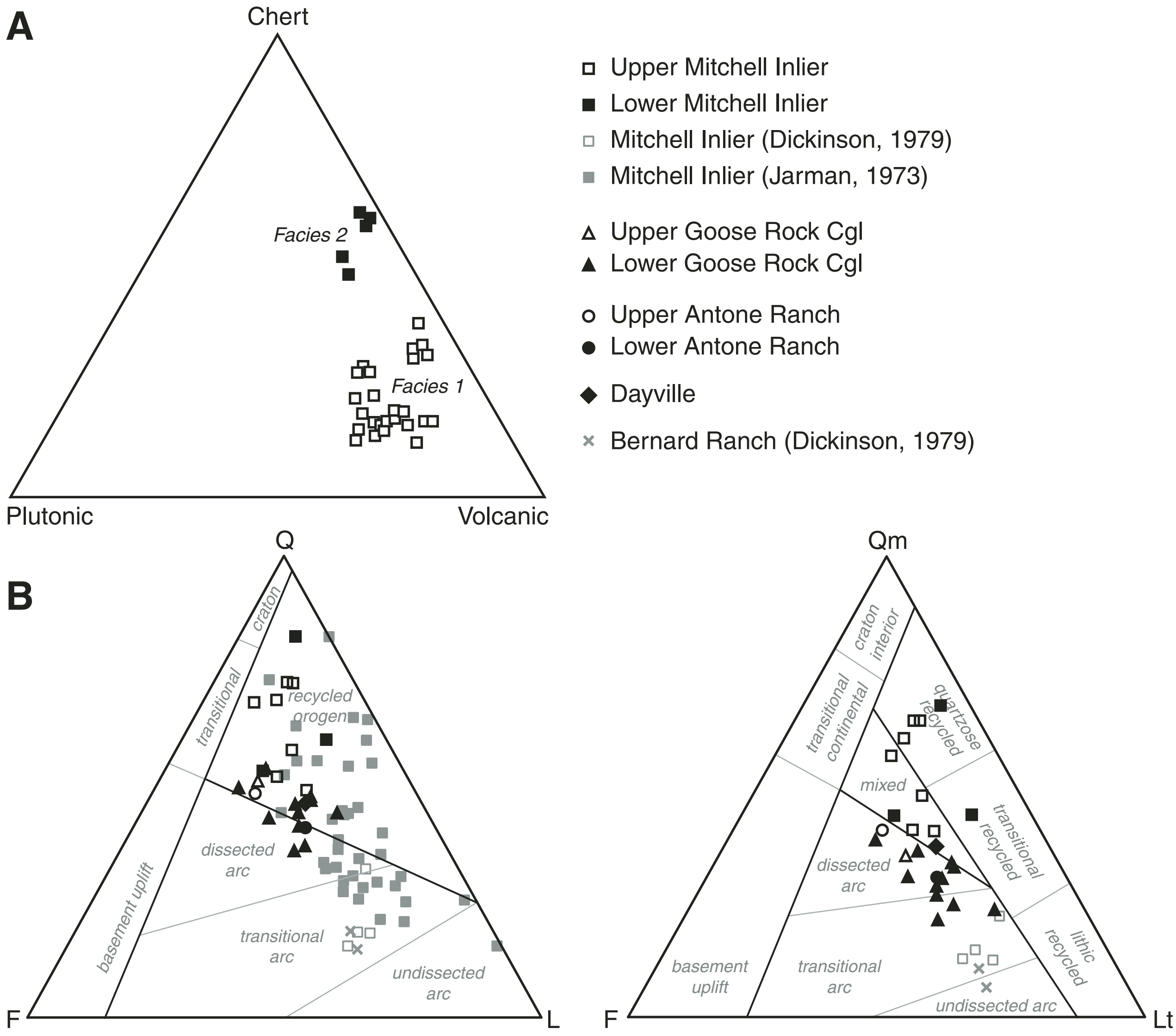

Figure 4. (A) Chert-plutonic-volcanic ternary diagram of conglomerate clast compositions showing the two conglomerate facies in the Mitchell inlier (Little, 1986). Cgl—Conglomerate. (B) Quartz-feldspar-lithics (QFL) and monocrystalline quartz–feldspar–total lithics (QmFLt) ternary plots of Ochoco basin sandstone composition. Provenance fields are from Dickinson et al. (1983). Sandstone data are from Jarman (1973), Dickinson (1979), and this study.

siltstone (Dobell, 1948; Little, 1986). Abundant thick-shelled pelecypod *Trigonia* sp. and leaf imprints in thick-bedded sandstones within the upper strata at Antone Ranch indicate a nearshore, shallow-marine depositional environment (Little, 1986; Dorsey and Lenegan, 2007). Mollusk fossils collected from two localities indicate a Late Cretaceous age (W. Stanton, personal commun., reported *in* Merriam, 1901). Foreset measurements from lower Antone Ranch cross-bedded sandstone and current lineations along bedding planes indicate north-northwest flow direction, which shifted to west-northwest flow in younger strata at Antone Ranch (present-day coordinates; Little, 1986). Conglomerate clast compositions at Antone Ranch are most similar to the Goose Rock Conglomerate in composition (Little, 1986).

Bernard Ranch inlier. The Bernard Ranch inlier crops out near Suplee, southeast of the city of Mitchell, Oregon, and it consists of ~500 m of fossiliferous shallow-marine to deltaic sandstone and conglomerate (Dickinson and Vigrass, 1965; Dickinson et al., 1979; Little, 1986). The conglomerate composition at Bernard Ranch is similar to facies 1 of the Gable Creek Formation at the city of Mitchell, Oregon (Little, 1986). Bernard Ranch sandstone is rich in volcanic lithic grains, plagioclase, and quartz, similar to the sandstone composition of the Gable Creek Formation in the Mitchell inlier (Dickinson et al., 1979). Ammonites

TABLE 1. RECALCULATED MODAL POINT-COUNT DATA FOR SANDSTONE SAMPLES FROM THE OCHOCO BASIN

			Q-F-L (%)			Qm-F-Lt (%)		
Inlier	Sample	Total	Q	F	L	Qm	F	Lt
Antone Ranch (lower)	15-AR-01	400	0.42	0.25	0.33	0.31	0.25	0.44
Antone Ranch (upper)	08-AR-03*	400	0.50	0.31	0.19	0.41	0.31	0.28
Dayville	13-KFC-01*	400	0.48	0.22	0.30	0.37	0.22	0.41
Goose Rock Conglomerate (lower)	13-GRC-01*	500	0.55	0.26	0.18	0.36	0.26	0.38
Goose Rock Conglomerate (lower)	13-GRC-03*	500	0.51	0.33	0.16	0.38	0.33	0.29
Goose Rock Conglomerate (lower)	13-GRC-04*	500	0.44	0.31	0.25	0.30	0.31	0.39
Goose Rock Conglomerate (lower)	13-GRC-05	500	0.47	0.24	0.28	0.30	0.24	0.45
Goose Rock Conglomerate (lower)	15-GRC-03	400	0.38	0.27	0.35	0.26	0.27	0.46
Goose Rock Conglomerate (lower)	15-GRC-04*	400	0.49	0.21	0.30	0.32	0.21	0.47
Goose Rock Conglomerate (lower)	15-GRC-05	400	0.37	0.30	0.33	0.21	0.30	0.49
Goose Rock Conglomerate (lower)	15-GRC-06	399	0.45	0.18	0.37	0.23	0.18	0.59
Goose Rock Conglomerate (lower)	15-GRC-07*	400	0.42	0.26	0.31	0.28	0.26	0.45
Goose Rock Conglomerate (lower)	15-GRC-08	400	0.45	0.25	0.30	0.24	0.25	0.51
Goose Rock Conglomerate (lower)	15-GRC-10*	400	0.48	0.21	0.31	0.33	0.21	0.46
Goose Rock Conglomerate (upper)	13-GRC-02*	500	0.52	0.29	0.19	0.35	0.29	0.36
Mitchell inlier (upper)	08-MI-09	522	0.70	0.21	0.09	0.57	0.21	0.22
Mitchell inlier (upper)	08-MI-11*	500	0.74	0.12	0.13	0.65	0.12	0.23
Mitchell inlier (upper)	08-MI-13*	500	0.74	0.11	0.14	0.65	0.11	0.24
Mitchell inlier (upper)	08-MI-14	500	0.71	0.16	0.13	0.61	0.16	0.23
Mitchell inlier (upper)	08-MI-16*	500	0.51	0.21	0.29	0.41	0.21	0.39
Mitchell inlier (upper)	08-MI-18*	500	0.59	0.19	0.22	0.48	0.19	0.33
Mitchell inlier (upper)	08-MI-19*	509	0.53	0.25	0.22	0.41	0.25	0.34
Mitchell inlier (lower)	08-MI-01*	500	0.55	0.27	0.18	0.44	0.27	0.29
Mitchell inlier (lower)	08-MI-03	500	0.85	0.06	0.10	0.68	0.06	0.26
Mitchell inlier (lower)	08-MI-06*	500	0.62	0.11	0.27	0.44	0.11	0.44

Note: QFL—quartz-feldspar-lithics; QmFLt—monocrystalline quartz–feldspar–total lithics.
*Detrital-zircon sample.

and other mollusks within the Bernard Ranch inlier indicate early Cenomanian deposition (Jones, 1960; Dickinson and Vigrass, 1965; Squires and Saul, 2002).

Dixie Butte inlier. Poorly exposed, Late Cretaceous fossiliferous sandstone in the Dixie Butte area just north of Prairie City in Grant County (Fig. 2) form the easternmost Cretaceous inlier. These rocks have been interpreted as shallow-marine deposits, based on abundant bivalves, which also indicate Cenomanian deposition (Brooks et al., 1984). In one detrital-zircon sample from Dixie Butte, Gaschnig et al. (2017) found only Phanerozoic grains with radiogenic ε_{Hf} values ranging from +15 to +6.5. Based on the apparent lack of Precambrian and 154–117 Ma grains, as well as the lack of 110–100 Ma grains with a mix of subchondritic and superchondritic Hf isotopic signatures, Gaschnig et al. (2017) inferred an Insular superterrane source for the Dixie Butte inlier.

Dayville inlier. The limited exposure at Dixie Butte is comparable to the poor exposure of fossiliferous Cretaceous sandstone and pebbly conglomerate that crops out near Dayville, Oregon (Thayer and Brown, 1966). Thin, fossiliferous sandstone beds within the Dayville outcrop contain numerous late Albian–Cenomanian and Cenomanian–early Turonian bivalves, as well as Cenomanian gastropods, all of which occur as broken specimens in concentrated beds (Squires and Saul, 2002).

METHODS AND RESULTS

Sandstone Petrography

Point counting of medium-grained sandstones from the Mitchell, Goose Rock, Antone Ranch, and Dayville inliers was conducted following the Gazzi-Dickinson method (Table 1; all point count data are given in Table DR1[1]; Dickinson, 1970, 1985; Ingersoll et al., 1984), but with a 5% cutoff between polycrystalline quartz and lithic grains. Thin sections were stained with cobaltinitrite to improve identification of potassium feldspar. At least 400 points were counted from 25 samples from Mitchell (10), Goose Rock (12), Antone Ranch (2), and Dayville (1). Framework grains in all samples consisted of quartz, feldspar, and lithic grains. Lithic grains typically comprised 10%–37% of total framework grains and included volcanic lithic grains (34%–73% of total lithics), chert (12%–48%), polycrystalline quartz (7%–25%), and relatively few metamorphic or sedimentary lithic grains (0%–11%). Chert comprised 27% of total lithic grains in

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[1] GSA Data Repository Item 2018253, Petrography, U-Pb data, and hafnium data, is available at www.geosociety.org/datarepository/2018/, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

the Mitchell samples, and 21% of total lithic grains in the other inliers. Matrix content (including possible pseudomatrix) ranged from 1% to 14% (average 7.3%) in Mitchell samples, and from 0% to 2% in Goose Rock, Antone Ranch, and Dayville samples. Unidentifiable, heavily altered grains accounted for up to 13.6% of a sample, but averaged only 5.2%. Some alteration of feldspar grains and unstable lithic grains was apparent in all sections.

On a quartz-feldspar-lithic (QFL) discrimination diagram, most samples plotted in the recycled orogenic provenance field of Dickinson et al. (1983), with a few samples plotting in the dissected magmatic arc field (Fig. 4B). Mitchell samples contained the highest total quartz (monocrystalline and polycrystalline quartz plus chert), with average $Q_{65}F_{17}L_{18}$, as compared with average $Q_{46}F_{26}L_{28}$ for the other inliers, due to more abundant chert in the Mitchell inlier. Including chert grains with total lithic grains (Lt) on a monocrystalline quartz–feldspar–total lithic (Qm-F-Lt) diagram shifted Antone Ranch samples into the dissected arc field, with the Dayville sample plotting close to this field, whereas Goose Creek samples fell in the dissected to transitional arc fields, and Mitchell samples fell in the mixed provenance to recycled orogen fields (Fig. 4B). Regardless of which ternary diagram is used, the Ochoco samples indicate provenance from both arc and recycled orogen sources (Fig. 4B).

We plotted our point-count data with compositional data from Jarman (1973) for the Mitchell inlier and from Dickinson et al. (1979) for four Gable Creek samples from the Mitchell inlier and two samples from the Bernard Ranch inlier (Fig. 4B). Jarman (1973) used traditional point-count methods, so her results can only broadly be compared with our data on a QFL diagram (Fig. 4B), because crystals greater than sand size (>0.0625 mm) that occur within larger rock fragments are counted as rock fragments using traditional methods, but as single grains in the Gazzi-Dickinson method. These methodological differences tend to result in higher Q and F and lower L percentages for the Gazzi-Dickinson method when compared to traditional counting methods (Ingersoll et al., 1984). Indeed, Jarman (1973) documented a greater spread of sandstone compositions in the Mitchell inlier, with more lithic content than our data, but still significant overlap in the recycled orogen and dissected arc fields (Fig. 4B). The six Dickinson et al. (1979) samples plot together in the transitional and dissected arc fields on a QFL diagram, and transitional to undissected arc on a QmFLt diagram (Fig. 4B). Higher lithic content in Dickinson et al.'s (1979) samples may reflect true compositional variability, but it may also result from use of a zero cutoff between polycrystalline quartz and lithic grains, such that a chert grain with very slight impurities would count as a sedimentary lithic (Ls) grain rather than polycrystalline quartz (Qp).

Zircon U-Pb Ages

Twenty-four sandstone samples were analyzed for U-Pb zircon ages: 11 from the Mitchell inlier, seven from the Goose Rock Conglomerate, three from Antone Ranch, two from Dixie Butte, and one from Dayville. In addition, five tonalitic plutonic cobbles were sampled from the Gable Creek Formation of the Mitchell inlier, and one quartzite cobble was sampled from the Goose Rock Conglomerate.

Zircons were isolated using standard separation techniques (e.g., Gehrels et al., 2006), and a random subset of zircon grains from each sandstone sample was mounted in epoxy and polished. U-Pb dating was completed at the University of Arizona LaserChron Center following methods described in Gehrels et al. (2006), and at the Radiogenic Isotope Laboratory of Washington State University (Chang et al., 2006). Following DeGraaff-Surpless et al. (2003), we included grains younger than 600 Ma that plotted within 10% of Tera-Wasserburg concordia along a mixing line from the common Pb value (^{207}Pb/^{206}Pb ratio of 0.86; Stacey and Kramers, 1975) through the data to concordia. For grains older than 600 Ma, only grains with less than 10% discordance were included in the probability density plots. Ages reported are ^{206}Pb/^{238}U ages for grains younger than 900 Ma and ^{207}Pb/^{206}Pb ages for grains 900 Ma and older (all U-Pb data in Table DR2 [see footnote 1]).

Detrital-zircon U-Pb results are displayed as histograms with superimposed probability density plots for each sample (Fig. 5). Individual samples are arranged in stratigraphic order for the Mitchell inlier and Goose Rock Conglomerate (Figs. 5A and 5B), and in order of decreasing maximum depositional age for the Dayville, Antone Ranch, and Dixie Butte inliers, where poor outcrop exposure and potential fault offset impeded recognition of clear stratigraphic relationships (Fig. 5C). We also included published data from one Dixie Butte sample (10RMG29; Gaschnig et al., 2017) with our data. All but one Antone Ranch sample (15-AR-02) were characterized by a primarily Mesozoic age distribution (84%–100% Mesozoic grains) and relatively few late Paleozoic (0%–16%) and Precambrian detrital zircon (0%–6%). Although pre-Mesozoic zircon grains were few in number, they occurred in most samples (Fig. 5). Mesozoic age distributions for 23 of the 24 samples included modes of Early Jurassic (200–180 Ma), Middle and Late Jurassic (175–150 Ma), and Early Cretaceous (120–100 Ma) ages, and 11 samples included a Late Cretaceous age mode (99–86 Ma). One Antone Ranch sample (15-AR-02; Fig. 5C) contained 27% Precambrian ages and only 63% Mesozoic ages, which were characterized by a large Late Triassic–Early Jurassic age mode, few Middle–Late Jurassic grains, an Early Cretaceous age mode (140–120 Ma), and several 120–90 Ma grains. Our Dixie Butte samples showed a similar age distribution as the sample of Gaschnig et al. (2017), but our samples included five Precambrian grains and 10 grains younger than 100 Ma that were absent in the Gaschnig et al. (2017) sample, and more Late Jurassic and Early Cretaceous grains (Fig. 5C).

Maximum depositional ages were estimated using the Unmix routine of Isoplot (Ludwig, 2012), where young ages ($n \geq 3$) form a distinct age mode or shoulder on a larger age mode. The Unmix routine assumes Gaussian distributions to deconvolve multiple age components, following the mixture-modeling method of Sambridge and Compston (1994), and all maximum depositional ages are reported at 2σ uncertainty. For accurate

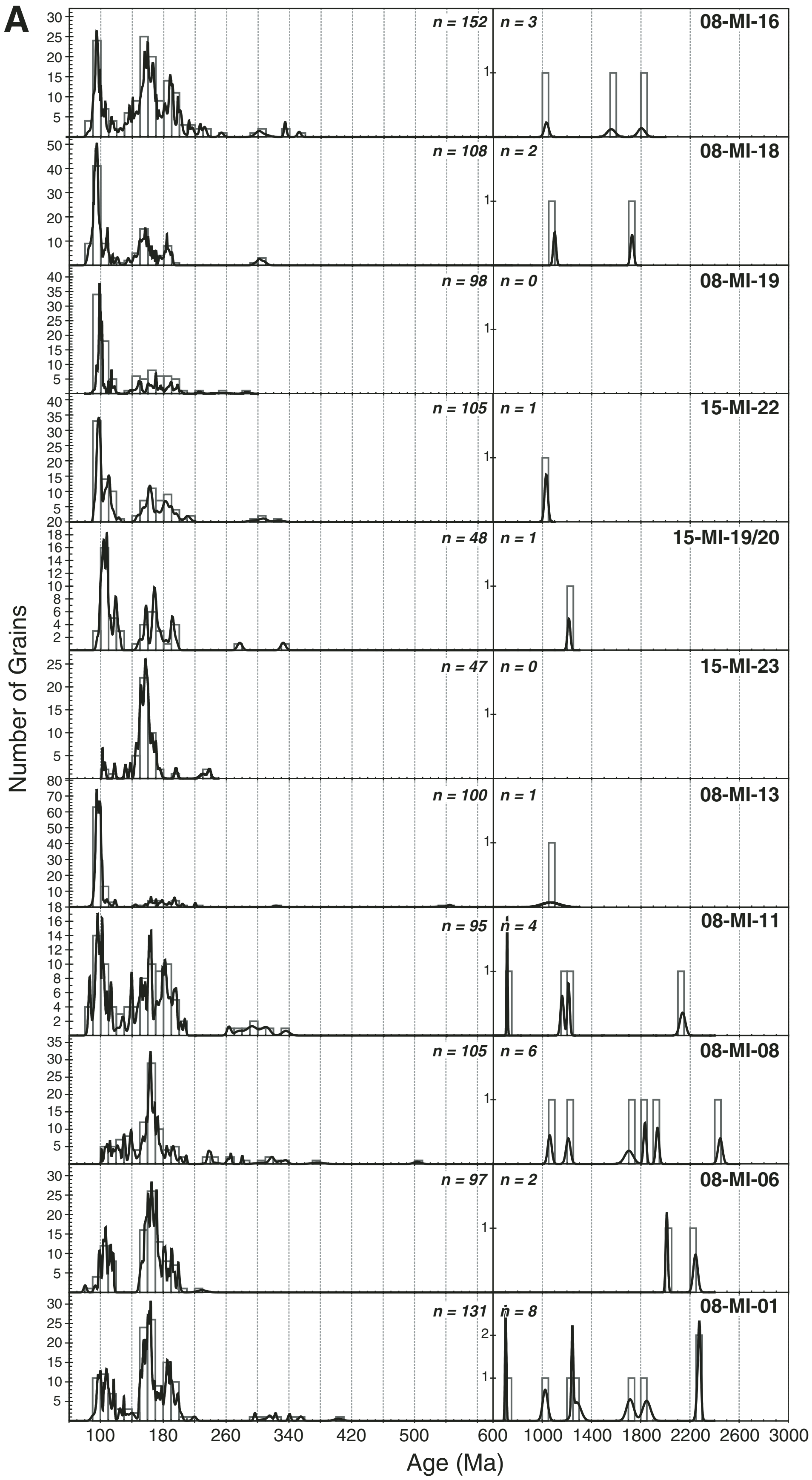

Figure 5 (*Continued on following pages*). Detrital-zircon U-Pb age distributions, shown as histograms with superimposed probability density curves for each sample; note the change of scale at 600 Ma. (A) Mitchell inlier samples, with samples arranged stratigraphically.

and precise Unmix results, the user must be able to specify the number of components with reasonable confidence (Ludwig, 2012), which is the case for all but one sample (15-MI-23). No reasonable maximum depositional age could be calculated for 15-MI-23 because the youngest four grains in this sample ranged from 102.4 to 131.6 Ma and did not overlap. Samples from the basal and main mudstone members of the Hudspeth Formation in the lower Mitchell inlier strata (Khb and Kh1; Fig. 3) exhibited maximum depositional ages of 107.5 ± 1.4 Ma, 98.9 ± 0.7 Ma, and 96.6 ± 1.3 Ma (Fig. 6A). Samples from higher in the Mitchell inlier strata (Kgc3 through Kh10–Kh11; Fig. 3) exhibited maximum depositional ages ranging from 100.8 ± 0.5 Ma to 86.0 ± 2.7 Ma (Fig. 6A), and the stratigraphically lowest of these samples (08-MI-11; Kgc3) had one of the youngest maximum depositional ages (86.0 ± 1.4 Ma).

Six of seven samples from the Goose Rock Conglomerate exhibited very similar age distributions (Fig. 5B) and maximum depositional ages ranging from 102.3 ± 1.3 Ma to 97.4 ± 0.9 Ma (Fig. 6B). Unlike the other Goose Rock Conglomerate samples, the uppermost sample (13-GRC-02) contained few Early Cretaceous grains and a large Late Cretaceous age mode, and it exhibited a maximum depositional age of 89.4 ± 1.1 Ma (Fig. 6B). Samples from Dayville and Dixie Butte exhibited maximum depositional ages of 105.9 ± 1.7 Ma (13-KFC-01), and 102.3 ± 1.1 Ma, 101.3 ± 2 Ma, and 95.7 ± 0.6 Ma (10RMG029, 15-DB-03, and 15-DB-01, respectively). Two samples from Antone Ranch exhibited similar maximum depositional ages of 101 ± 2.3 Ma and 98.9 ± 1.7 Ma (15-AR-05 and 15-AR-02), and one sample had a much younger maximum depositional age of 89.1 ± 0.6 Ma (08-AR-03).

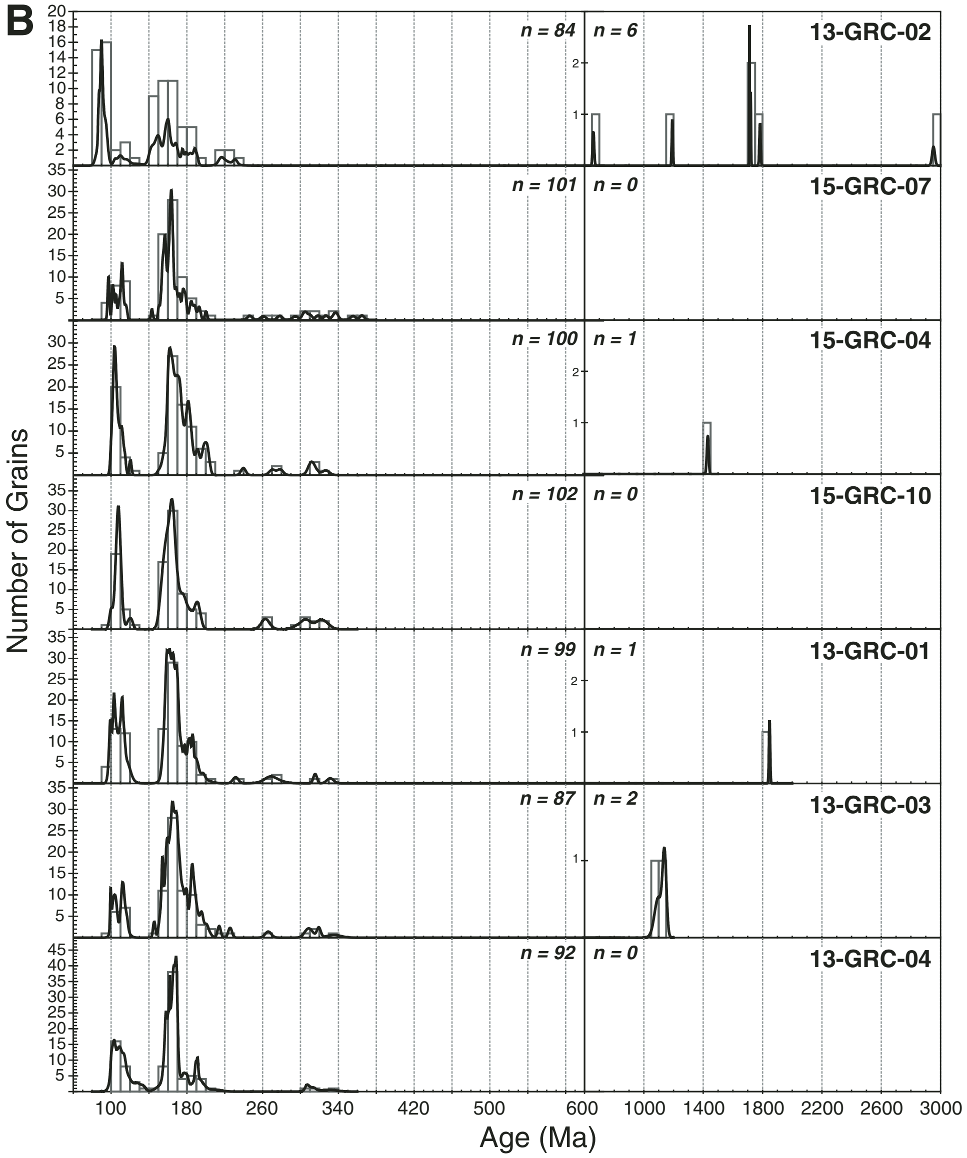

Figure 5 (*Continued*). (B) Goose Rock Conglomerate samples.

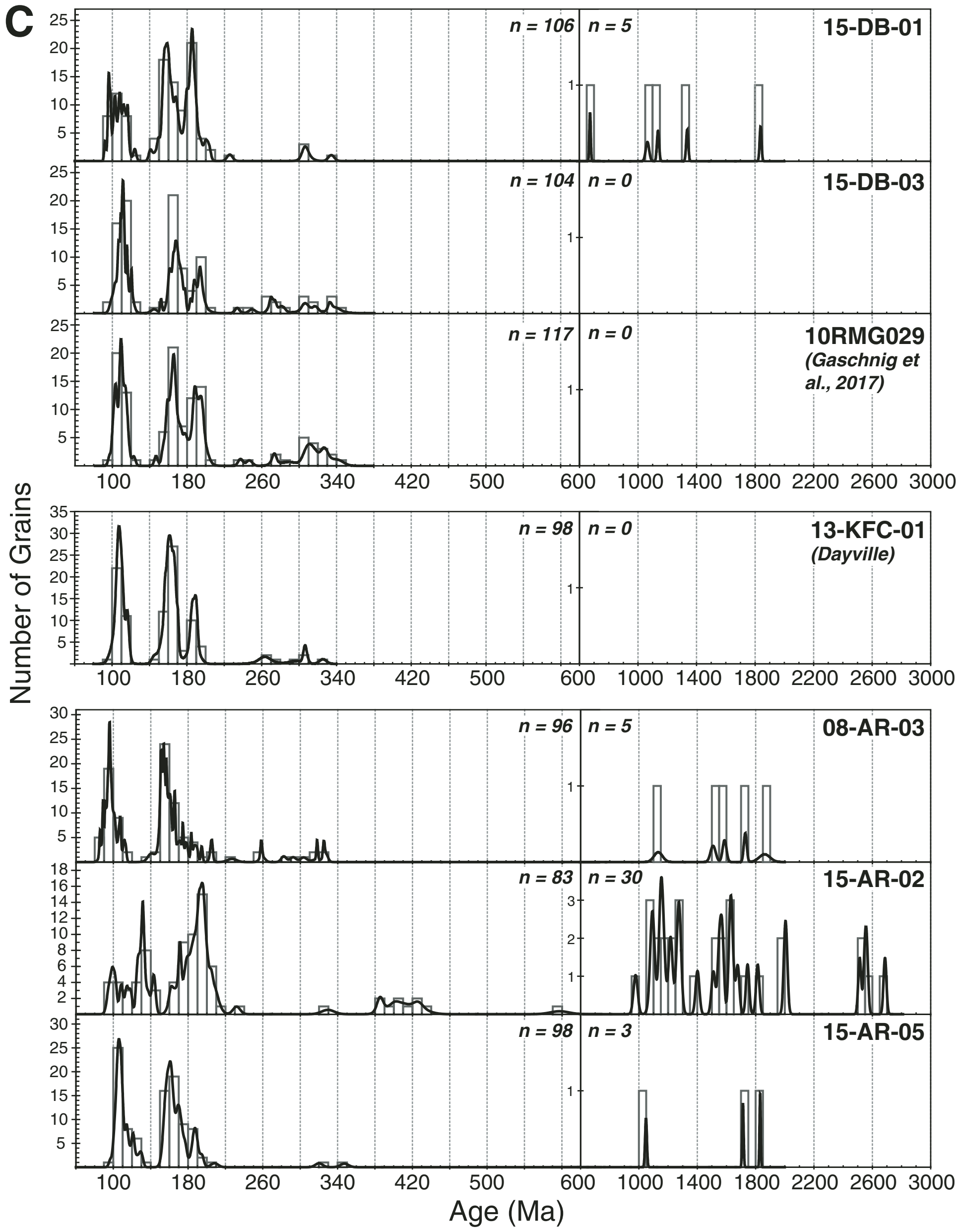

Figure 5 (*Continued*). (C) Dixie Butte (including data from Gaschnig et al., 2017), Dayville, and Antone Ranch samples.

The five plutonic cobbles from the Mitchell inlier (units Kgc5 and Kgc6) exhibited ages ranging from 154 ± 3 Ma to 151 ± 2 Ma (2σ uncertainty; Fig. 7). The quartzite cobble from the Goose Rock Conglomerate contained only two grains younger than 1800 Ma, and it had a prominent age mode ca. 1838 Ma, smaller modes ca. 2080 and 1915 Ma, and several grains between 2900 and 2400 Ma (Fig. 8).

Zircon Hafnium Analysis

Hafnium isotopic analysis was completed at the University of Arizona LaserChron Center and at the Radiogenic Isotope Laboratory of Washington State University, following methods described in Cecil et al. (2011) and Fisher et al. (2014a). Isotopic compositions were collected from 216 selected, previously dated detrital-zircon grains in eight samples from the Mitchell inlier, Dixie Butte, Antone Ranch, and Goose Rock Conglomerate, using laser ablation of either the previously ablated U-Pb analysis location, or another location within the same zone of the zircon (all Hf data are given in Table DR3 [see footnote 1]). Hf analysis was completed only on grains with significant Cretaceous (85–118 Ma) and Jurassic (160–200 Ma) age modes in our eight samples, and we included published Hf results from the Dixie Butte sample of Gaschnig et al. (2017). Jurassic and Cretaceous grains 105 Ma and older yielded positive, radiogenic ε_{Hf} values typically between +4 and +12, with an average of +8.7 ± 3.1 (1σ; Fig. 9). In contrast,

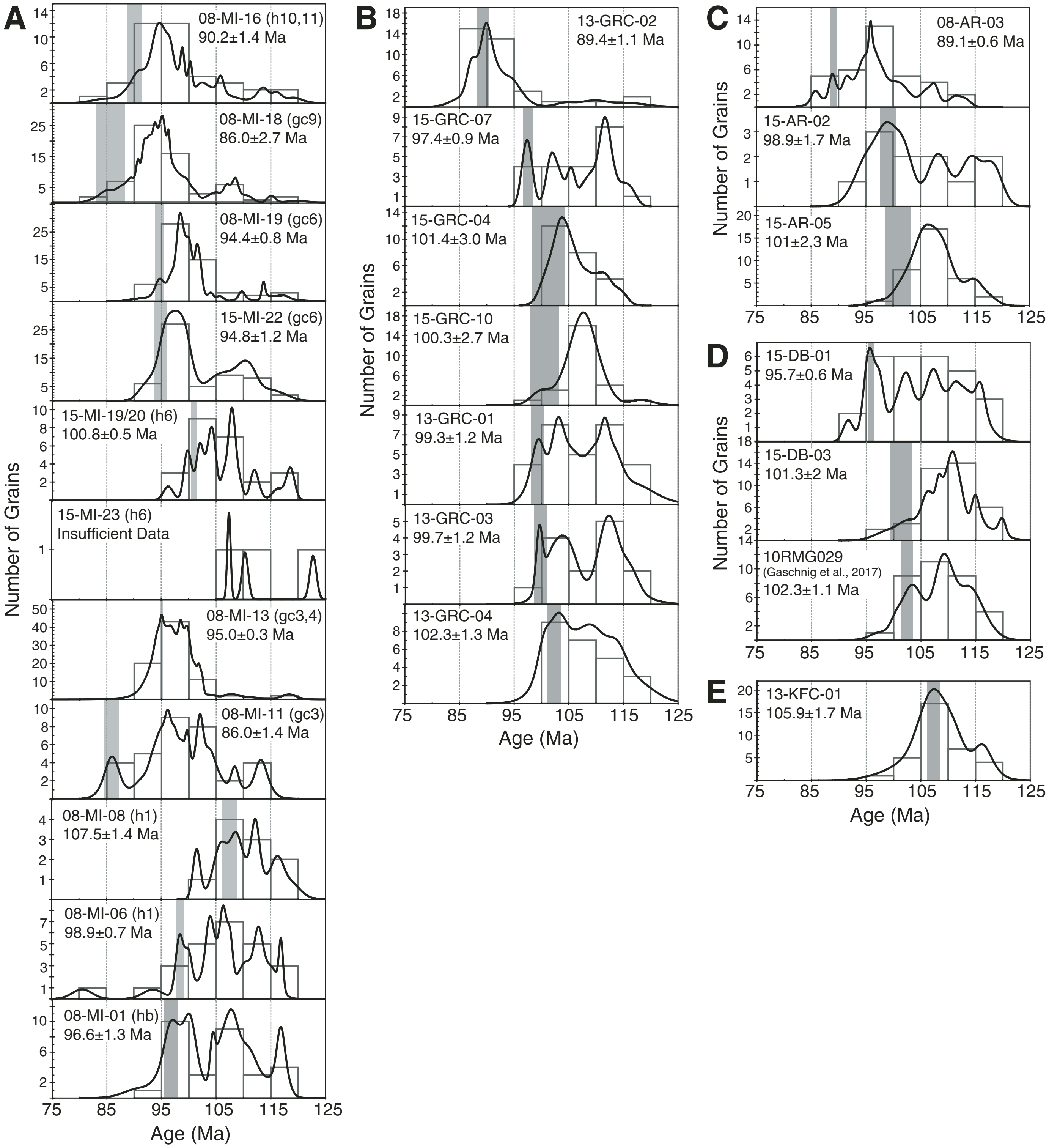

Figure 6. Detrital-zircon U-Pb age distributions for grains younger than 125 Ma in each sample, shown as histograms with superimposed probability density curves. Calculated maximum depositional ages with uncertainties are given and shown as gray bands in each sample plot. (A) Mitchell inlier samples. (B) Goose Rock Conglomerate samples. (C) Antone Ranch samples. (D) Dixie Butte samples (including data from Gaschnig et al., 2017). (E) Dayville sample.

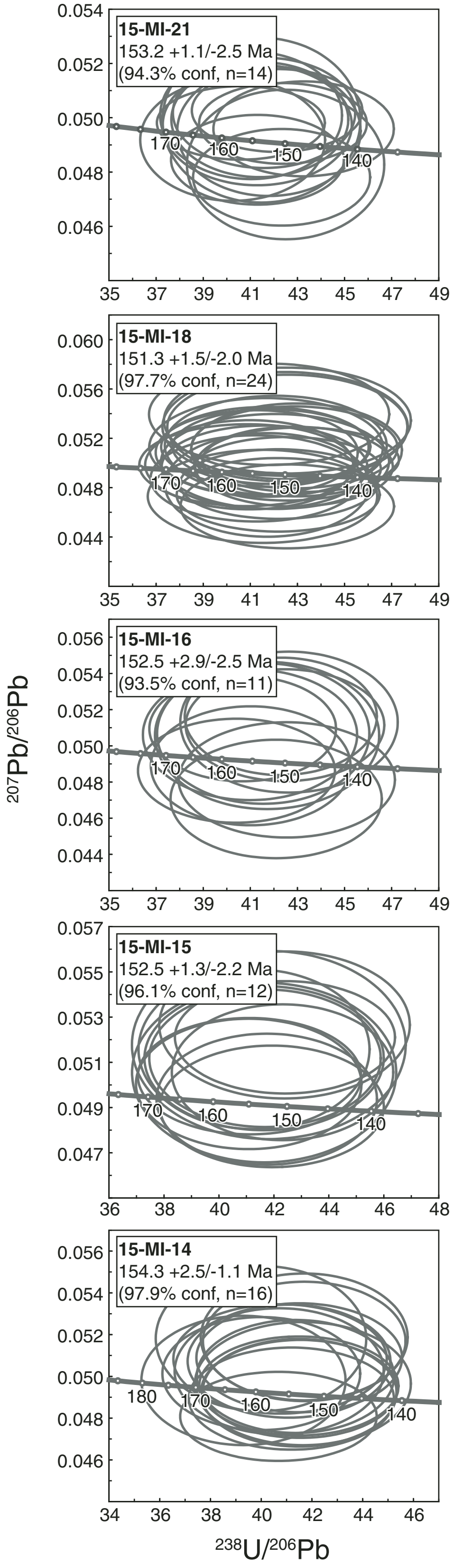

Figure 7. U-Pb concordia plots and calculated ages for five plutonic cobbles collected from the Gable Creek Formation in the Mitchell inlier.

Cretaceous grains younger than 105 Ma showed greater isotopic variability, with ε_{Hf} values ranging from +11.4 to −15.2 and an average ε_{Hf} of −3.9 ± 7.7 (1σ; Fig. 9B).

Hafnium analysis was also completed on zircon grains from the five plutonic cobbles using laser-ablation split stream (LASS), following the methods of Fisher et al. (2014b). All five Late Jurassic cobbles were very radiogenic, with ε_{Hf} values ranging from +12.2 to +15.8 (Fig. 9A).

DISCUSSION

Depositional Age Constraints

Mitchell Inlier

Two samples from the lower Hudspeth Formation of the Mitchell inlier near Toney Butte (Khb and Kh1; 08-MI-01 and 08-MI-06) have Cenomanian (100.5–93.9 Ma; time scale of Cohen et al., 2013) maximum depositional ages of 96.6 ± 1.3 Ma and 98.9 ± 0.7 Ma, respectively (Fig. 6A). A third sample collected from the lower Hudspeth Formation near the core of the Mitchell anticline (Kh1; 08-MI-08) has an Albian (113.0–100.5 Ma; time scale of Cohen et al., 2013) maximum depositional age of 107.5 ± 1.4 Ma (Fig. 6A). Ammonite fossils collected from the lower Hudspeth Formation indicate lower and upper Albian deposition for at least the basal and lower part of the main mudstone members of the Hudspeth Formation (Jones et al., 1965; P. Rodda, personal commun. reported *in* Dorsey and Lenegan, 2007), yet our detrital-zircon maximum depositional ages permit Albian deposition for only one of three samples (08-MI-08; Fig. 6A). Using both detrital zircon and fossil data, we consider that the basal and main mudstone members of the Hudspeth Formation are of Albian–Cenomanian age.

Five samples collected from the Gable Creek Formation and three samples from stratigraphically higher in the Hudspeth Formation have maximum depositional ages of 86.0 ± 1.4 Ma (08-MI-11) for Kgc3, 95.0 ± 0.3 Ma (08-MI-13) for Kgc3,4, 100.8 ± 0.5 Ma (15-MI-19/20) for Kh6, 94.8 ± 1.2 Ma (15-MI-22) and 94.4 ± 0.8 Ma (08-MI-19) for Kgc6, 86.0 ± 2.7 Ma (08-MI-18) for Kgc9, and 90.2 ± 1.4 Ma (08-MI-16) for Kh10,11. The maximum depositional age of 86.0 ± 1.4 from unit Kgc3, relatively low in the Mitchell stratigraphy, and the maximum depositional age of 86.0 ± 2.7 from Kgc9 suggest that the majority of deposition in the Mitchell inlier was Coniacian–Santonian (89.8–86.3/86.3–83.0 Ma; time scale of Cohen et al., 2013) or younger.

These maximum depositional ages may indicate that slow deposition of the basal and main mudstone members of the Hudspeth Formation in a sediment-starved, distal submarine fan environment occurred for an extended period, from Albian until at least Coniacian time, when upper-fan channel systems of the Gable Creek Formation entered the basin. Alternatively, a disconformity may exist between the Albian to Cenomanian basal and main mudstone members of the Hudspeth Formation and the Coniacian–Santonian (or younger) Gable Creek and Hudspeth Formations. Our maximum depositional age data cannot

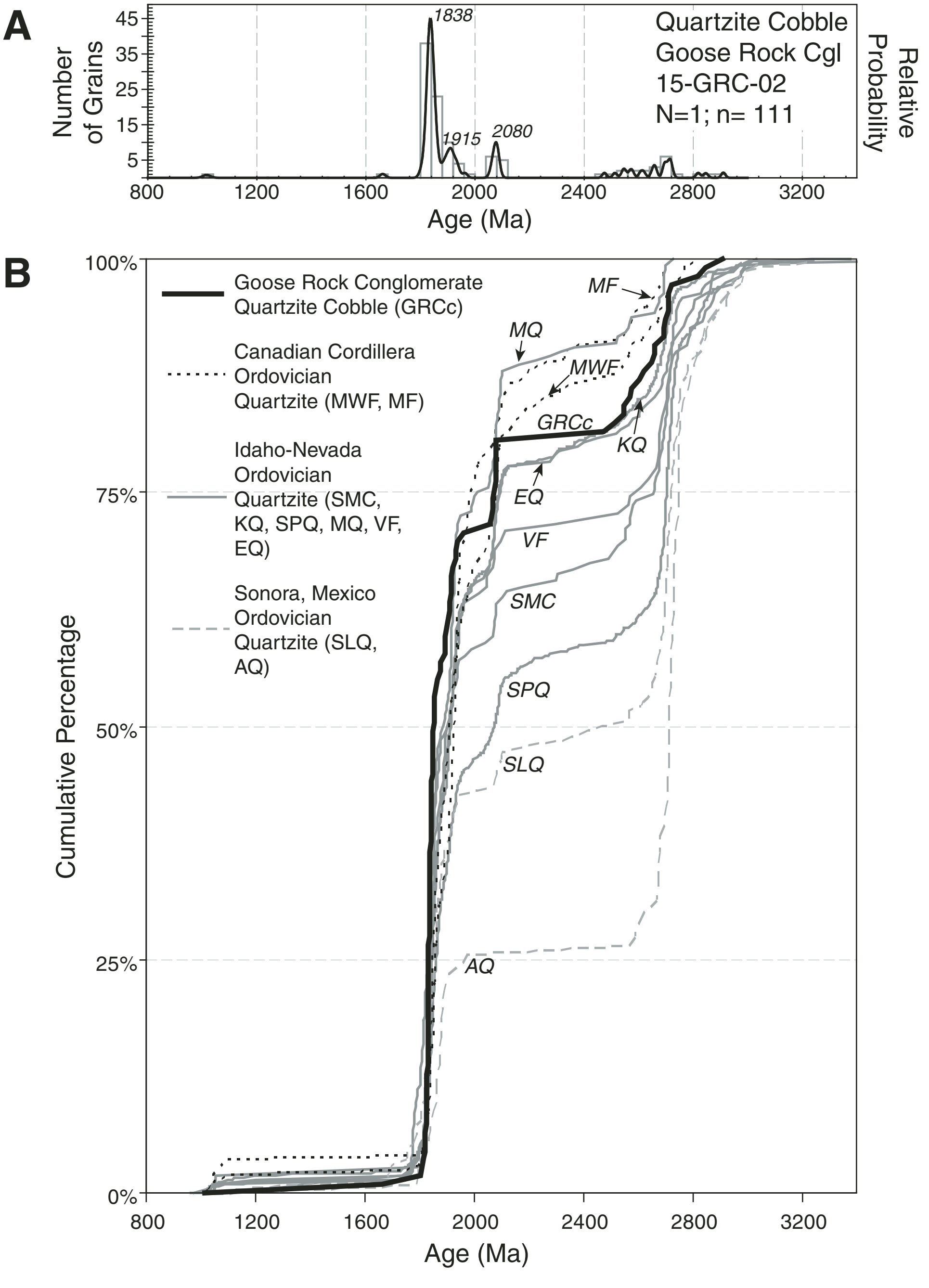

Figure 8. (A) Detrital-zircon U-Pb data shown as histogram with superimposed relative probability curve for quartzite cobble collected from the Goose Rock Conglomerate. (B) Cumulative age distribution curves for the Goose Rock Conglomerate quartzite cobble (GRCc) and detrital-zircon data from Cordilleran Ordovician quartzites. AQ—Aliso Quartzite; EQ—Eureka Quartzite; KQ—Kinnikinic Quartzite; MF—Monkam Formation; MQ—McAfee Quartzite; MWF—Mount Wilson Formation; SLQ—Sierra Lopez Quartzite; SMC—Sawtooth metamorphic complex; SPQ—Swan Peak Quartzite; VF—Valmy Formation (data from Gehrels and Stewart, 1998; Baar, 2009; Wulf, 2011; Workman, 2012; Gehrels and Pecha, 2014; Ma et al., 2015; Linde et al., 2016).

distinguish between these two possibilities, but Dorsey and Lenegan (2007) inferred that structural and stratigraphic relationships in the Toney Butte area resulted from syndepositional folding of the Toney Butte anticline during Albian deposition of the Hudspeth main mudstone member, followed by deposition of the overlying Gable Creek Formation, suggesting a possible local unconformity in the basin.

Other Cretaceous Inliers

Six samples collected from the Goose Rock Conglomerate have maximum depositional ages ranging from 97.4 ± 0.9 Ma to 102.3 ± 1.6 Ma (Fig. 6B) and remarkably consistent detrital-zircon age signatures (Fig. 5B). These maximum depositional ages and Mesozoic detrital-zircon age signatures also overlap with those of the lower three Mitchell inlier samples (Fig. 5A). Like the lower Hudspeth Formation, deposition of the Goose Rock Conglomerate may have begun as early as late Albian, and continued into Cenomanian time. One sample collected in the upper part of the Goose Rock Conglomerate outcrop (13-GRC-02) has a maximum depositional age of 89.4 ± 1.1 Ma, indicating Turonian–Coniacian (93.9–89.8/89.8–86.3; time scale of Cohen et al., 2013) or younger deposition, and a detrital-zircon age

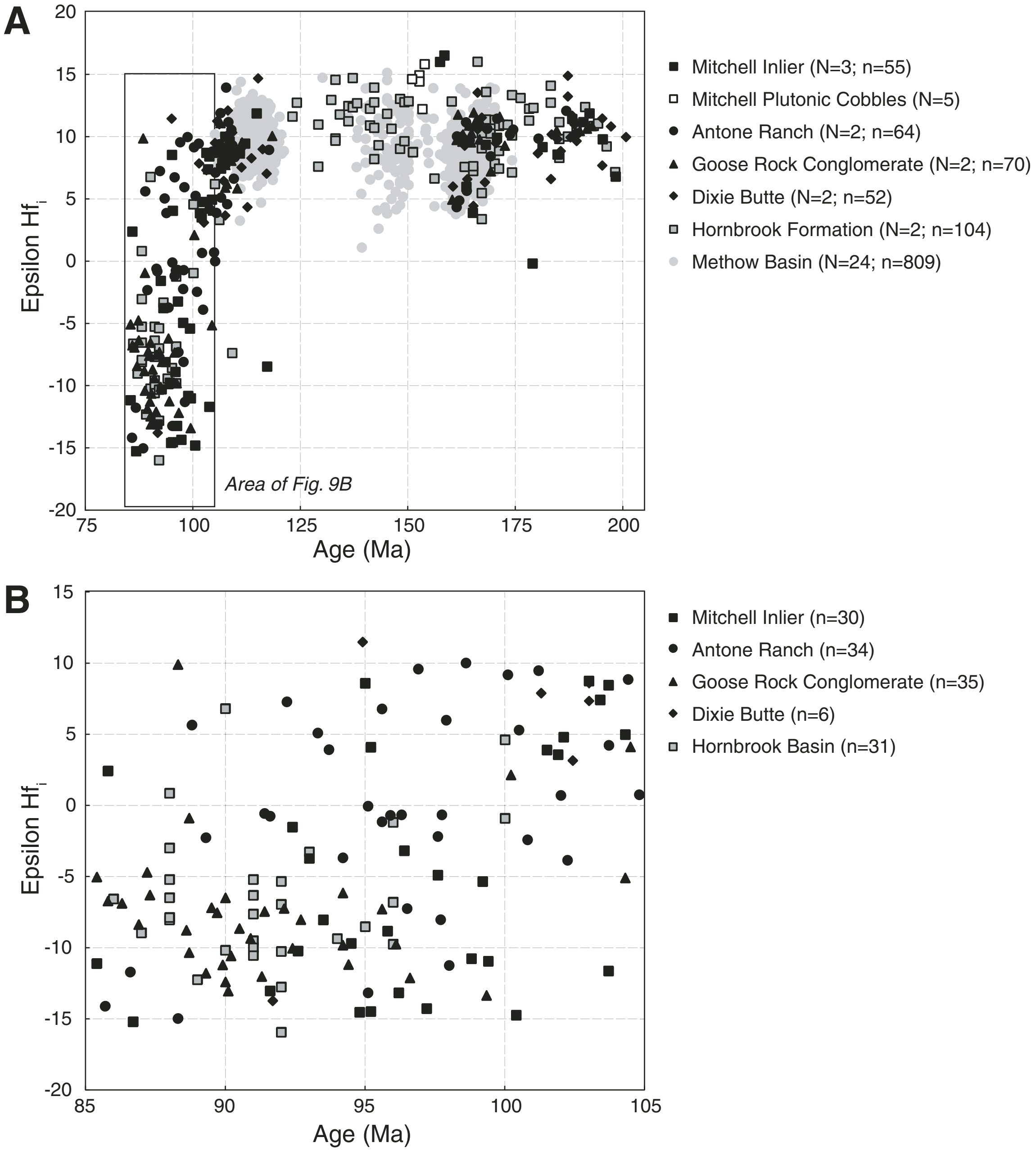

Figure 9. $\varepsilon_{\mathrm{Hf}_i}$ data vs. age for selected zircon grains from the Mitchell, Antone Ranch, Goose Rock Conglomerate, and Dixie Butte inliers (this study; Gaschnig et al., 2017), as well as the Hornbook Formation (gray squares; data from Surpless, 2015) and Methow basin (gray circles; data from Surpless et al., 2014). (A) All Jurassic and Cretaceous zircon. (B) Zircon younger than 105 Ma.

signature that contains abundant Late Cretaceous grains (37% of Mesozoic grains) and fewer Early Cretaceous grains (13% of Mesozoic grains).

Two samples collected from Antone Ranch have maximum depositional ages of 98.9 ± 1.7 Ma (15-AR-02) and 101 ± 2.3 Ma (15-AR-05), consistent with Albian–Cenomanian deposition. One sample from Antone Ranch (08-AR-03) has a maximum depositional age of 89.1 ± 0.6 Ma, suggesting Coniacian (89.8–86.3; time scale of Cohen et al., 2013) or younger deposition. Like the upper Goose Rock Conglomerate sample, this Antone Ranch sample also contains abundant Late Cretaceous grains (28% of Mesozoic grains) and fewer Early Cretaceous grains (15% of Mesozoic grains).

Two samples collected from Dixie Butte have maximum depositional ages of 95.7 ± 0.6 Ma (15-DB-01) and 101.3 ± 2 Ma (15-DB-03), consistent with Albian–Cenomanian deposition, and very similar detrital-zircon age signatures (Figs. 5C and 6D). One sample collected near Dayville (13-KFC-01) has a maximum depositional age of 105.9 ± 1.7 Ma (Fig. 6E), suggesting Albian or younger deposition, which is consistent with Cenomanian deposition indicated by fossils (Squires and Saul, 2002).

Early and Late Ochoco Basin

Similar Jurassic and Cretaceous age modes (Fig. 5) with similar ε_{Hf} ranges (Fig. 9), and a similar overall range in sandstone petrography and conglomerate clast compositions (Fig. 4) characterize all inliers, suggesting that sedimentation at all of these localities recorded deposition in a single, contiguous Ochoco basin. Nonmarine and shallow-marine deposition at Goose Rock, Dixie Butte, Antone Ranch, and Bernard Ranch was likely linked to deeper-water deposition at the Mitchell inlier and in wells south of Mitchell, Oregon. Collectively, these exposures represent the remnants of a large mid- to Late Cretaceous basin deposited unconformably on the western flank of the Blue Mountains Province. Within this large Ochoco basin, key differences in the proportions of different ages, particularly the presence and abundance of Late Cretaceous grains, maximum depositional ages, and conglomerate compositions, permit recognition of local-to regional-scale variation in sources through time.

Samples from Dayville, Dixie Butte, two samples from Antone Ranch, the lower six samples from the Goose Rock Conglomerate, and the lower three samples from the Mitchell inlier all have maximum depositional ages suggesting deposition began no earlier than Albian–Cenomanian time, which is consistent with published biostratigraphic ages from the lower Mitchell inlier (Dorsey and Lenegan, 2007), Dixie Butte (Brooks et al., 1984), and Antone Ranch (Merriam, 1901). With the exception of one Antone Ranch sample, all of these Albian–Cenomanian samples have very similar Mesozoic detrital-zircon age signatures that consist of three age modes of 200–180 Ma, 170–150 Ma, and 120–95 Ma, which together comprise 84%–98% of all ages in each sample (Fig. 5). One sample from Antone Ranch (15-AR-02) shares the same mid-Cretaceous age mode of 120–95 Ma, but it has additional Mesozoic age modes of 210–160 Ma and 145–135 Ma; these Mesozoic ages comprise 63% of all ages in the sample. The lower Mitchell inlier, Goose Rock, and Antone Ranch localities are all part of conglomerate facies 2 (Little, 1986). Sandstone petrography of these samples indicates that they typically contain less monocrystalline quartz than the rest of the Mitchell inlier samples, and they largely plot in dissected and transitional arc and mixed provenance fields on a Qm-F-Lt ternary diagram (Fig. 4B).

Given the similarities in sediment composition, detrital-zircon age signatures, and maximum depositional ages, we infer that Albian–Cenomanian sedimentation at all of these localities records the early stages of deposition in a contiguous Ochoco basin. We therefore combined all 15 samples that share these characteristics into one composite age distribution for the Albian–Cenomanian Ochoco basin (Fig. 10A). The composite plot contains an Early Cretaceous age mode (ca. 110 Ma; 27.5%), Middle Jurassic age mode (ca. 165 Ma; 45.6% of Mesozoic grains), and Early Jurassic age mode (ca. 185 Ma; 21.1%; Fig. 10A). In addition, 7.4% of this composite Albian–Cenomanian Ochoco basin signature is Paleozoic, with primarily Pennsylvanian–Permian ages in all but one sample (08-MI-06), and nine Silurian–Devonian grains that all occurred in one Antone Ranch sample (15-AR-02). Also, 3.7% of this composite signature is Precambrian, with grains spanning 2100–1000 Ma and a handful of grains spanning 2700–2250 Ma; 30 of these Precambrian grains occurred in one Antone Ranch sample (15-AR-02), and the other 23 occurred in eight of 13 samples, with one to eight grains in each sample (Fig. 5). Precambrian grains occurred in all localities.

Three samples from the upper Mitchell inlier, one from the upper Goose Rock Conglomerate, and one from Antone Ranch exhibited younger maximum depositional ages (90–86 Ma; Fig. 6), fewer pre-Mesozoic grains, and abundant Late Cretaceous grains (Fig. 5). Importantly, sample 08-MI-11, with a maximum depositional age of 86 ± 1.4 Ma, was collected low in the Mitchell inlier section (Kgc3), which suggests that all seven samples collected stratigraphically above 08-MI-11 are also Coniacian or younger, even though their calculated maximum depositional ages range from ca. 101 to 86 Ma (Fig. 6A). All eight of these Coniacian and younger samples showed the same three Mesozoic age ranges (200–180 Ma, 170–150 Ma, 120–90 Ma), but in variable proportions (Fig. 5A). Five of these eight Coniacian and younger Mitchell inlier samples exhibited more 120–90 Ma grains than 170–150 Ma grains, two had relatively similar proportions of 120–90 Ma and 170–250 Ma grains, and only 15-MI-23 had more 170–150 Ma grains (Fig. 5A). We infer that the variability of age distributions within the overall similar Mesozoic age ranges likely resulted from local, short-term (<5 m.y.) changes in drainage systems and source rock exposure, rather than more regional, long-term (>5 m.y.) changes in provenance.

Little (1986) considered the Mitchell inlier conglomerate associated with these eight Coniacian and younger Mitchell detrital-zircon samples part of his facies 1, and he noted that conglomerate compositions are very consistent throughout this part of the Mitchell stratigraphy (Kgc3–Kgc11). Sandstone petrography documents abundant monocrystalline quartz in these samples, with provenance largely in mixed and quartzose recycled orogen fields on a Qm-F-Lt diagram (Fig. 4B). Compositional and age similarities suggest that these samples together represent Coniacian and younger sedimentation in the Ochoco basin. We therefore combined all 10 samples into a composite age distribution for the Coniacian and younger Ochoco basin, which is characterized by Late Cretaceous (ca. 97 Ma; 33% of Mesozoic grains), Early Cretaceous (ca. 108 Ma; 18.9%), Middle Jurassic (ca. 165 Ma; 30.6%), and Early Jurassic (ca. 185 Ma; 14.2%) age modes (Fig. 10B). Mesozoic grains comprise 93.5% of the upper Ochoco basin age distribution, with 4.1% Paleozoic grains (largely Pennsylvanian–Permian) and 2.4% Precambrian grains.

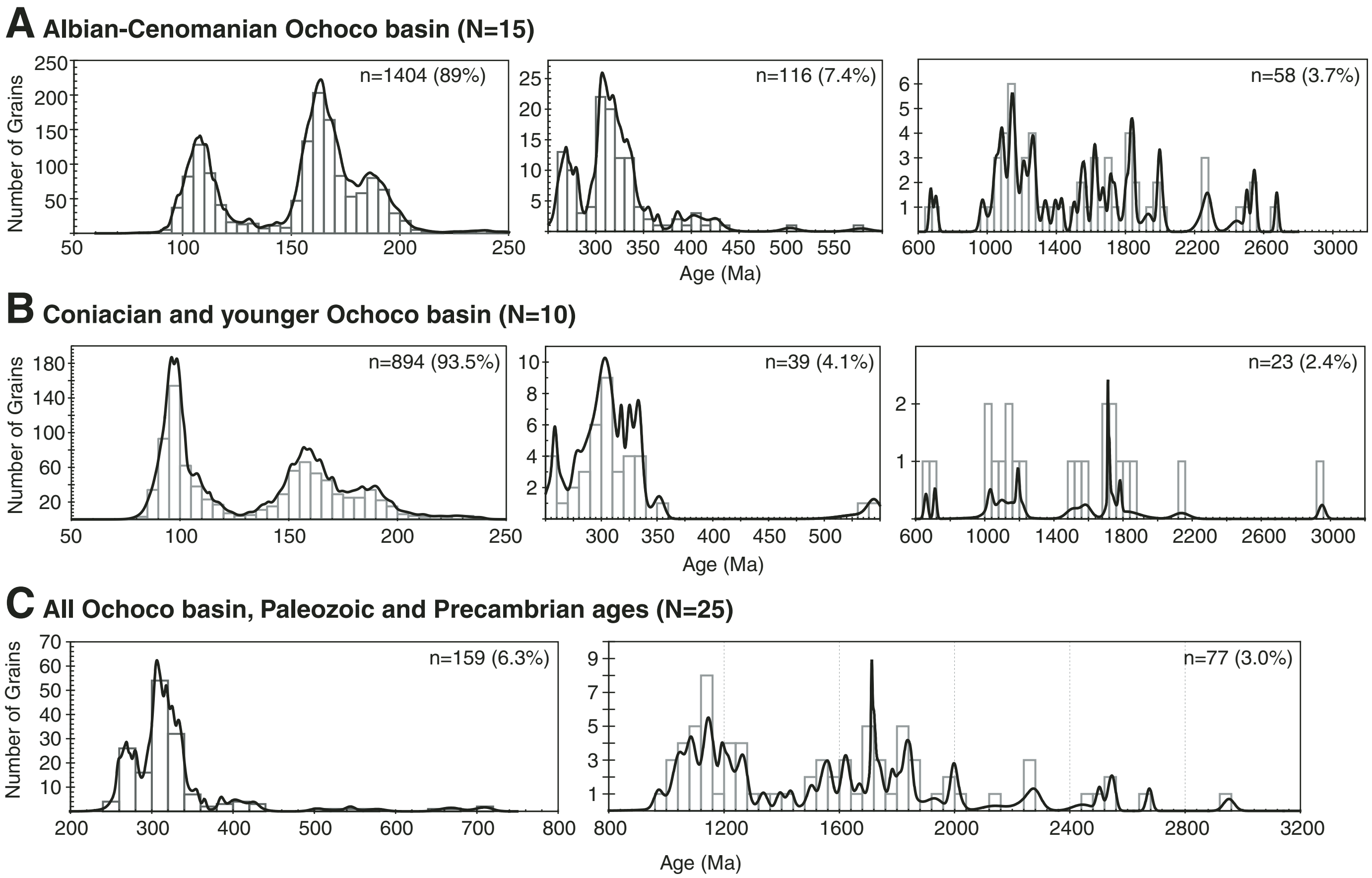

Figure 10. Compiled U-Pb detrital data for (A) Albian–Cenomanian Ochoco basin; (B) Coniacian and younger Ochoco basin; and (C) all Ochoco Paleozoic and Precambrian zircon.

Paleozoic grains occurred in all but one sample (13-GRC-02), and Precambrian grains occurred in all but two samples, both of which had $n < 47$ (15-MI-23 and 08-MI-19).

Ochoco Basin Provenance

Similarity in detrital-zircon age distributions, ε_{Hf} ranges, and sediment compositions throughout all Ochoco basin samples suggests long-term stability in the source region, with variability in the proportion of different age modes and sandstone compositions between individual samples resulting from short-term and local to regional changes at given locations within the strata. Throughout Ochoco basin deposition, source compositions included arc and recycled orogen sources. The primary differences between Albian–Cenomanian strata and Coniacian and younger strata are the relative abundance of Late Cretaceous grains (from 3% to 32.9% of Mesozoic grains), and the relative reduction of pre-Mesozoic grains (from 11.1% to 6.5% of all grains; Fig. 10) with time. Although the number of pre-Mesozoic grains in the basin decreased with time, the range of pre-Mesozoic ages (late Paleozoic and a wide spread of Precambrian ages) remained consistent throughout deposition (Fig. 10).

Sediment sources were characterized by Early Jurassic ages, abundant Middle and Late Jurassic ages, and Cretaceous age modes that shifted from primarily late Early Cretaceous in Albian–Cenomanian strata to Late Cretaceous in Coniacian and younger strata. The ε_{Hf} values of Early Jurassic (200–180 Ma) grains from the Mitchell inlier (Coniacian and younger depositional age), Goose Rock Conglomerate (both Albian–Cenomanian and Coniacian and younger depositional ages), Antone Ranch (both Albian–Cenomanian and Coniacian and younger depositional ages), and Dixie Butte (Albian–Cenomanian depositional age) are consistently radiogenic, with an average of 10.3 ± 1.7 (Fig. 9A). Middle to Late Jurassic (175–155 Ma) grains are also highly radiogenic, with an average ε_{Hf} value of 9.5 ± 2.7. We did not collect Hf data from 155–150 Ma detrital-zircon grains, but five 154–151 Ma tonalitic cobbles from Coniacian and younger strata in the Mitchell inlier (Kgc6) exhibited an average ε_{Hf} value of 14.4 ± 1.3, indicative of highly radiogenic plutonic source rocks. Cretaceous grains older than 105 Ma had an average ε_{Hf} value of 8.3 ± 3.3, which is only slightly less radiogenic than Jurassic detrital-zircon grains, but with greater variability. Thus, Jurassic and Early Cretaceous zircon grains likely were derived from source rocks intruded into accreted terranes, without significant involvement of continental material. Grains younger than 105 Ma from all four inliers for which we have Hf data (Mitchell, Goose Rock, Antone Ranch, and Dixie Butte) showed an average ε_{Hf} value of −3.7 ± 7.8 (Fig. 9B), suggesting that mid- to Late Cretaceous grains were derived from rocks that originally intruded across the continental margin. The presence of five Precambrian grains (1838, 1291, 1140, 1055, and 683 Ma) and Cretaceous grains younger than 105 Ma with ε_{Hf} values ranging from +11.4 to −13.7 in our Dixie Butte samples suggests involvement of continental source regions within the North American craton, which contradicts the interpretation of Gaschnig et al. (2017) that Dixie Butte provenance was entirely in the accreted terranes of the Insular superterrane.

Paleocurrent data from the Mitchell inlier and Goose Rock Conglomerate localities indicate dominantly southwesterly flow, with more variability in the lower and upper parts of the Mitchell inlier (Little, 1986; Dorsey and Lenegan, 2007; Hopson et al., 2013). Wilkinson and Oles (1968) and Little (1986) considered the overall southwesterly flow direction in the Mitchell inlier to represent the average paleoslope orientation, suggesting that submarine channels were oriented parallel to the paleoslope. Restoration of 37° of possible post-Cretaceous clockwise rotation (Housen and Dorsey, 2005) indicates primarily southerly paleoflow at the Mitchell and Goose Rock sites, with subordinate flow to the west-northwest in the lower Mitchell inlier and to the northeast in the uppermost Mitchell inlier, suggesting sediment sources north of Mitchell and Goose Rock, with possible input from the southeast and southwest. Paleoflow measurements from Antone Ranch restore to northwest- and west-directed flow, indicating sediment sources southeast and east of Antone Ranch, which may account for the slightly different age distribution of 15-AR-02, which includes Early Cretaceous (145–135 Ma) grains not characteristic of other Ochoco basin samples, but possibly derived from the Early Cretaceous Sierran arc, and more abundant Precambrian grains. Overall, paleocurrent indicators suggest sediment sources for the Ochoco basin were mainly located north and east, with some input from the southwest and southeast, although flow direction may also have been influenced by paleoslope, obstructions within the basin, and/or autogenic processes in submarine fans.

Known sediment sources in the Blue Mountains Province (Walker, 1995; Johnson et al., 1997; Schwartz et al., 2010, 2011a, 2014; LaMaskin et al., 2011, 2015) and western Idaho (Manduca et al., 1993; Giorgis et al., 2005, 2008; Unruh et al., 2008; Benford et al., 2010; Gaschnig et al., 2010, 2016) can account for the lithology and many of the detrital-zircon ages in Ochoco basin strata, including the abundant radiogenic Middle and Late Jurassic grains and late Early Cretaceous grains, volcanic clasts, chert, and plutonic cobbles that characterize the Albian–Cenomanian Ochoco basin. Detrital-zircon ε_{Hf} values of Jurassic and Early Cretaceous detrital zircon grains are positive, consistent with sources within oceanic or fringing arc terranes (Fig. 9). Although Hf isotopic data are not available for most of the Blue Mountains terranes, Schwartz and Johnson (2014) described 162–154 Ma plutons with ε_{Hf} values ranging from 0 to +15 in the Baker and Wallowa terranes, and Anderson et al. (2011) documented 161.3–145.6 Ma plutons within the Mountain Home metamorphic complex with initial ε_{Hf} values of +16.3 to +4.2. Initial $^{87}Sr/^{86}Sr$ values <0.706 throughout Blue Mountains terranes (Fleck and Criss, 1985; Manduca et al., 1993) would suggest similarly radiogenic Hf values for these rocks. Thus, the five Late Jurassic plutonic cobbles from the middle of the Mitchell inlier Gable Creek Formation that have highly radiogenic Hf isotopic values are consistent with local derivation from Late Jurassic plutons intruded into the subduction/accretionary complex of the Baker terrane, island-arc assemblages of the Wallowa terrane, and/or the Mountain Home metamorphic complex (Fig. 2). Early Jurassic detrital-zircon grains are common in Triassic and Jurassic clastic rocks of the Blue Mountains (LaMaskin et al., 2011), and plutons of this age are abundant in the Black Rock terrane of northwest Nevada (Wyld, 1990, 1996; Quinn et al., 1997). Early Jurassic detrital zircon in the Ochoco basin may be derived from the Black Rock terrane, or possibly recycled through older Mesozoic strata of the Blue Mountains. Western Idaho plutons can account for the 120–100 Ma detrital zircon in the Ochoco basin, including the greater variability in detrital-zircon ε_{Hf} values. The western Idaho shear zone marks the continental boundary (Lund and Snee, 1988; Manduca et al., 1993; McClelland et al., 2000), and ε_{Hf} values for 120–109 Ma plutons intruded across this boundary range from +10 to +4.7 (Patzke et al., 2017), with more positive ε_{Hf} associated with $^{87}Sr/^{86}Sr$ values < 0.7045 to the west and more negative ε_{Hf} associated with $^{87}Sr/^{86}Sr$ values > 0.7070 to the east across the shear zone ($^{87}Sr/^{86}Sr$ values from Fleck and Criss, 1985). Giorgis et al. (2005) suggested that restoring 105–90 Ma transpressional deformation along the western Idaho shear zone results in a 110–100 Ma magmatic arc that may have been comparable in width to the Cretaceous Sierra Nevada batholith. Volcanic-rich and plutonic sediment derived from this active ca. 105 Ma Idaho arc may have been shed southwest and south into the newly developing Ochoco forearc basin.

The influx of Late Cretaceous zircon (100–86 Ma) with ε_{Hf} values ranging from +11.4 to −15.2 in the Coniacian and younger Ochoco strata cannot be accounted for completely by a Blue Mountains–western Idaho shear zone source, but it could represent erosion of the early phases of the Idaho batholith that intruded into continental rocks east of the western Idaho shear zone. Gaschnig et al. (2016) documented evidence of 100–85 Ma magmatism in the Idaho batholith east of the western Idaho shear zone that includes the border-zone and early metaluminous suites of the Idaho batholith, as well as ca. 98–87 Ma zircon xenocrysts that occur throughout younger phases of the central and southern Atlanta suite of the Idaho batholith. Gaschnig et al. (2016) speculated that much of the 98–87 Ma arc intruded at shallower crustal levels than the younger Atlanta suite and has been eroded away, suggesting that the modern outcrop area significantly underrepresents the original extent of the 98–87 Ma magmatic arc in Idaho. We infer that the Turonian and younger Ochoco basin strata may contain much of the detrital record of the 120–100 Ma plutons and associated volcanic rocks of the western Idaho shear zone and 100–87 Ma Idaho batholith. Ca. 105–90 Ma transpression along the western Idaho shear zone may have resulted in the shift from abundant late Early Cretaceous zircon derived from within the western Idaho shear zone plutons and associated volcanic rocks in the Albian–Cenomanian Ochoco basin to an influx of Late Cretaceous zircon into the Coniacian and younger Ochoco basin strata. In this scenario, drainage systems would have transported sediment south and southwest from the western Idaho shear zone and early Idaho batholith into the Ochoco forearc basin as dextral transpression along the active western Idaho shear zone translated the Blue Mountains Province and overlying Ochoco basin northward and eastward, closer to the Idaho arc.

Alternatively, the Late Cretaceous batholith of the northern Sierra Nevada may have provided 100–86 Ma detrital zircon to the Ochoco basin. Like the early phases of the Idaho batholith, the Late Cretaceous Sierran batholith intruded across the boundary between oceanic terranes and the continent (Kistler and Peterman, 1973; Saleeby et al., 1987; Kistler, 1990; Chen and Tilton, 1991), and ε_{Nd} values of northern Sierran Cretaceous plutons range from +2.5 to –7.5 (DePaolo, 1981; Cecil et al., 2012). Although ε_{Hf} values for much of the Sierra Nevada are not available, intrusion of these plutons across the $^{87}Sr/^{86}Sr$ 0.706 isopleth marking the boundary between continent and accreted terranes suggests that ε_{Hf} values of Late Cretaceous plutons in the northeastern Sierra Nevada would also range from highly radiogenic to more negative values; indeed, Lackey et al. (2012) documented ε_{Hf} values of +6.4 to –4.7 in the 124–105 Ma Fine Gold intrusive suite, and Miller et al. (2014) reported a 15-epsilon-unit range in ε_{Hf} values from the 98–86 Ma Sierra Crest intrusions. Our sandstone petrography and detrital-zircon data cannot preclude a northern Sierra Nevada source, but the dominantly south-directed paleoflow (restored direction) in much of the Ochoco basin suggests sources primarily to the north and northwest (Blue Mountains terranes, western Idaho, and Idaho batholith), with subordinate sources from the east and south (Black Rock terrane and northern Sierra Nevada batholith).

Additional potential sources of radiogenic Jurassic and Cretaceous detrital zircon in the Ochoco basin include regions further north, such as the Coast Mountains batholith and Omineca belt in southern British Columbia and northern Washington State. The Coast Mountains batholith intruded across the suture between the Insular and Intermontane superterranes and extended south into the North Cascades, and it includes evidence of abundant Late Jurassic (160–140 Ma), Early Cretaceous (120–100 Ma), and Late Cretaceous (100–80 Ma) magmatism, with a magmatic lull from 140 to 120 Ma (Gehrels et al., 2009). The Omineca belt occurs between the Intermontane superterrane and the North American craton (Monger et al., 1982), and a compilation of U-Pb ages from Mesozoic intrusions in the southern Omineca Belt in British Columbia includes 212–180 Ma, 175–145 Ma, and 110–104 Ma ages (Breitsprecher and Joseph, 2010). In Washington State, the Okanogan Range within the southern Intermontane superterrane includes 166–154 Ma plutons (Rb-Sr dates, consistent with K-Ar dates; Petö and Armstrong 1976) and 114–110 Ma plutons (U-Pb dates; Greig et al., 1992; Hurlow, 1993; Hurlow and Nelson, 1993). These Jurassic and Cretaceous ages match well with Mesozoic age modes in the Ochoco basin and may represent an additional northern source region. Although Hf data are not available for Okanogan plutons, the mean $^{87}Sr/^{86}Sr$ value of 0.7042 for the Jurassic plutons is consistent with magma derivation from metabasic rocks without input of older, continental crustal material (Petö and Armstrong, 1976). Zircon ε_{Hf} values from these rocks would likely reflect this juvenile geochemical signature, consistent with the radiogenic Jurassic detrital zircon in the Ochoco basin. However, ε_{Hf} values of zircon in the Coast Mountains batholith do not match well with the Ochoco detrital-zircon values, particularly for the less radiogenic Late Cretaceous detrital zircon. Coast Mountains plutons intruded into the Insular superterrane (western belt) yielded zircon ε_{Hf} values between +8 and +6, plutons intruded into the Intermontane superterrane (eastern belt) yielded zircon ε_{Hf} values between +15 and +10, and plutons intruded into a belt of mid-Cretaceous thrust faults between the eastern and western belts displayed the widest range of ε_{Hf} values, from +11.6 to +1.5 (Cecil et al., 2011). Even this wide range does not approach the +11.4 to –15.2 range of Ochoco basin zircon younger than 105 Ma. We therefore consider these northern regions as possible contributors to the Ochoco basin, but not exclusive sources.

The combined Ochoco basin detrital-zircon age signature includes 6.3% Paleozoic grains, most of which are 340–260 Ma (Fig. 10C). Gaschnig et al. (2017) found consistently radiogenic ε_{Hf} values of +13.2 to +10.9 (average of 12 ± 0.9) from eight late Paleozoic grains from the Dixie Butte inlier, suggesting that these grains were derived from accreted terranes rather than continental sources. Likely sources exist in remnants of Carboniferous–Permian magmatism in the Eastern Klamath terranes (Miller, 1989; Gehrels and Miller, 2000), or through recycling of older strata within the Blue Mountains Province. These late Paleozoic ages occur in the chert- and volcanic-rich Elkhorn Ridge argillite of the Bourne subterrane within the Baker terrane, which is 84% Paleozoic (418–255 Ma) and 15% Precambrian (2710–1186 Ma; Alexander and Schwartz, 2009), but the Elkhorn Ridge argillite is characterized by more abundant ca. 1800 Ma and Archean grains, with fewer 1800–1000 Ma grains (LaMaskin et al., 2011). Late Paleozoic ages also occur in the Late Triassic Vester Formation of the Izee terrane within the Blue Mountains Province (LaMaskin et al., 2011), but the Vester Formation also includes Silurian and Devonian detrital zircon that the Ochoco basin largely lacks, and the Ochoco basin includes 1300–1000 Ma grains that are nearly absent in the Vester Formation. Given that pre-Mesozoic grains comprise less than 10% of the Ochoco basin age distribution, the mismatch between the age signatures of the Ochoco basin and older Mesozoic strata of the Blue Mountains Province may result from dilution of the older age signatures in the Ochoco basin by other sediment sources, or it may indicate that these grains were not recycled through strata of the Baker and Izee terranes. LaMaskin et al. (2011) suggested a late Paleozoic subduction-accretionary complex source in the Eastern Klamath and Northern Sierran terranes for late Paleozoic grains in the Vester Formation, and these sources may also have provided sediment to the Ochoco basin.

The Precambrian age signature from the composite Ochoco basin includes only 3% of detrital-zircon ages in the basin (Fig. 10C), and it includes Precambrian ages found throughout the North American Cordillera. Middle and Late Jurassic strata of the Izee terrane within the Blue Mountains contain few Archean grains, abundant 2000–1800 Ma grains, and a significant 200–180 Ma age mode (LaMaskin et al., 2011), which is similar to the Ochoco basin age signatures. However, the Ochoco basin largely lacks the Neoproterozoic and early Paleozoic ages that also characterize Jurassic strata of the Izee terrane, suggesting that Ochoco rocks may not have been recycled through these proximal, older Mesozoic strata of the Blue Mountains. Local strata within the Blue Mountains may not have provided abundant Precambrian grains to the Ochoco basin, but the Precambrian age distribution recorded by the Ochoco basin sandstone is not diagnostic of a unique source region.

The detrital-zircon age signature of the Goose Rock Conglomerate quartzite cobble closely resembles that of Ordovician quartzite found in the North American Cordillera from Canada to Mexico (Fig. 8; Gehrels and Stewart, 1998; Baar, 2009; Wulf, 2011; Workman, 2012; Gehrels and Pecha, 2014; Ma et al., 2015; Linde et al., 2016). Although the overall uniformity of detrital-zircon age signatures in these Ordovician quartzites precludes confident identification of a unique source, subtle differences in proportion, such as a prominent ca. 2700 Ma peak characteristic of southern Cordilleran quartzites, suggest that the Goose Rock quartzite may be a closer match to Ordovician equivalents found in Nevada, Idaho, and British Columbia than those found in Sonora and southern California (Fig. 8). Based on detrital-zircon age and hafnium isotopic analysis, combined with sandstone petrography and conglomerate clast composition, we infer sources of the Albian–Cenomanian Ochoco basin largely within the northeastern Blue Mountains terranes and the western Idaho region, with possible additional input from Sierran sources to the south, Black Rock terrane sources to the southeast, and Okanogan and/or Coast Mountains batholith sources to the north. In addition to these possible sources, the Coniacian and younger Ochoco basin also includes sediment derived from the early phase of the Idaho batholith and possibly the Late Cretaceous Sierran batholith.

However, the potential for significant (>400 km) postdepositional dextral translation of the Ochoco basin (Housen and Dorsey, 2005) requires that we consider alternative sources in the southern Sierra Nevada and Mojave-Sonora regions. The Ochoco basin lacks significant Triassic zircon characteristic of both the Peninsular Ranges and the Sierra Nevada (Paterson and Ducea, 2015; Kirsch et al., 2012) and the abundant 1.4–1.2 Ga and 1.8–1.6 Ga zircon modes that characterize the Mojave region (e.g., Wooden et al., 2012), but if the Blue Mountains terranes and western Idaho rocks were also located south of the Sierra Nevada during mid-Cretaceous time (Housen and Dorsey, 2005; Dorsey and Lenegan, 2007), only potential sources inboard of these locations may help distinguish between northern and southern paleolocations for the Ochoco basin. If the Ochoco basin and Blue Mountains terranes were south of the Sierra Nevada, the southern Sierra Nevada batholith or the Late Cretaceous Peninsular Ranges batholith would be the most likely sources of the 105–85 Ma detrital zircon. Although Hf data are not available, Late Cretaceous plutons of the southern Sierra Nevada intrude across the $^{87}Sr/^{86}Sr = 0.706$ line (Kistler and Peterman, 1973), with Late Cretaceous magmatism recording $^{87}Sr/^{86}Sr$ values of 0.70425–0.7073 (Saleeby et al., 1987), suggesting that ε_{Hf} values would also vary in detrital zircon derived from these plutons. However, because Late Cretaceous zircon grains from the southern Sierra Nevada were transported westward into the Great Valley forearc basin with little lag time between crystallization and deposition (DeGraaff-Surpless et al., 2002), Late Cretaceous detrital zircon likely would be similarly transported to an Ochoco forearc basin located to the southwest of the arc, yet these zircon are prominent in the Ochoco strata only after ca. 89 Ma, as much as 11 m.y. after crystallization. Despite this uncertainty, our provenance data from the Ochoco basin cannot preclude a tectonic model that places the accretion of the Blue Mountains to the North American continent south of the Sierra Nevada.

Comparison with Other Cretaceous Forearc Basins

An alternative test of the extent of postdepositional translation of the Ochoco basin is to compare Ochoco strata with coeval basins for which the Cretaceous paleolatitude is more certain. The Hornbrook Formation was deposited unconformably on accreted terranes of the Klamath Mountains in southwestern Oregon and northern California during latest Albian through Maastrichtian time (McKnight, 1971; Nilsen, 1984, 1993). The Klamath Mountains may have undergone significant pre-Cretaceous clockwise rotation, but no significant latitudinal displacement (Mankinen and Irwin, 1982; Mankinen, 1984; Mankinen and Irwin, 1990). The current configuration between the Sierra Nevada Foothills metamorphic belt and correlative units in the Klamath Mountains was established prior to deposition of the Hornbrook Formation on the eastern Klamath Mountains (Irwin, 1960; Jones and Irwin, 1971; Ernst et al., 2008; Ingersoll, 2008; Ernst, 2012). Restoration of 37° of post-Albian clockwise rotation (Housen and Dorsey, 2005) and ~50 km of shortening and a minimum of 40 km of dextral offset in the western Idaho shear zone (Wyld et al., 2006) places the Blue Mountains Province close to the Hornbrook Formation at 100 Ma, consistent with a combined Hornbrook-Ochoco basin (Kleinhans et al., 1984; Nilsen, 1986; Wyld and Wright, 2001; Wyld et al., 2006).

Sediment sources for the Hornbrook Formation likely included the Klamath Mountains, northern Sierra Nevada, and possibly Blue Mountains, early phases of the Idaho batholith, and northwestern Nevada (Surpless and Beverly, 2013; Surpless, 2015). Like the Ochoco basin, the Hornbrook Formation received a significant influx of Late Cretaceous detrital zircon with variable ε_{Hf} values beginning after Santonian time, which may have resulted from uplift of the Nevadaplano and the Sierran arc rocks that form its western flank, as well as erosion of rapidly exhumed rocks in the western Idaho shear zone and early phases of the Idaho batholith (Surpless, 2015).

Several workers have suggested that the Hornbrook Formation forms the northern extension of the Great Valley forearc basin in California (e.g., Nilsen, 1984, 1986; Miller et al., 1992). The Late Cretaceous northern Great Valley Group was deposited unconformably on metamorphosed island arc terranes and ophiolitic fragments of the Klamath Mountains and the western Sierra Nevada metamorphic belt (Cady, 1975; Schweickert, 1997, 2015; Ernst et al., 2008), which includes Early Cretaceous plutons of the Sierran arc (Saleeby et al., 1989). Paleomagnetic data from mid-Cretaceous Sierran plutons indicate no significant latitudinal translation of the Sierra Nevada since Late Cretaceous time (Frei et al., 1984; Frei, 1986). Based on comparison of detrital-zircon age and ε_{Hf} data, as well as whole-rock trace-element geochemistry and ε_{Nd} data, Surpless and Beverly (2013) concluded that the Hornbrook and northern Great Valley basins shared a similar provenance in the Klamath Mountains in early Late Cretaceous time, but were not part of a single system until Santonian time, when sediment sources for both basins shifted farther east, concomitant with uplift in eastern sources that included the eastern Sierra Nevada and possibly Idaho batholith.

Wyld et al. (2006) restored terranes of southern Canada, including the Insular and Intermontane superterranes, Coast Mountains batholith, and Omineca belt, to a position north of the Klamath Mountains and outboard of the Blue Mountains in their minimum-offset model for 100 Ma. In this reconstruction, Wyld et al. (2006) suggested that the Methow basin, an overlap sequence deposited on the Insular superterrane, may have formed the northern continuation of a combined Hornbrook-Ochoco basin during mid-Cretaceous time. Alternatively, Umhoefer and Blakey (2006) suggested that the Methow basin may have been located outboard of the Great Valley Group during mid-Cretaceous deposition, and the “Baja–British Columbia” hypothesis places the Methow basin at the latitude of Baja California (Irving, 1985; Irving et al., 1985; Irving and Wynne, 1990; Garver and Brandon, 1994). Detrital zircon data from the Albian–Santonian Harts Pass and Winthrop Formations and the Goat Wall unit of the Methow basin are characterized by two primary age modes throughout deposition, Middle to Late Jurassic (175–150 Ma) and Early Cretaceous (125–110 Ma), with very few pre-Mesozoic grains (1%) that are 1200–1000 Ma, Neoproterozoic, and Permian (DeGraaff-Surpless et al., 2003; Surpless et al., 2014). Jurassic and Early Cretaceous detrital-zircon grains range in ε_{Hf} values from +1.1 to +15.1, with an increase in mean ε_{Hf} values from +8.4 ± 1.9 for Middle to Late Jurassic grains to +10 ± 1.5 for Early Cretaceous grains (Fig. 9A; Surpless et al., 2014). Surpless et al. (2014) interpreted Methow provenance in the eastern Coast belt and Okanogan Range, but provenance data do not preclude postdepositional large-scale translation of the Methow basin along with its eastern sediment sources.

Comparison of the Mesozoic detrital-zircon signature of the Albian–Cenomanian Ochoco basin with those from the Albian–Cenomanian northern Great Valley Group, Albian–Turonian Hornbrook Formation, and Albian–Cenomanian(?) Methow basin reveals mismatches across all significant age ranges (Fig. 11A). Although the Albian–Cenomanian Hornbrook Formation includes an Early Jurassic peak and numerous Middle and Late Jurassic grains, the dominant early Early Cretaceous peak (ca. 140–130 Ma) that characterizes the Albian–Turonian Hornbrook Formation is all but absent in the Albian–Cenomanian Ochoco basin, and the large late Early Cretaceous peak (ca. 110 Ma) that characterizes the Albian–Cenomanian Ochoco basin is absent in the Albian–Cenomanian Hornbrook Formation. Similarly, the Albian–Cenomanian northern Great Valley Group lacks the Early Jurassic and late Early Cretaceous peaks that characterize the Albian–Cenomanian Ochoco basin, and it includes abundant Late Jurassic–early Early Cretaceous grains in a nearly unimodal age mode of 145 Ma (Fig. 11A). The Albian–Cenomanian(?) Methow basin shares a prominent Middle to Late Jurassic age peak with the Albian–Cenomanian Ochoco basin, but it lacks the Early Jurassic grains that characterize the Albian–Cenomanian Ochoco basin, and it has an Early Cretaceous peak ~10 m.y. older than that of the Albian–Cenomanian Ochoco basin. The ε_{Hf} values for Jurassic and Early Cretaceous grains in the Ochoco, Hornbrook, and Methow basins are similarly radiogenic, although 150–130 Ma Methow grains tend to be less radiogenic than in the Hornbrook Formation, and 125–105 Ma grains tend to be more radiogenic than in the Ochoco basin (Fig. 9). These detrital-zircon age comparisons suggest that each basin was characterized by mostly proximal sediment sources during Albian–Cenomanian deposition, with Hornbrook Formation and northern Great Valley Group sediment sources largely in the Klamath Mountains and northern Sierran Nevada, Methow basin sources in the Coast belt and Intermontane superterrane, and Ochoco basin sources mostly in the Blue Mountains and western Idaho, with possible input from the Coast belt and the Sierra Nevada.

In contrast, comparison of the Mesozoic detrital-zircon signatures for the Coniacian and younger Ochoco basin with those from the Coniacian–Maastrichtian northern Great Valley Group, Coniacian and younger Hornbrook Formation, and Cenomanian(?) and younger Methow basin (Fig. 11B) suggests more integrated depositional systems that included more distal source areas. For Coniacian and younger samples, Hornbrook and Ochoco basin strata provide the closest detrital-zircon age signature match, with remarkable similarity in both age modes and relative proportions. In addition, detrital-zircon ε_{Hf} values from upper Ochoco and Hornbrook strata also overlap, with the same wide range in ε_{Hf} values for zircon younger than 105 Ma (Fig. 9B).

The Coniacian–Maastrichtian northern Great Valley Group also resembles the Coniacian and younger Ochoco basin and Hornbrook age signatures, with similar Jurassic through Early

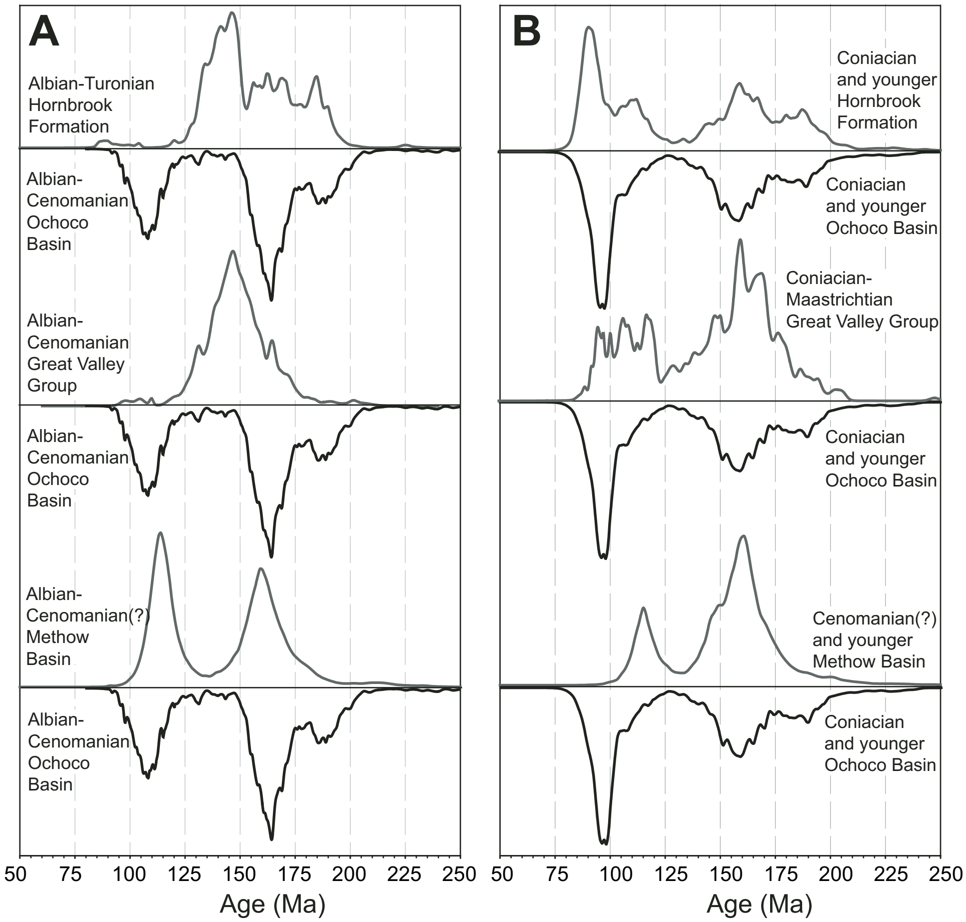

Figure 11. (A) Comparison of composite U-Pb relative probability curve for the Albian–Cenomanian Ochoco basin (downward-facing curves) with the Albian–Turonian Hornbrook Formation, Albian–Cenomanian Great Valley Group, and Albian–Cenomanian(?) Methow basin. (B) Comparison of composite U-Pb relative probability curve for the Coniacian and younger Ochoco basin (downward-facing curves) with the Coniacian and younger Hornbrook Formation, Coniacian–Maastrichtian Great Valley Group, and Cenomanian(?) and younger Methow basin. Hornbrook Formation data are from Surpless and Beverly (2013) and Surpless (2015); Great Valley Group data are from DeGraaff-Surpless et al. (2002), Surpless and Augsburger (2009), and Surpless (2014); Methow basin data are from DeGraaff-Surpless et al. (2003) and Surpless et al. (2014).

Cretaceous detrital-zircon age peaks, but it lacks the abundant Late Cretaceous grains that characterize the Hornbrook and Ochoco basin strata. A Cenomanian–Coniacian drainage divide along the axis of the Cretaceous Cordilleran arc may have prevented westward transport of Late Cretaceous zircon from the eastern Sierra into the Great Valley forearc region (DeGraaff-Surpless et al., 2002; Sharman et al., 2015), and relatively little Late Cretaceous zircon eroded from the western Idaho region may have traveled as far south as the Great Valley Group. Following Surpless (2015), we infer that some of the detritus eroded from the Late Cretaceous rocks of the Sierran Crest intrusive suite and/or coeval plutons in the northern Sierra Nevada may have been transported northward and westward into the combined Hornbrook-Ochoco basin, while detritus eroded from the western Idaho shear zone and early phases of the Idaho batholith were transported southward into the basin.

The Cenomanian(?) and younger Methow basin also includes a Middle to Late Jurassic age mode that is typical of the Ochoco basin, but it completely lacks the Late Cretaceous grains found in the Coniacian and younger Hornbrook and Ochoco basins, and it has few of the Early Jurassic grains that characterize the Coniacian and younger Ochoco and Hornbrook strata. The Methow strata also record a prominent 115 Ma age mode that is nearly absent in Coniacian and younger Ochoco strata (Fig. 11B). These data suggest that the Methow basin was not a northern continuation of the combined Hornbrook-Ochoco basin, but it remained a separate system with more local sources than the other basins. This interpretation is supported by the near-complete lack of pre-Mesozoic zircon in the Cretaceous Methow basin (1%), the consistency of detrital-zircon age distributions throughout Cretaceous deposition in the Methow basin, east- or west-directed deposition in the Cretaceous Methow strata, and Methow sandstone compositions that plot within basin uplift and transitional arc fields (Surpless et al., 2014). Although the Methow and Hornbrook-Ochoco basins may have shared some similar Jurassic and Early Cretaceous sources, our results indicate that they were not part of the same depositional system.

Tectonic Implications

Ochoco basin provenance analysis suggests sediment sources in the Blue Mountains terranes, western Idaho shear zone, and early phases of the Idaho batholith, which would have been north and northeast of the basin during Late Cretaceous deposition. Additional sediment may have been derived from sources in northwestern Nevada and the northern Sierra Nevada, as well as terranes in southern Canada and northern Washington. Additionally, both the Ochoco and Hornbrook basins record an influx of Late Cretaceous zircon with highly variable ε_{Hf} values, indicating similar sources for both regions, with source rocks that span the boundary between accreted terranes and the North American continent. Based on these observations, we prefer a tectonic reconstruction similar to the Wyld et al. (2006) minimum-offset model, which places the combined Hornbrook-Ochoco basin less than 400 km south of its current location relative to the North American craton, and closely juxtaposes all potential source regions (Fig. 12).

Beginning in Albian time, subsidence in the Hornbrook-Ochoco region resulted in fluvial-deltaic to outer-shelf deposits on the southwest side (Albian–Cenomanian Hornbrook Formation) and fluvial, marginal-marine, and basin-plain deposits on the northeast side of the basin (Albian–Cenomanian Ochoco basin), with proximal sediment sources largely in the Klamath Mountains and northern Sierran terranes (Albian–Cenomanian Hornbrook Formation; Surpless and Beverly, 2013; Surpless, 2015) and Blue Mountains and western Idaho (Albian–Cenomanian Ochoco basin; this study). Syndepositional deformation recorded by transpression in the western Idaho shear zone at 105–90 Ma (e.g., Giorgis et al., 2005) and development of the Toney Butte anticline within the Mitchell inlier (Dorsey and Lenegan, 2007) may have led to erosion of some basin strata, resulting in localized to regional unconformity (cf. Wheeler, 1981; Surpless and Beverly, 2013). Beginning as early as Coniacian time, an influx of submarine-fan deposits with both proximal and distal sources required a large, integrated source region for the Hornbrook-Ochoco basin that included the 100–85 Ma Idaho batholith (cf. Gaschnig et al., 2016) and possibly northeastern Sierran batholith, Blue Mountains, and possibly Klamath terranes and the southern Intermontane terrane, Omineca belt, and Coast Mountains batholith. Late Cretaceous subsidence within the Hornbrook-Ochoco and Great Valley basins may have resulted in a large, single forearc basin beginning in Coniacian to Santonian time, because the similar provenance in Coniacian and younger strata of all three basins (Fig. 10B) suggests similar sources but does not require a single depositional basin. These basins were not likely connected with the Methow basin to the north, which may have shared some similar sources with the Hornbrook-Ochoco basin, but which has distinct provenance indicators.

Based on paleomagnetic results from Mitchell inlier strata, Housen and Dorsey (2005) offered three alternative paleogeographic models. In their preferred model, Cretaceous strata of the Mitchell inlier form part of a large Hornbrook-Ochoco basin deposited 1200–1700 km south of its current location on the Blue Mountains and Klamath terranes, which in turn are linked to the Intermontane superterrane and the Sierra Nevada block (Housen and Dorsey, 2005). This model requires that the Sierra Nevada arc was translated ~700 km northward relative to the North American craton after Late Cretaceous deposition of the Mitchell inlier strata, with the Klamath Mountains and Blue Mountains terranes continuing north another 500–1000 km (Housen and Dorsey, 2005). Dorsey and Lenegan (2007) argued that the compositional mismatch between primarily chert, low-grade metavolcanic, and plutonic clasts in the Gable Creek conglomerate of the Mitchell inlier and high-grade metamorphic rocks in western Idaho precludes a western Idaho source for Mitchell rocks and supports a southern position for the Ochoco basin and Blue Mountains Province. However, the data presented here suggest a mixed provenance for the Ochoco basin, with sediment sources in the Blue Mountains terranes and western Idaho sources, with possible additional sources in the Sierra Nevada, Black Rock terrane, and the North Cascades and southern Canada. High-grade metamorphic rocks currently exposed in the western Idaho shear zone were likely at much greater depth during Late Cretaceous time, with erosion of unmetamorphosed to low-grade metamorphosed arc rocks contributing to Ochoco basin sediment.

Our new depositional age constraints for the Mitchell inlier indicate a Coniacian maximum depositional age for much of the strata; Thompson et al. (1984) documented Albian through Campanian strata in the subsurface, indicating that Ochoco basin deposition continued through at least 83 Ma. Hornbrook Formation deposition continued into Maastrichtian time (72–66 Ma; Nilsen, 1984). Therefore, the proposed large-scale dextral fault system between the Sierra Nevada block and Blue Mountains–Klamath system with the overlying Hornbrook-Ochoco basin could have been active between 66 Ma and 54 Ma, i.e., the age of undisplaced Clarno volcanics that overlie Mitchell strata (Grommé et al., 1986; Bestland et al., 1999). Northward displacement of 1200–1700 km thus requires an average northward plate motion rate of 100–142 mm/yr relative to the North American plate. Moreover, the well-documented evolution of the Great Valley Group south of the Klamath Mountains and west of the Sierra Nevada (e.g., Dickinson and Rich, 1972; Mansfield, 1979; Ingersoll, 1979, 1983; Suchecki, 1984; Moxon, 1990; Williams, 1997; Constenius et al., 2000; Williams and Graham, 2013)

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Figure 12. Paleogeographic schematic for (A) Albian–Cenomanian, and (B) Coniacian–Campanian times showing inferred source regions and shorelines for the Ochoco, Hornbrook, and Great Valley basins. Following Wyld et al.'s (2006) reconstruction, Cenozoic Basin and Range extension, western California strike-slip faulting, and 37° of post-Cretaceous clockwise rotation of the Blue Mountains have been restored. We did not restore contraction and limited (~50 km) dextral displacement along the western Idaho shear zone that occurred during late Albian–Turonian (ca. 105–90 Ma) time. The extent of discontinuous mid- to Late Cretaceous magmatism (ca. 120–85 Ma) is based on the paleogeographic map of Van Buer et al. (2009), the possible extent of early Late Cretaceous Idaho batholith magmatism (Gaschnig et al., 2016), and 120–90 Ma plutons of western Idaho (Unruh et al., 2008) and the western Idaho shear zone (Manduca et al., 1993; Giorgis et al., 2008; Benford et al., 2010). Inferred location of the Cretaceous shoreline is after Surpless and Beverly (2013), Sharman et al. (2015), Surpless (2015), and this study.

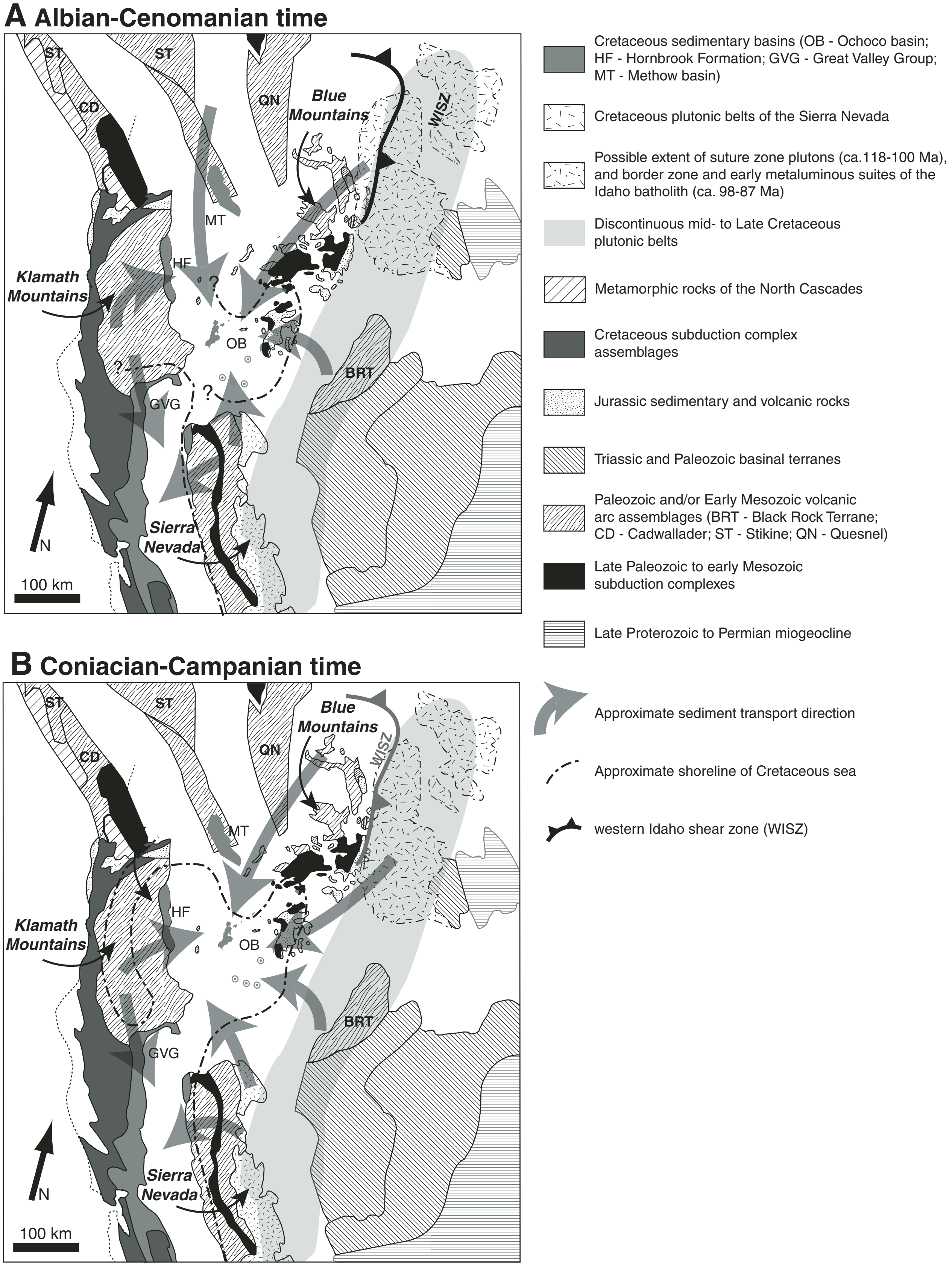
A Albian-Cenomanian time
ST
ST
CD
QN
Blue Mountains
WISZ
MT
HF
Klamath Mountains
?
OB
BRT
?
?
GVG
N
Sierra Nevada
100 km
B Coniacian-Campanian time
ST
ST
CD
QN
Blue Mountains
WISZ
MT
HF
Klamath Mountains
OB
BRT
GVG
N
Sierra Nevada
100 km
Cretaceous sedimentary basins (OB - Ochoco basin; HF - Hornbrook Formation; GVG - Great Valley Group; MT - Methow basin)
Cretaceous plutonic belts of the Sierra Nevada
Possible extent of suture zone plutons (ca.118-100 Ma), and border zone and early metaluminous suites of the Idaho batholith (ca. 98-87 Ma)
Discontinuous mid- to Late Cretaceous plutonic belts
Metamorphic rocks of the North Cascades
Cretaceous subduction complex assemblages
Jurassic sedimentary and volcanic rocks
Triassic and Paleozoic basinal terranes
Paleozoic and/or Early Mesozoic volcanic arc assemblages (BRT - Black Rock Terrane; CD - Cadwallader; ST - Stikine; QN - Quesnel)
Late Paleozoic to early Mesozoic subduction complexes
Late Proterozoic to Permian miogeocline
Approximate sediment transport direction
Approximate shoreline of Cretaceous sea
western Idaho shear zone (WISZ)

Figure 12.

would require complete reinterpretation to be consistent with the proposed paleogeography, as would proposed links between the Hornbrook-Ochoco and northern Great Valley basins (Kleinhans et al., 1984; Nilsen, 1986; Miller et al., 1992; Surpless and Beverly, 2013; this study).

In their second paleogeographic model, Housen and Dorsey (2005) considered that the Ochoco and Hornbrook basins rest on a sliver of forearc crust distinct from the rest of the Blue Mountains terranes, Klamath terranes, and Sierra Nevada. Only this crustal segment would have been 1200–1700 km south during Ochoco deposition, and it then translated northward along a fault boundary separating it from central and eastern parts of the Blue Mountains (Housen and Dorsey, 2005). However, more easterly Cretaceous sedimentary inliers can be confidently correlated with Mitchell strata (Dickinson and Thayer, 1978; Dickinson et al., 1979; Kleinhans et al., 1984; Little, 1986; this study), and our study provides evidence of source regions within the Blue Mountains terranes and western Idaho. Furthermore, numerous studies of the Blue Mountains terranes demonstrate that they were stitched together by Late Jurassic or Early Cretaceous time (e.g., Brooks and Vallier, 1978; Avé Lallemant, 1995), well before deposition of Ochoco strata.

In their third paleogeographic model, Housen and Dorsey (2005) attributed much of the paleomagnetic inclination anomaly to the effects of inclination error, placing the Ochoco basin and Blue Mountains terranes close to their present locations. Although Housen and Dorsey (2005) argued that their data do not support this interpretation, they noted that inclination errors of 9°–12° have been proposed for similar rocks (Butler et al., 2001; Kim and Kodama, 2004). An inclination error for the Mitchell inlier of ~9°–12° would place the Ochoco basin and Blue Mountains terranes within 500 km of their present locations, consistent with paleogeographic models of Wyld and Wright (2001), Wyld et al. (2006), LaMaskin et al. (2011), and this study. Preliminary results of recent paleomagnetic analysis of Mitchell inlier rocks indicate that the inclination error may indeed be greater than originally interpreted (Callebert et al., 2016).

In our preferred paleogeographic model, deposition of the combined Hornbrook-Ochoco basin occurred up to 400 km south of its present location relative to the North American craton (Fig. 12), and its strata record tectonic changes related to reorganization of the plate margin during early Late Cretaceous time, including dextral transpression along the western Idaho shear zone during basin deposition. The Late Cretaceous change from nearly head-on convergence to oblique transpression between the Farallon and North American plates (Page and Engebretson, 1984; Liu et al., 2008) likely triggered large-scale effects throughout Cordilleran arc-forearc systems. Pre–100 Ma convergence of 5 cm/yr normal to the margin increased to 9 cm/yr from 100 to 85 Ma (Page and Engebretson, 1984), and convergence vectors shifted 38° counterclockwise from 100 to 90 Ma (Liu et al., 2008). In western Idaho, transpression of the western Idaho shear zone from 105 to 90 Ma was nearly synchronous with emplacement of the 100–85 Ma calc-alkaline magmatic flare-up of the Idaho batholith (Gaschnig et al., 2016). Gaschnig et al. (2016) concluded that erosion was a primary mechanism for removal of large parts of the 100–85 Ma Idaho arc and suggested that significant detritus would be expected in basins east and west of the arc. In the eastern Sierra, shear zones developed contemporaneously with voluminous magmatism associated with the mid-Late Cretaceous magmatic flare-up (peak 98.5 ± 8.5 Ma; Glazner, 1991; Tobisch et al., 1995; Tikoff and Greene, 1997). DeCelles (2004) linked voluminous mid- to Late Cretaceous magmatism in the Sierra Nevada batholith with shortening in the Sevier thrust belt and development of an elevated Nevadaplano. Thermochronology indicates exhumation and erosional denudation of the northern Sierra Nevada from 90 to 60 Ma, as a result of earlier orogenic thickening of the crust and emplacement of the Late Cretaceous batholith (Cecil et al., 2006). In our preferred model, Late Cretaceous subsidence of the Hornbrook-Ochoco forearc region and the post–89 Ma influx of sediment from the 100–85 Ma magmatic flare-up in the Idaho and perhaps Sierran batholiths preserved a detrital record of these Late Cretaceous tectonic and magmatic events.

CONCLUSIONS

Our detailed provenance analysis of Cretaceous inliers in central and eastern Oregon permits recognition of a single, large Ochoco basin. Albian through Campanian depositional ages indicate that the Ochoco basin was largely Late Cretaceous, and provenance data are consistent with proximal sources in the Blue Mountains terranes, as well as the Salmon River suture zone, western Idaho shear zone, early Idaho batholith, and Cretaceous Sierran batholith. Our provenance results suggest that the Hornbrook Formation and Ochoco basin form two sides of the same depositional system, which may have been linked to the Great Valley Group to the south beginning in Santonian time. These results limit northward displacement of the Ochoco basin and Blue Mountains Province to less than 400 km, consistent with the minimum-offset model of Wyld et al. (2006). Coniacian and younger Ochoco basin strata may represent the destination of much of the "missing" Idaho arc (cf. Giorgis et al., 2005; Gaschnig et al., 2016) that was intruded and eroded during and following rapid transpression along the western Idaho shear zone from 105 to 90 Ma. Paleomagnetic analysis of Mitchell inlier strata suggests deposition 1200–1700 km farther south, but our revised depositional ages for Ochoco basin strata dramatically shorten the time available for northward translation, and our inferred Ochoco basin provenance and correlation with the Hornbrook Formation and Great Valley Group suggest that the anomalously shallow paleomagnetic inclinations may result from significant inclination error, rather than deposition at low latitudes. Our results demonstrate that detailed provenance analysis of forearc basin strata complements the incomplete record of arc magmatism and tectonics preserved in bedrock exposures and permits improved understanding of Late Cretaceous Cordilleran paleogeography.

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