Early Mesozoic paleogeography and tectonic evolution of the western United States: Insights from detrital zircon U-Pb geochronology, Blue Mountains Province, northeastern Oregon

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ABSTRACT

This study assesses early Mesozoic provenance linkages and paleogeographic-tectonic models for the western United States based on new petrographic and detrital zircon data from Triassic and Jurassic sandstones of the "Izee" and Olds Ferry terranes of the Blue Mountains Province, northeastern Oregon. Triassic sediments were likely derived from the Baker terrane offshore accretionary subduction complex and are dominated by Late Archean (ca. 2.7–2.5 Ga), Late Paleoproterozoic (ca. 2.2–1.6 Ga), and Paleozoic (ca. 380–255 Ma) detrital zircon grains. These detrital ages suggest that portions of the Baker terrane have a genetic affinity with other Cordilleran accretionary subduction complexes of the western United States, including those in the Northern Sierra and Eastern Klamath terranes. The abundance of Precambrian grains in detritus derived from an offshore complex highlights the importance of sediment reworking. Jurassic sediments are dominated by Mesozoic detrital ages (ca. 230–160 Ma), contain significant amounts of Paleozoic (ca. 290, 380–350, 480–415 Ma), Neoproterozoic (ca. 675–575 Ma), and Mesoproterozoic grains (ca. 1.4–1.0 Ga), and have lesser quantities of Late Paleoproterozoic grains (ca. 2.1–1.7 Ga). Detrital zircon ages in Jurassic sediments closely resemble well-documented age distributions in transcontinental sands of Ouachita-Appalachian provenance that were transported across the southwestern United States and modified by input from cratonal, miogeoclinal, and Cordilleran-arc sources during Triassic and Jurassic time. Jurassic sediments likely were derived from the Cordilleran arc and an orogenic highland in Nevada that yielded recycled sand from uplifted Triassic backarc basin deposits. Our data suggest that numerous Jurassic Cordilleran basins formed close to the Cordilleran margin and support a model for moderate post-Jurassic translation (~400 km) of the Blue Mountains Province.

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INTRODUCTION

There is significant controversy regarding the early Mesozoic paleogeography and tectonic evolution of allochthonous and parautochthonous terranes of the western U.S. Cordillera. Workers generally agree that Cordilleran terranes represent oceanic and craton-fringing crustal fragments that were accreted to western Laurentia prior to development of an integrated Andean-type convergent margin in Cretaceous time; however, the configuration and construction of the "pre-Andean" western Laurentian margin remain debated. Numerous contrasting tectonic models have been proposed to explain early Mesozoic development of the continental-margin arc in Arizona-California and marginal arc-basin complexes of the Sierra Nevada foothills and Klamath Mountains (Fig. 1; e.g., Harper and Wright, 1984; Ingersoll and Schweickert, 1986; Burchfiel et al., 1992; Saleeby, 1992; Saleeby and Busby-Spera, 1992; Dickinson, 2000, 2008; Dickinson et al., 1996; Day and Bickford, 2004; Gray and Oldow, 2005; Snoke, 2005; Ernst et al., 2008), and the Blue Mountains Province (Dickinson, 1979, 2000; Burchfiel et al., 1992; Saleeby, 1992; Saleeby and Busby-Spera, 1992; Avé Lallemant, 1995; Vallier, 1995; Dorsey and LaMaskin, 2007, 2008). This proliferation of models reflects, in part, insufficient constraints on provenance links to North America, the early Mesozoic latitude of marginal arc-basin complexes, and the amount of subsequent post-Jurassic margin-parallel displacement.

Accreted terranes of the Blue Mountains Province in northeastern Oregon and western Idaho preserve one of the most complete and least-deformed early Mesozoic stratigraphic records in the western U.S. Cordillera (Fig. 1; see stratigraphic compilations *in* Saleeby and Busby-Spera, 1992). Marine deposition took place in this region from Late Triassic through early Late Jurassic time, preserving a record of terrane and marginal-basin evolution (Dickinson and Vigrass, 1965; Dickinson and Thayer, 1978; Dickinson, 1979; Vallier, 1995; Dorsey and LaMaskin, 2007, 2008; LaMaskin et al., 2008a). In this paper, we use petrographic and detrital zircon U-Pb age data from Triassic and Jurassic Cordilleran margin sedimentary basins of the Blue Mountains Province in Oregon to assess potential linkages to cratonal North America and place new constraints on tectonic and paleogeographic models for the western United States (Fig. 2). Our objectives are to (1) test and refine existing correlations of early Mesozoic sedimentary successions from eastern Oregon to western Idaho, (2) document the evolution of sediment source areas through time, (3) evaluate paleogeographic and paleotectonic models for the Blue Mountains, and (4) assess the implications of our results for the pre-Cretaceous configuration of the western Laurentian margin.

In the John Day region of northeastern Oregon, sediment is interpreted to have been derived from both *outboard* subduction-accretionary complexes and *inboard* volcanic-dominated

GSA Bulletin; September/October 2011; v. 123; no. 9/10; p. 1939–1965; doi: 10.1130/B30260.1; 15 figures; 3 tables; Data Repository item 2011188.

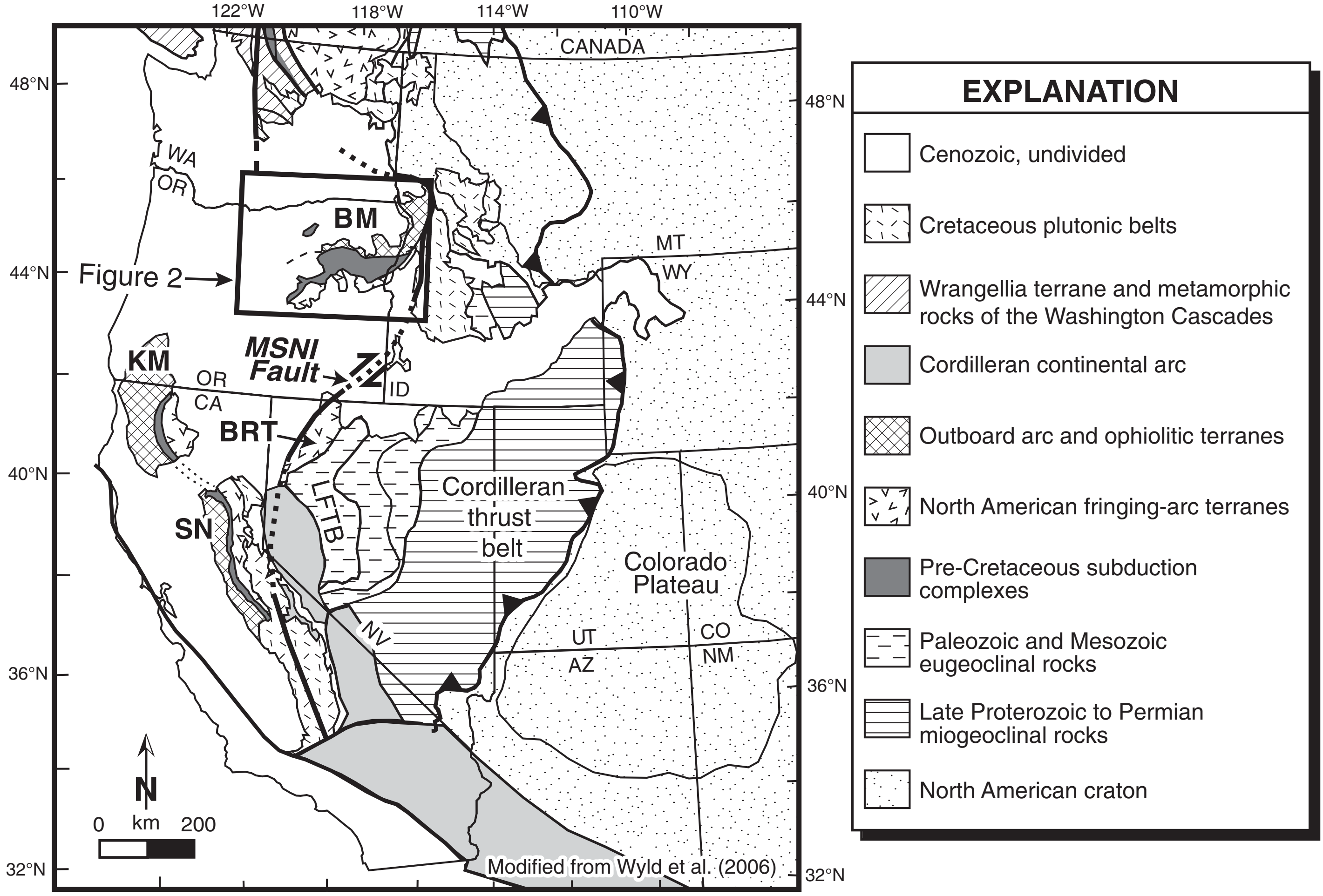

Figure 1. Simplified pre-Tertiary geology of the western United States, modified from Wyld et al. (2006). BM—Blue Mountains Province; BRT—Black Rock terrane; KM—Klamath Mountains; SN—Sierra Nevada; MSNI—Mojave–Snow Lake–Nevada–Idaho fault (after Wyld and Wright, 2005); LFTB—Luning-Fencemaker thrust belt.

sources (Dickinson and Thayer, 1978; Dickinson, 1979; Dickinson et al., 1979). This sandstone provenance framework provides important constraints for understanding detrital zircon age distributions in the same deposits. Our new detrital zircon data are consistent with—and provide new insights into—previously documented shifts in sandstone composition from Late Triassic to early Late Jurassic time (e.g., Dickinson, 1979; Dickinson et al., 1979). In particular, these data suggest that Jurassic basins of the Blue Mountains Province were linked to a large, Triassic–Jurassic transcontinental sediment-dispersal system (i.e., Rahl et al., 2003; Dickinson and Gehrels, 2003; 2009), either directly or via tectonic and sedimentary recycling.

The presence of Laurentian detrital zircon grains in sediments of the Blue Mountains Province has implications for the proximity of

Figure 2 (*on following page*). Geologic map of the Blue Mountains Province, modified from LaMaskin (2009). Ages of plutons are shown where data are available; z—U-Pb zircon age; K-Ar—potassium-argon age. Question marks indicate uncertain terrane affiliations and/or terrane boundary locations. The Bourne and Greenhorn subterranes, Grindstone terrane, and Burnt River Schist are here considered subterrane-level units of the Baker terrane. Pz—Paleozoic; Mz—Mesozoic; Tr—Triassic; Jr—Jurassic; K—Cretaceous; MS—megasequence (after Dorsey and LaMaskin, 2007); BRS—Burnt River Schist; BMB—Bald Mountain batholith; WB—Wallowa batholith; PCF—Poison Creek fault; Cpx.—complex; Ldg.—landing; WA—Washington; OR—Oregon; ID—Idaho. Data were compiled from numerous sources, including Dickinson and Vigrass (1965); Brown and Thayer (1966, 1977); Thayer and Brown (1966); Hendricksen et al. (1972); Brooks et al. (1976); Dickinson and Thayer (1978); Brooks (1979); Walker and MacLeod (1991); Walker (1986, 1995); Vallier (1995, 1998); Ashley (1995); Ferns and Brooks (1995); Leeman et al. (1995); Ferns et al. (2001); Lewis (2002); Lund (2004); Kays et al. (2006); Dorsey and LaMaskin (2007); Mann and Vallier (2007); Parker et al. (2008); Unruh et al. (2008); J. Schwartz (personal commun., 2009), and K. Johnson (personal commun., 2009).

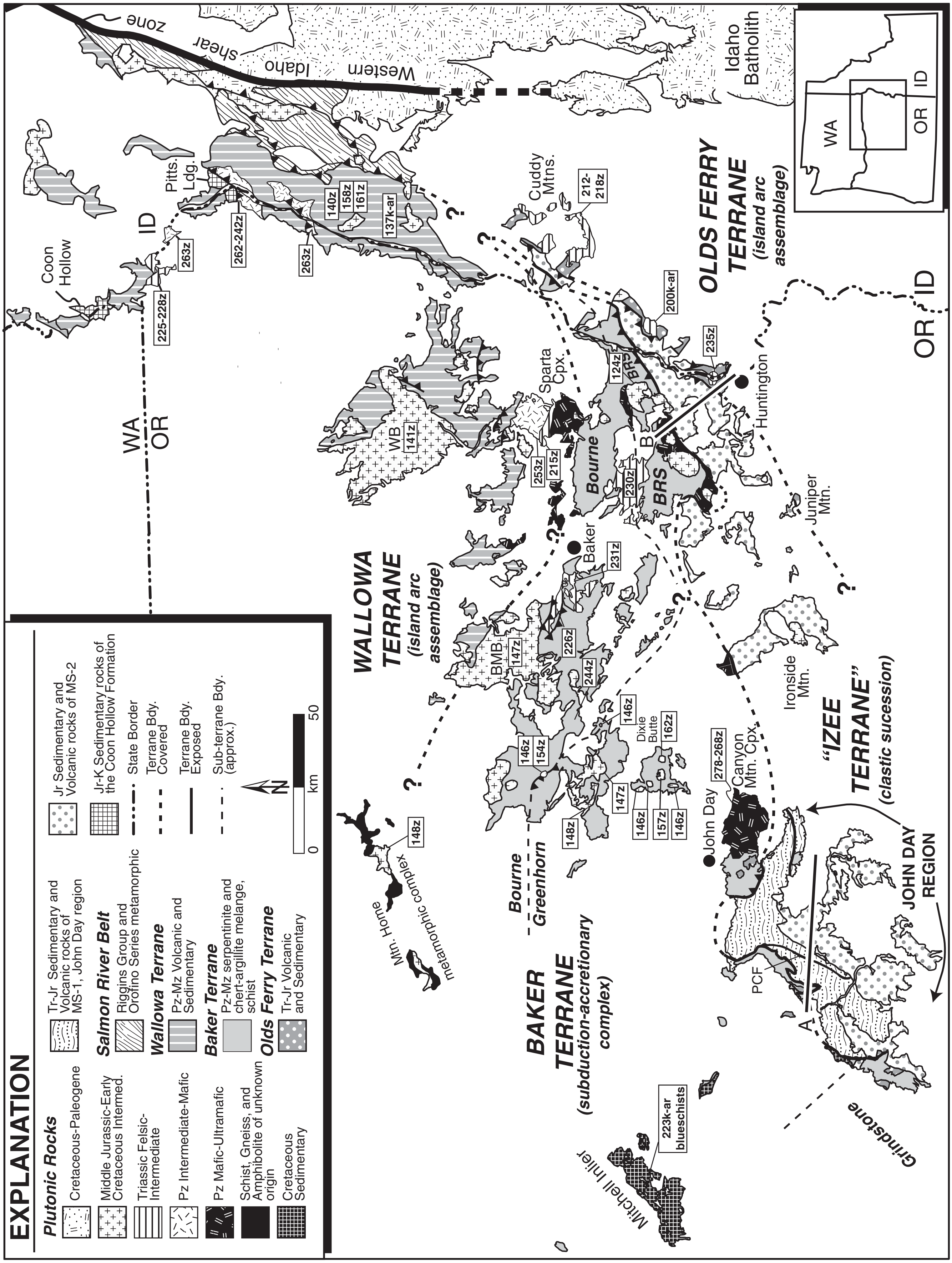
EXPLANATION
Plutonic Rocks
Cretaceous-Paleogene
Middle Jurassic-Early Cretaceous Intermed.
Triassic Felsic-Intermediate
Pz Intermediate-Mafic
Pz Mafic-Ultramafic
Schist, Gneiss, and Amphibolite of unknown origin
Cretaceous Sedimentary
Tr-Jr Sedimentary and Volcanic rocks of MS-1, John Day region
Salmon River Belt
Riggins Group and Orofino Series metamorphic
Wallowa Terrane
Pz-Mz Volcanic and Sedimentary
Baker Terrane
Pz-Mz serpentinite and chert-argillite melange, schist
Olds Ferry Terrane
Tr-Jr Volcanic and Sedimentary
Jr Sedimentary and Volcanic rocks of MS-2
Jr-K Sedimentary rocks of the Coon Hollow Formation
State Border
Terrane Bdy. Covered
Terrane Bdy. Exposed
Sub-terrane Bdy. (approx.)
N
0
50
km
WALLOWA TERRANE
(island arc assemblage)
BAKER TERRANE
(subduction-accretionary complex)
OLDS FERRY TERRANE
(island arc assemblage)
"IZEE TERRANE"
(clastic sucession)
JOHN DAY REGION
Western Idaho shear zone
Idaho Batholith
WA
OR
ID
Coon Hollow
Pitts. Ldg.
Cuddy Mtns.
Sparta Cpx.
Bourne
Greenhorn
BRS
B
Huntington
Baker
Juniper Mtn.
Ironside Mtn.
Dixie Butte
Canyon Mtn. Cpx.
John Day
Mtn. Home metamorphic complex
Mitchell Inlier
Grindstone
PCF
A
WB
BMB
225-228z
263z
262-242z
140z
158z
161z
137k-ar
212-218z
200k-ar
235z
124z
141z
253z
215z
230z
231z
226z
147z
244z
146z
154z
162z
148z
157z
278-268z
223k-ar blueschists

Figure 2.

so-called "allochthonous" Cordilleran basins to the North American craton. In addition, our results highlight the complexities of matching detrital zircon data to potential source regions and illustrate the importance of sedimentologic and stratigraphic setting for making reliable interpretations.

GEOLOGIC SETTING

Regional Geology

The Blue Mountains Province in Oregon, Idaho, and Washington (Fig. 2) is an assemblage of variably metamorphosed accreted terranes that are situated in a key position between coeval accreted terranes of California, Nevada and southern British Columbia (Hamilton, 1963; Armstrong et al., 1977; Vallier, 1977, 1995; Dickinson and Thayer, 1978; Brooks and Vallier, 1978). It has been divided into two late Paleozoic to early Mesozoic volcanic island-arc assemblages (the Wallowa and Olds Ferry terranes), a Paleozoic to early Mesozoic subduction-accretionary complex (Baker terrane), and a Triassic–Jurassic clastic sedimentary succession (Izee terrane; Silberling et al., 1984). Rocks of all four terranes appear to have been affected by Late Jurassic deformation (Avé Lallemant, 1995), and terrane-bounding faults are crosscut by Late Jurassic to Early Cretaceous granodioritic plutons that indicate terrane amalgamation prior to ca. 144 Ma (Fig. 2; Walker, 1986, 1989). Faunal data suggest that during Late Triassic time, rocks of the Blue Mountains Province, which originated in an eastern Pacific, Central Tethyan location, were transported northward to Northern Tethyan latitudes by Early Jurassic time, and to boreal latitudes by Middle Jurassic time (Pessagno and Blome, 1986; Pessagno, 2006). Although we retain the conventional terminology for terranes in the Blue Mountains Province, some of these tectonostratigraphic units do not have entirely distinct origins and are, to varying degrees, genetically related (cf. Dorsey and LaMaskin, 2007, 2008; Dickinson, 2008; LaMaskin et al., 2008a; Schwartz et al., 2010).

The upper Paleozoic to lower Mesozoic Wallowa terrane is an intra-oceanic volcanic arc succession that occupies the most outboard position in the Blue Mountains Province (Fig. 2; Vallier, 1977, 1995; Walker, 1986, 1995; LaMaskin et al., 2008a). It has been correlated to either the Wrangellia terrane (Wernicke and Klepacki, 1988; Dickinson, 2004) or the Stikine terrane in British Columbia (Mortimer, 1986; Oldow et al., 1989; Yancey and Stanley, 1999). The Upper Triassic to Lower Jurassic Olds Ferry terrane is a volcanic arc succession that occupies the most inboard position in the Blue Mountains Province (Brooks and Vallier, 1978; Brooks, 1979; Vallier, 1995; Walker, 1995; Tumpane et al., 2008; Tumpane and Schmitz, 2009; LaMaskin, 2008). The Olds Ferry terrane has been correlated with the Quesnel terrane in British Columbia (Dickinson, 2004) and the Black Rock terrane in Nevada (Wyld and Wright, 2001; Dorsey and LaMaskin, 2007) and likely represents a Japan-type, continent-fringing volcanic arc (LaMaskin et al., 2008a). Permian plutonic rocks (ca. 286–268 Ma) of the Canyon Mountain complex and Aldrich Mountains of central Oregon may represent exhumed forearc crust of the Olds Ferry arc (e.g., Avé Lallemant, 1995), or these rocks may be more appropriately grouped with the Baker terrane.

The Baker terrane accretionary subduction complex (Fig. 2) is situated between the Wallowa and Olds Ferry terranes and includes both island-arc and oceanic-related sedimentary, volcanic, and plutonic rocks (Carpenter and Walker, 1992; Hotz et al., 1977; Bishop, 1995a, 1995b; Ferns and Brooks, 1995; Leeman et al., 1995; Vallier, 1995). Sedimentary units in the Baker terrane include variably deformed Devonian through Triassic clastic and carbonate successions with minor occurrences of Jurassic strata (Jones et al., 1976; Coward, 1983; Morris and Wardlaw, 1986; Blome and Nestell, 1991; and references therein). Regionally, portions of the Baker terrane have been interpreted to represent a disrupted forearc region (Greenhorn subterrane) and an associated oceanward accretionary prism (Bourne subterrane; Ferns and Brooks, 1995; Schwartz et al., 2010). The Baker terrane is widely considered to be correlative to similar rocks of the Cache Creek terrane in British Columbia and the Eastern Hayfork and Stuart Fork terranes and Central metamorphic belt in the Klamath Mountains (Saleeby, 1983; Miller, 1987; Oldow et al., 1989; Hacker and Goodge, 1990; Burchfiel et al., 1992; Wyld et al., 2006; Kays et al., 2006).

The Izee terrane, as traditionally defined (Fig. 2), consists of (1) Triassic and Jurassic sedimentary rocks in central Oregon that rest depositionally on the Baker terrane, and (2) Jurassic deposits in eastern Oregon and western Idaho, which are thrust to the southeast over the Triassic and Jurassic Olds Ferry terrane (Brooks, 1979; Dickinson, 1979; Silberling et al., 1984; Tumpane, 2010). Correlation of Middle Jurassic rocks in the John Day region of Oregon with the Coon Hollow Formation in the Wallowa terrane (Pessagno and Blome, 1986; White et al., 1992) has led workers to interpret a stratigraphic overlap assemblage that linked the Blue Mountain terranes by Early to Middle Jurassic time (i.e., Pessagno and Blome, 1986; White et al., 1992; Dorsey and LaMaskin, 2007, 2008; LaMaskin et al., 2008a).

Rocks of the Blue Mountains Province are overthrust in the northeast by high-grade metamorphic rocks of the Salmon River belt (Lund and Snee, 1988; Selverstone et al., 1992; Manduca et al., 1992, 1993; Lund, 2004; Gray and Oldow, 2005; Lund et al., 2008). The Salmon River belt is bounded on the east by the Western Idaho shear zone (Fig. 1), a complex structural boundary with the Laurentian continental margin. The Western Idaho shear zone is overprinted by Late Cretaceous to Early Tertiary plutons that define an anomalously sharp discontinuity between accreted oceanic and continental lithosphere (Lund and Snee, 1988; Getty et al., 1993; Manduca et al., 1992, 1993; McClelland et al., 2000; Tikoff et al., 2001; Selverstone et al., 1992; Giorgis et al., 2005, 2008).

It has been postulated that during Early(?) to Late Cretaceous time, northward translation of the Blue Mountains Province was accommodated by various amounts of dextral-transpressive shear along the Western Idaho shear zone. Restoration of <100 km of displacement (e.g., Saleeby and Busby-Spera, 1992; McClelland et al., 1992; Dickinson, 2004, 2006; Gray and Oldow, 2005) suggests that during pre-Cretaceous time, the Blue Mountains Province was located outboard of a cryptic continental margin, the history of which has been obscured by pluton emplacement and Cretaceous shortening in the Salmon River belt and Western Idaho shear zone. Alternatively, restoration of ~400 km of dextral displacement (e.g., Wyld and Wright, 2001; Wright and Wyld, 2007) juxtaposes the Blue Mountains Province with the Triassic Cordilleran fringing arc in western Nevada (Black Rock terrane), which was separated from the continent by an extensional backarc basin (Speed, 1978; Oldow, 1984; Oldow et al., 1989; Smith et al., 1993; Wyld, 2000, 2002). Closure of the backarc basin in Jurassic time resulted in accretion of the fringing arc, crustal shortening and thickening, and development of a Jurassic orogenic belt in western and central Nevada (Luning-Fencemaker fold-and-thrust belt; Speed, 1978; Oldow et al., 1989; Wyld, 2002; Wyld et al., 2003). According to a third hypothesis, restoration of >1000 km of displacement (e.g., Housen and Dorsey, 2005, post–94 Ma) places the Blue Mountains Province at the approximate latitude of southwestern Arizona and northern Mexico as an offshore arc of uncertain relationship to the Triassic–Jurassic continental magmatic arc (Saleeby and Busby-Spera, 1992; Dickinson and Lawton, 2001). Detrital zircon data presented here serve as a partial test of these different proposed reconstructions.

Early Mesozoic Stratigraphy and Structure of Northeastern Oregon and Western Idaho

Megasequence Stratigraphy

We divide the early Mesozoic sedimentary succession of northeastern Oregon and western Idaho into two regionally correlative, unconformity-bound megasequences, megasequence 1 and megasequence 2 (Figs. 3 and 4; Dorsey and LaMaskin, 2007, 2008; LaMaskin et al., 2008a, 2009). A megasequence is a large-scale, composite stratal unit (hundreds to thousands of meters thick and tens of millions of years in duration) that accumulates during a distinct phase of basin evolution. Boundaries between megasequences typically form due to changes in tectonic boundary conditions that control basin development (e.g., Phinney et al., 1999). They differ from traditional stratigraphic "sequences" (cf. Vail et al., 1977; Van Wagoner et al., 1990) by being thicker, longer-duration, composite units bounded by angular unconformities that record major changes in regional tectonic setting.

John Day Region

Early Mesozoic sedimentary rocks are traditionally assigned to the "Izee terrane" in the John Day region of northeastern Oregon. Here, early Mesozoic rocks are found in depositional

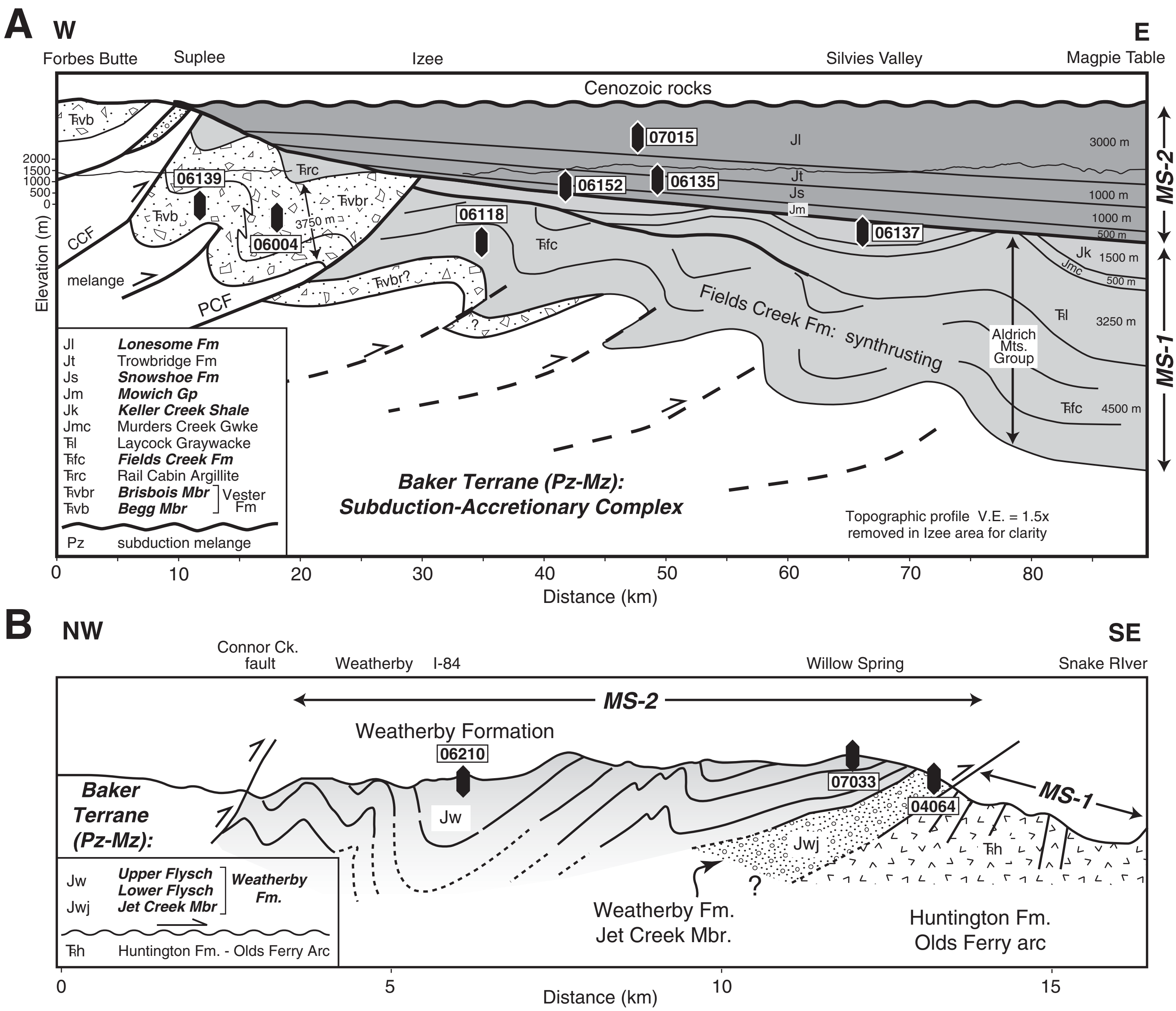

Figure 3. Schematic cross sections of Mesozoic rocks in the John Day and Huntington, Oregon, areas prior to Late Jurassic deformation. Lines of section are shown on Figure 2. Black zircon crystals and sample numbers indicate approximate detrital zircon sample locations. Formation names in bold italics (lower left insets) indicate sampled intervals. MS—megasequence. (A) Stratigraphic-structural reconstruction of John Day region modified from Dorsey and LaMaskin (2007). Image is projected into E-W line of section using maps and data from Dickinson and Thayer (1978), Dickinson and Vigrass (1965), and Brown and Thayer (1966). CCF—Camp Creek fault; PCF—Poison Creek fault. (B) NW-SE cross section of Huntington, Oregon, area modified from Avé Lallemant (1983).

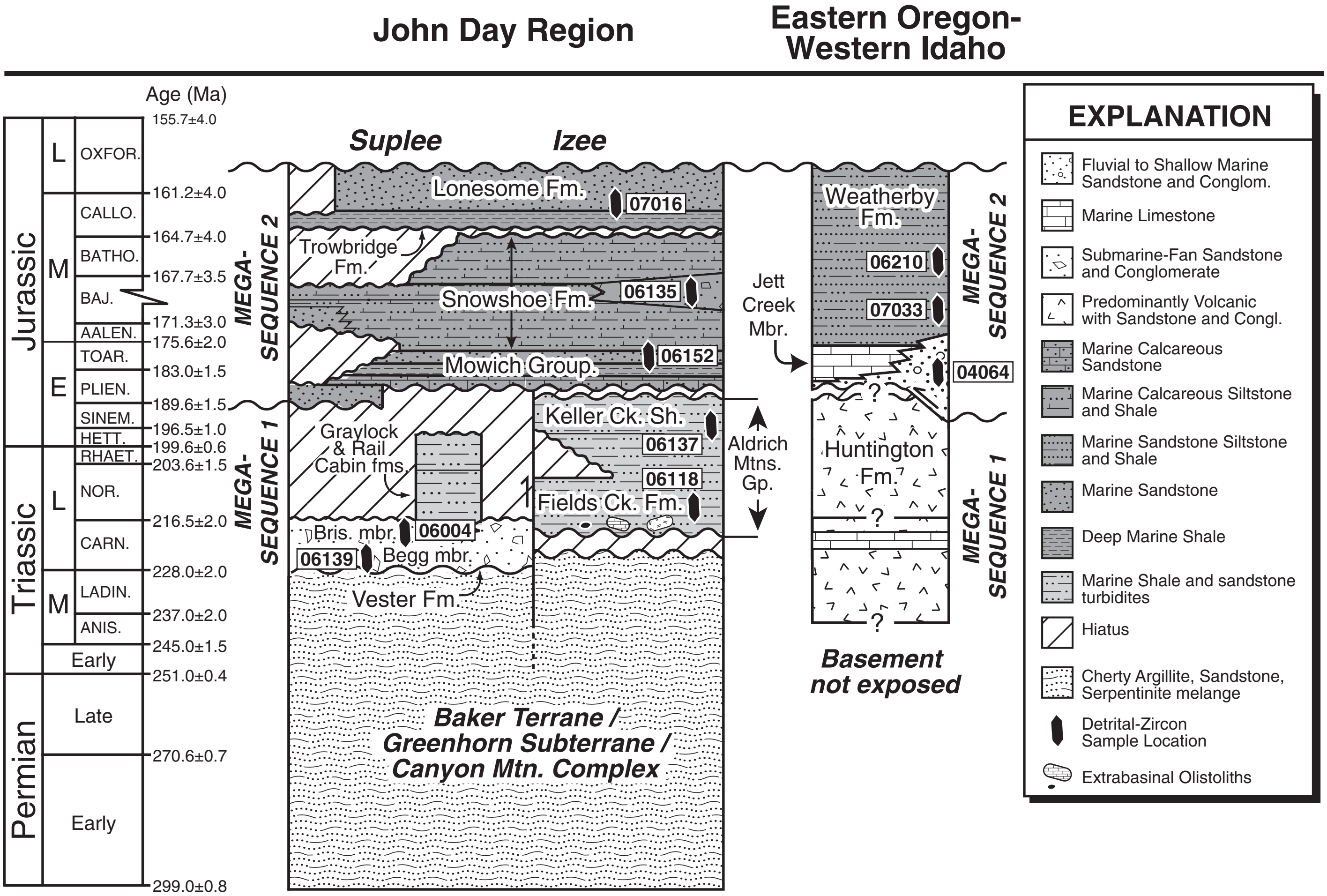

Figure 4. Sample locations (zircon crystal shapes) plotted on a chronostratigraphic correlation chart for sedimentary and volcanic rocks in the Blue Mountains. Bris.—Brisbois; mbr.—Member; Ck.—creek; Gp.—group. Figure is modified from Dorsey and LaMaskin (2007). See Dorsey and LaMaskin (2007) for additional data sources.

and fault contact with disrupted Paleozoic to Mesozoic basement of the Baker terrane, including intrusive rocks of the Canyon Mountain Complex (Figs. 3A and 4; Dickinson and Vigrass, 1965; Brown and Thayer, 1977; Dickinson and Thayer, 1978; Dickinson, 1979).

Megasequence 1. Rocks of megasequence 1 include: (1) the Vester Formation (~3750 m), which consists of chert-rich conglomerate and turbiditic sandstone with lesser amounts of black shale, polymict breccia, and local volcanic rocks (Dickinson and Vigrass, 1965; Brown and Thayer, 1977; Dickinson and Thayer, 1978); (2) the Fields Creek Formation (~4500 m), which is the lower portion of the Aldrich Mountains Group and represents a turbiditic succession of fine sandstone and black shale with large chaotic slide breccias and olistostromes at the base (Brown and Thayer, 1977; Dickinson and Thayer, 1978); and (3) the Keller Creek Shale (~1500 m), which includes black shale and volcaniclastic "graywacke" sandstone (Brown and Thayer, 1977).

The Middle (?) to Late Triassic Vester and Fields Creek Formations of megasequence 1 were derived from the Baker terrane (an *outboard* source) as indicated by the presence of (1) voluminous reworked chert clasts with radiolaria that match Baker terrane faunas, (2) olistostromes that match the lithologies of plutons and sedimentary units in the Baker terrane located to the northwest, and (3) abundant southeast-directed paleocurrent data (modern coordinates; Dickinson and Thayer, 1978; Dickinson, 1979; Blome et al., 1986; Yeh, 1989; Blome and Nestell, 1991; Carpenter and Walker, 1992). Late Triassic uplift and erosion of the Baker terrane that caused chert-rich detritus to be shed eastward into a large syntectonic basin in the John Day region may have been caused by localized back thrusting (Dickinson, 1979), nascent arc-arc collision between the Wallowa and Olds Ferry arcs (Dorsey and LaMaskin, 2007, 2008), or from collisional events involving other crustal blocks within the Baker terrane that currently are not well understood.

Rocks of megasequence 1 record marine deposition in actively deforming, convergent fault-bounded basins (Brown and Thayer, 1977; Dickinson and Thayer, 1978; Dickinson, 1979). Late Triassic to Early Jurassic syndepositional deformation (D_1 of Avé Lallemant, 1995) is recorded by north-northeast–trending faults and folds (modern coordinates) associated with cannibalization of older deposits. Deformed Late Triassic to Early Jurassic megasequence 1 rocks in the John Day region are overlain by less-deformed Lower Jurassic shallow-marine deposits of megasequence 2 (Dickinson and Vigrass, 1965; Brown and Thayer, 1977; Dickinson and Thayer, 1978; Dickinson, 1979; Avé Lallemant, 1995; Dorsey and LaMaskin, 2007).

Megasequence 2. Deposits of megasequence 2 overlie Triassic to Early Jurassic rocks and structures along an angular unconformity, and they are not affected by the first major deformation episode in the area (D_1 of Avé Lallemant, 1995). Megasequence 2 begins with ~2500 m of Lower and Middle Jurassic volcaniclastic sedimentary and minor volcanic rocks of the Mowich Group and Snowshoe Formation (Figs. 3A and 4). These deposits record Jurassic transgression from ca. 190 to 161 Ma, concluding with deposition of black shales of the Trowbridge Formation. The overlying Lonesome Formation records subsequent deposition of an ~3000-m-thick regressive sequence of sandy volcaniclastic turbidites that display a notable increase in metamorphic and sedimentary lithic fragments during Callovian time (Dickinson, 1979; Dickinson et al., 1979).

Deposits of megasequence 2 were previously interpreted to be derived from inboard sources, based in part on abundant west-northwest–directed paleocurrent indicators (Dickinson and Thayer, 1978; Dickinson, 1979; Dickinson et al., 1979). Strongly enriched trace-element geochemistry and unradiogenic Nd isotopic compositions (negative ε_{Nd} values) of megasequence 2 mudrocks support the idea that Middle to early Late Jurassic sediments in the John Day region received input from inboard continental sources (LaMaskin et al., 2008a, 2008b). Megasequence 2 deposits are variably deformed by Late Jurassic contractile folds and faults (D_2 of Avé Lallemant, 1995).

Eastern Oregon–Western Idaho

Megasequence 1. In eastern Oregon and western Idaho, Triassic through Lower Jurassic volcanic and volcaniclastic rocks of the Olds Ferry terrane comprise megasequence 1 (locally the Huntington Formation; Avé Lallemant, 1983, 1995; Brooks et al., 1976; Brooks, 1979; Payne and Northrup, 2003; San Filippo, 2006; Dorsey and LaMaskin, 2007; LaMaskin, 2008; Tumpane et al., 2008; Tumpane and Schmitz, 2009). These rocks are overlain along a poorly understood unconformity and SE-vergent shear zone by megasequence 2 sedimentary rocks of the Lower to Middle Jurassic Weatherby Formation (Figs. 3B and 4).

Megasequence 2. The Weatherby Formation includes a basal unit of red and green volcaniclastic conglomerate (~10–250 m; the Jet Creek–McChord Butte member), overlain by ~5000–7000 m of Lower to Middle Jurassic quartzose and volcaniclastic sandstone and mudstone (Jurassic Flysch of Brooks and Vallier, 1978; Brooks, 1979; Imlay, 1986; Hooper et al., 1995; Payne and Northrup, 2003). It is widely agreed that the Weatherby Formation in eastern Oregon and western Idaho correlates with the megasequence 2 Jurassic succession in the John Day region. Previous workers concur that rocks of both successions represent forearc or intra-arc deposits related to east-dipping subduction of an oceanic plate beneath the Olds Ferry arc (e.g., Dickinson, 1979; Vallier, 1995; Avé Lallemant, 1995; Gray and Oldow, 2005). Recent studies have proposed a new model—based on regional stratigraphic relationships and the paleogeographic reconstruction of Wyld and Wright (2001)—in which Jurassic rocks of the Blue Mountains region accumulated in a collisional basin adjacent to a large Jurassic orogenic belt in western Nevada (Luning-Fencemaker thrust belt) (Dorsey and LaMaskin, 2007, 2008; LaMaskin et al., 2008a, 2009).

SAMPLE COLLECTION AND ANALYTICAL PROCEDURES

Sandstone Petrography

We collected sandstone samples for petrographic analysis to permit comparison with previously well-documented shifts in sandstone composition in Mesozoic rocks of the John Day region (Dickinson et al., 1979; see previous summary). Sandstone samples were analyzed to assess the age of the change from outboard Baker terrane sources to inboard sources, and the relationship between sandstone petrofacies and detrital zircon ages. In the John Day region, we collected sandstones from the Fields Creek Formation and Keller Creek Shale (Aldrich Mountains Group). In eastern Oregon–western Idaho, we collected sandstone samples from multiple locations in the Weatherby Formation flysch unit. Point-counting parameters are listed in Table 1, and a description of procedures for sandstone petrography is presented in the GSA Data Repository.[1]

TABLE 1. SUMMARY OF PARAMETERS FOR SANDSTONE MODAL ANALYSIS

Quartz (Q)	
Qm = Monocrystalline quartz	
Qp = Polycrystalline quartz	
Ch = Chert	
Feldspar (F)	
P = Plagioclase	
K = Potassium feldspar	
Lithic fragments (L)	
Ls = Lithic sedimentary	
	Lsm = Shale/mudstone
	Lsa = Argillite
	Lssi = Siltstone
	Lsst = Sandstone (traditional method only)
Lm = Lithic metamorphic	
	Lmp = Phyllite
	Lms = Slate
	Lma = Quartz-mica aggregate
	Lmt = Quartz-mica tectonite
Lv = Lithic volcanic	
	Lvmi = Microlitic
	Lvm = Lathwork
	Lvf = Felsitic
	Lvv = Vitric
Recalculated parameters:	
$Q/F/L = Q_{(Qm + Qp + Ch)}/F_{(P + K)}/L_{(Ls + Lm + Lv)}$	
$Qm/F/Lt = Qm/F_{(P + K)}/Lt_{(Ls + Lm + Lv + Qp + Ch)}$	
$Qp/Lv/Lsm = Qp_{(Qp + Ch)}/Lv/Lsm_{([Ls - Ch] + Lm)}$	

Detrital Zircon Analysis

We collected 5 to 10 kg samples of sandstone from biostratigraphically dated horizons in both the John Day region ("Izee terrane" of Silberling et al., 1984) and eastern Oregon–western Idaho ("Olds Ferry terrane" of Silberling et al., 1984). Sampled Triassic rocks include the Begg and Brisbois Members of the Vester Formation and the Fields Creek Formation in the John Day region (Figs. 3 and 4; Table 2). Numerous attempts to extract zircons from Triassic sandstones of the Huntington Formation in eastern Oregon were unsuccessful. We sampled Jurassic rocks including the Keller Creek Shale and the Hyde, Snowshoe, and Lonesome Formations in the John Day region, and the Weatherby Formation in eastern Oregon. U-Pb data for 10 samples were obtained by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) at Washington State University following the method of Chang et al. (2006). U-Pb data for one additional sample was analyzed at Stanford University on the joint U.S. Geological Survey (USGS)–Stanford sensitive high-resolution ion microprobe–reverse geometry (SHRIMP-RG). A description of U-Pb analytical procedures is presented in the GSA Data Repository (see footnote 1).

[1]GSA Data Repository item 2011188, (1) description of petrographic procedures, (2) description of U-Pb analytical procedures, (3) Table DR1—raw petrographic point-count data, and (4) Table DR2—U-Pb analytical data tables, is available at http://www.geosociety.org/pubs/ft2011.htm or by request to editing@geosociety.org.

RESULTS

Sandstone Petrography

Raw point-count data from sandstone modal analysis and detailed petrofacies descriptions are provided in the GSA Data Repository (see footnote 1), and recalculated parameters are presented in Table 3. Examples of sandstone grains in thin section are shown in Figure 5, and Figure 6 illustrates ternary plots of sandstone detrital modes.

Fields Creek Formation

Modal analysis of the Late Triassic Fields Creek Formation (John Day region) suggests two distinct petrofacies: volcaniclastic and

TABLE 2. SAMPLE LOCATION INFORMATION

Sample no.	Formation	Easting*	Northing
04064	Weatherby Formation, Jet Creek Member	0480251	4917982
06004	Vester Formation, Brisbois Member	0305333	4890634
06118	Fields Creek Formation	0317144	4912041
06135	Snowshoe Formation	0321824	4894722
06137	Keller Creek Shale	0352220	4897386
06139	Vester Formation, Begg Member	0289898	4883972
06152	Hyde Formation	0314433	4889370
06210	Weatherby Formation	0472495	4925662
07015	Lonesome Formation	0311902	4878318
07033	Weatherby Formation	0472736	4911171
IZEE-7	Lonesome Formation	0311191	4880448
IZEE-9	Lonesome Formation	0311887	4877935

*UTM Datum NAD 27 CONUS, UTM zone 11.

quartzolithic (Fig. 6). Volcaniclastic sandstones contain abundant plagioclase and volcanic lithic fragments. They plot in the transitional arc field on Q-F-L and Qm-F-Lt ternary diagrams and in, or close to, the magmatic arc field on a Qp-Lv-Lsm diagram (Fig. 6). These samples contain greater amounts of quartz and feldspar and more sedimentary and metamorphic lithic fragments than "Jurassic volcaniclastics" in the overlying Mowich Group and Snowshoe Formation (Dickinson et al., 1979), suggesting a distinct provenance for Triassic volcaniclastic sediments of the Fields Creek Formation.

Quartzolithic sandstones are low in feldspar and volcaniclastic content and contain abundant lithic fragments of principally sedimentary and metamorphic composition. Sedimentary lithic fragments consist of shale-mudstone and argillite (Fig. 5A). Low-grade meta-sandstone and meta-graywacke grains (e.g., Fig. 5B) are also present. Metamorphic lithic fragments include abundant phyllite-schist, quartz-mica tectonite (Fig. 5C), and quartz-mica aggregate grains with subordinate quantities of slate. Grains of silicic plutonic rocks that display distinctive granophyric textures are also present (Fig. 5D).

Quartzolithic sandstones of the Fields Creek Formation plot in recycled orogen fields on Q-F-L, Qm-F-Lt, and Qp-Lvm-Lsm diagrams (Fig. 6), consistent with derivation from the uplifted Baker terrane accretionary subduction complex as suggested in previous studies (Dickinson and Thayer, 1978; Blome et al., 1986; Dorsey and LaMaskin, 2007). Although Dickinson et al. (1979) noted the presence of chert-rich, mélange-derived detritus in the Fields Creek Formation, here we document that the quartzolithic petrofacies in the Fields Creek Formation is uniquely enriched in sandstone and metamorphic lithic fragments that range from slate to quartz-mica tectonite (Figs. 5A, 5B, 5C, and 6).

Keller Creek Shale and Weatherby Formation

Volcaniclastic sandstones in the Lower Jurassic Keller Creek Shale (John Day region) and Middle Jurassic Weatherby Formation (eastern Oregon–western Idaho) are characterized by variable mixtures of feldspar (Fig. 5E) and volcanic lithic fragments. Observed sedimentary lithic fragments are limited to shale and mudstone. In addition to these framework constituents, detrital pyroxene grains form 6%–10% of total framework and accessory grains (Fig. 5F). Sandstones in the Keller Creek Shale and Weatherby Formation plot in the magmatic arc field on Qp-Lv-Lsm plots (Fig. 6A) and transitional to undissected arc fields on Q-F-L and Qm-F-Lt plots (Figs. 6B and 6C). These samples plot very close to other Jurassic volcaniclastics as reported by Dickinson et al. (1979). Our limited analysis suggests that selected horizons in the Weatherby Formation may contain either higher quartz or higher volcanic lithic content than Jurassic volcaniclastics of the John Day region, but sandstones from both regions have very similar modal compositions.

Detrital Zircon Analysis

Complete U-Pb zircon data tables are provided in the accompanying GSA Data Repository (see footnote 1). Data are illustrated on Tera-Wasserburg plots in Figure 7, and relative probability plots and histograms are provided in Figure 8. Reported ages are based on $^{206}Pb/^{238}U$ for grains younger than ca. 1000–1200 Ma and $^{207}Pb/^{206}Pb$ for grains older than ca. 1000–1200 Ma. Results are summarized next.

John Day Region: Late Triassic Samples of Megasequence 1

Detrital zircon age-probability distributions from the Begg Member (sample 06139) and Brisbois Member (sample 06004) of the Vester Formation include very few Mesozoic-age zircon grains (Figs. 8 and 9). These samples contain abundant Devonian-, Mississippian-, Pennsylvanian-, and Permian-age grains and have

TABLE 3. RECALCULATED MODAL POINT-COUNT DATA FOR SANDSTONE SAMPLES OF THE BLUE MOUNTAINS PROVINCE, OREGON

Formation		Sample no.	Total	Q-F-L (%) Q	F	L	Qm-F-Lt (%) Qm	F	Lt	Qp-Lv-Lsm (%) Qp	Lv	Lsm	Lv-Ls-Lm (%) Lv	Ls	Lm
Fields Creek Formation		06122	401	40	7	53	23	7	70	25	9	67	12	41	48
		06123	446	43	4	53	24	4	72	26	8	65	11	45	43
		06009	380	46	2	52	19	2	79	34	15	52	22	28	50
		06118*	429	21	45	34	10	45	45	25	59	16	79	21	0
		06129	392	19	58	24	9	58	33	28	55	17	77	22	1
Keller Creek Shale		06131	403	5	46	49	3	46	51	3	89	9	91	8	1
		06130	406	5	42	53	3	42	56	4	92	4	96	4	0
		06133	412	3	47	50	2	47	51	2	97	1	99	1	0
		06137*	408	6	43	51	4	43	53	4	92	4	96	4	0
Weatherby Formation	*Lower Flysch*														
		07033e*	406	4	20	76	4	20	76	0	98	2	98	2	0
		07035	432	13	19	68	12	19	70	2	97	1	99	1	0
	Main Flysch														
		07038	407	4	32	65	2	32	66	2	97	1	99	1	0
		07039	403	5	17	78	2	17	81	4	95	1	99	1	0
		07040	422	2	26	72	2	26	72	1	99	0	100	0	0
		07044	439	4	18	78	3	18	79	2	98	0	100	0	0
		06210†	399	5	26	70	4	26	70	1	98	1	99	1	0
		07042	404	19	18	63	2	18	79	21	79	0	100	0	0

*Detrital zircon sample.

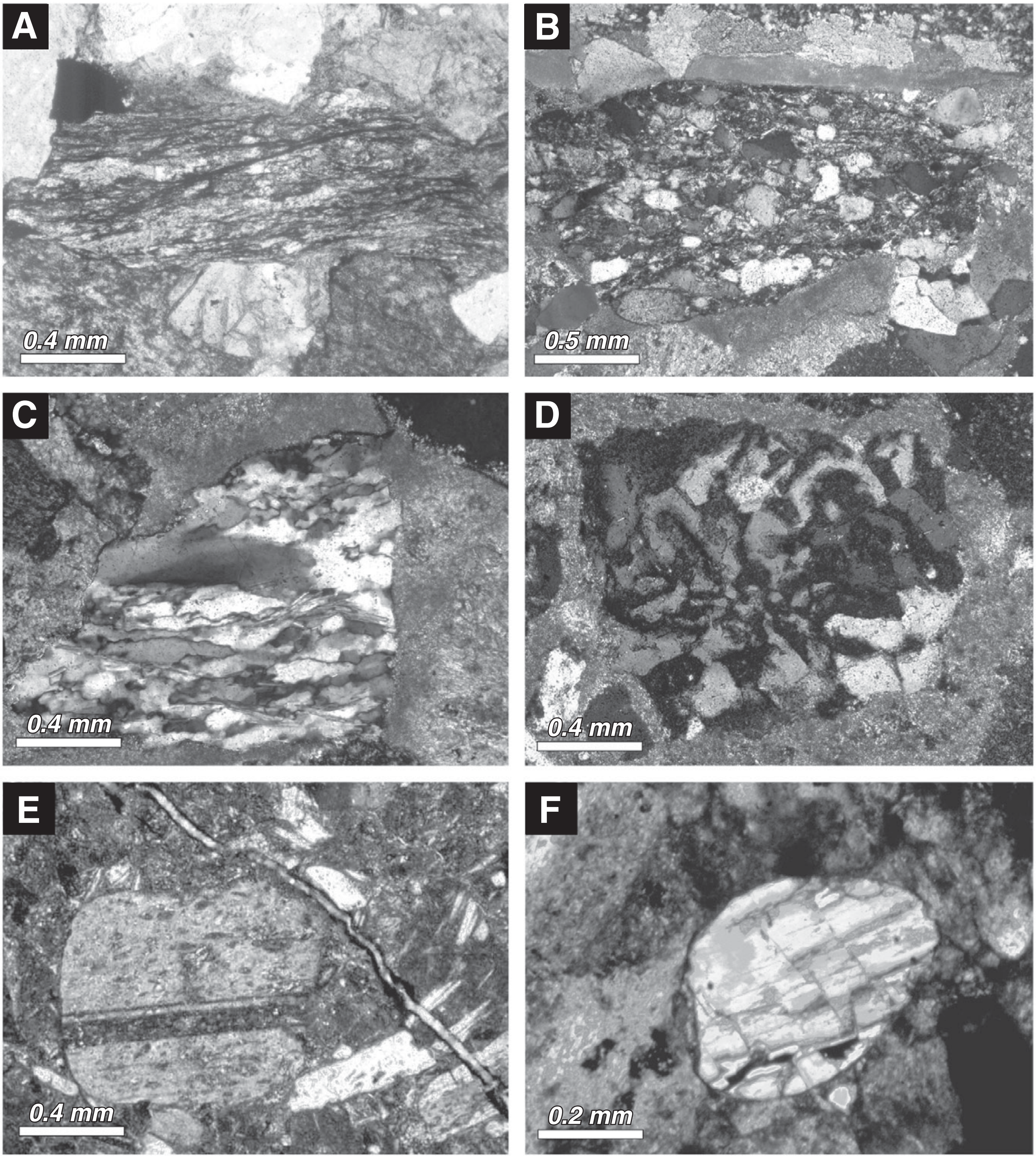

Figure 5. Photomicrographs of key framework grain types in Blue Mountains Province sandstone samples. All photomicrographs were taken in cross-polarized light. (A) Lithic fragment of silty argillite to slate from quartzolithic petrofacies of Fields Creek Formation. Note selective internal calcite replacement and breakdown to form pseudomatrix along grain edges. (B) Lithic fragment of low-grade metagraywacke in calcite-cemented sandstone from quartzolithic petrofacies of the Fields Creek Formation. Phyllosilicate minerals replace clay-rich matrix within detrital grain. (C) Lithic grain of quartz-mica tectonite from quartzolithic petrofacies of Fields Creek Formation. Note strong planar fabric of elongated quartz and aligned phyllosilicate minerals. (D) Lithic grain of plutonic origin displaying distinctive granophyric texture from volcaniclastic petrofacies of the Fields Creek Formation. (E) Typical view of volcaniclastic petrofacies of Keller Creek Shale. Note well-rounded plagioclase grains, lithic grains displaying lathwork texture, and abundant pseudomatrix. (F) Well-rounded detrital pyroxene grain from the Weatherby Formation.

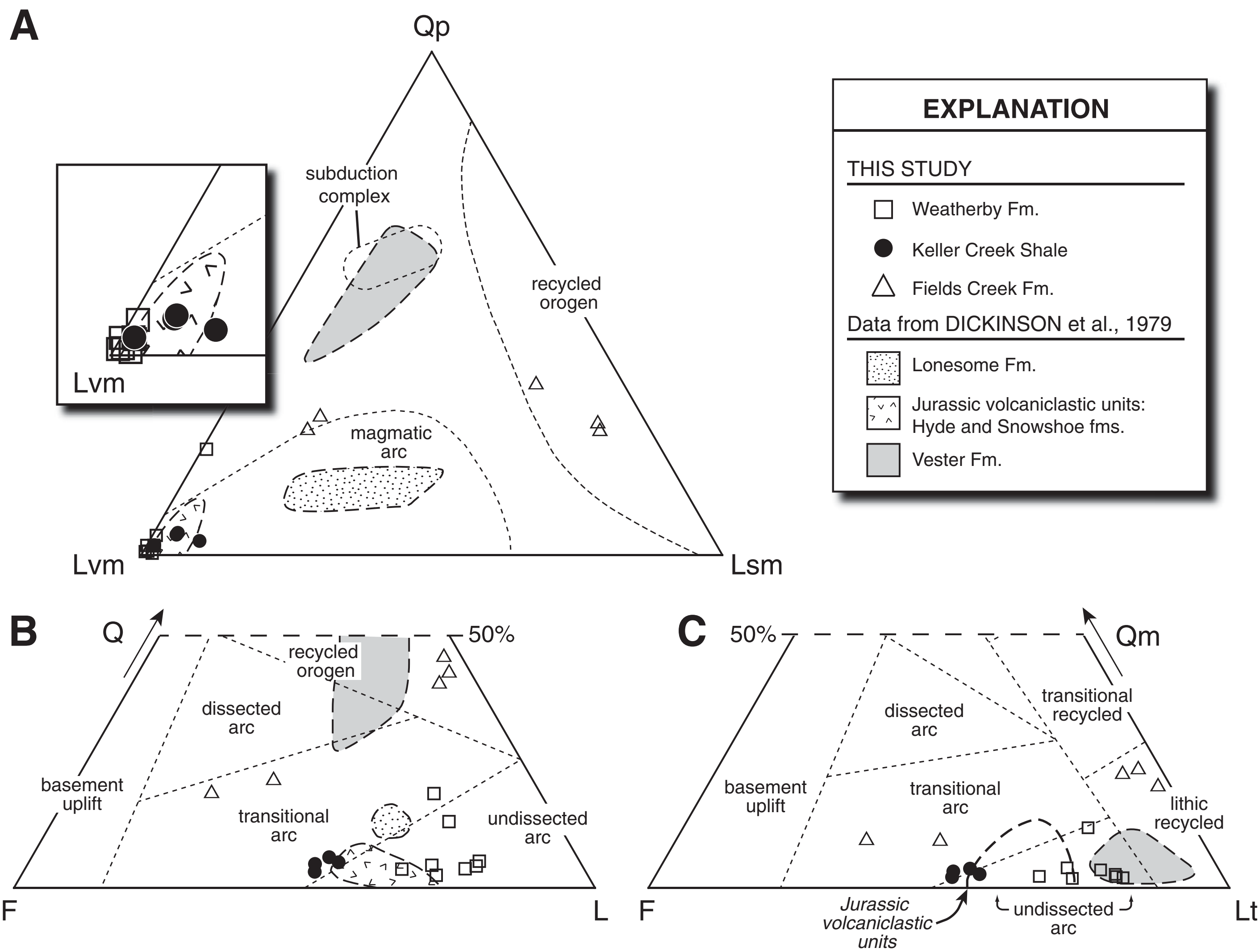

Figure 6. Ternary diagrams illustrating sandstone detrital modes for the Fields Creek Formation, Keller Creek Shale, and Weatherby Formation. (A) Qp-Lvm-Lsm. Inset is a close-up of the Lsm apex to show detail. (B) Q-F-L. (C) Qm-F-Lt. Tectonic setting classification fields are from Dickinson and Suczek (1979); Dickinson et al. (1983); and Dickinson (1985). Also shown are results taken graphically from Dickinson et al. (1979) for the Vester Formation, "Jurassic volcaniclastic" units, and the Lonesome Formation.

abundant Precambrian age peaks in the late Paleoproterozoic (ca. 2.2–1.6 Ga) and Late Archean (ca. 2.7–2.5 Ga). The Fields Creek Formation sample (06118) has predominantly Permian–Triassic (ca. 280–242 Ma) and Silurian–Devonian ages (ca. 436–385 Ma), with fewer Precambrian grains from Late Paleoproterozoic (ca. 1.9–1.6 Ga) to Mesoproterozoic (ca. 1.4–1.0 Ga).

John Day Region: Early Jurassic Samples of Megasequence 1

Sandstone in the Keller Creek Shale (sample 06137) is characterized by a single major distribution of Late Triassic to Early Jurassic grains (ca. 218–181 Ma; peak at 195 Ma; Figs. 8 and 9) and fewer Mesoproterozoic (ca. 1.5–1.0 Ma) and Paleoproterozoic (ca. 1.9–1.7 Ga) grains.

John Day Region: Middle and Early Late Jurassic Samples of Megasequence 2

All zircons in the Hyde Formation of the Mowich Group (sample 06152) are Mesozoic, with a unimodal age distribution from 199 to 172 Ma and a peak at 180 Ma. Our samples from the Snowshoe Formation (06135) and from the Lonesome Formation (07016, IZEE-7, and IZEE-9) have similar age-probability distributions (Figs. 8 and 9). These samples have zircons with complex, multimodal distributions in the Late Triassic to early Late Jurassic (ca. 217–159 Ma). The Lonesome Formation has a relatively continuous distribution of Paleozoic detrital zircon grains. Precambrian grains include abundant Neoproterozoic (ca. 675–576 Ma) and Mesoproterozoic ages (ca. 1.5–1.0 Ga) with lesser amounts of late Paleoproterozoic (ca. 1.9–1.8 Ga) and few Archean grains.

Eastern Oregon: Early to Middle Jurassic Samples of Megasequence 2

Samples from the basal Jet Creek Member of the Weatherby Formation (sample 04064) and lower part of the overlying flysch member (sample 07033) contain zircons with a range of ages from Late Triassic to Early Jurassic (ca. 225–190 Ma) with a major peak at ca. 200 Ma (Figs. 8 and 9). Both of these samples are void of Precambrian or Paleozoic zircons. In sample 07033, three detrital zircon grains define an additional age peak at ca. 178 Ma. One sample from the upper flysch of the Weatherby Formation (sample 06210) yielded only Late Triassic to Middle Jurassic ages (ca. 214–169 Ma), with two dominant peaks evident at ca. 178 and ca. 196 Ma (Figs. 8 and 9). Five zircons from this sample have pre-Mesozoic ages.

DISCUSSION

Sandstone Petrography

In Fields Creek Formation samples, the presence of abundant sedimentary lithic fragments in addition to volcanic detritus is interpreted to represent a "relict petrofacies," where an arc system is no longer active but is still contributing detritus to the basin (cf. Graham et al., 1993; Critelli and Ingersoll, 1995). Our new U-Pb data support this interpretation because the associated sandstone sample does not contain zircons with U-Pb ages that overlap the well-established biostratigraphic age of the Fields Creek Formation (Fig. 9; and see following). We therefore conclude that there was not an active arc supplying detritus to this part of the basin during Late Triassic time.

Notable granophyric plutonic grains (Fig. 5D) in the Fields Creek Formation are clearly derived from granophyric plutonic rocks that are located immediately to the northwest in the Baker terrane (Carpenter and Walker, 1992) and are also observed as olistostromal slide blocks in basal parts of the Fields Creek Formation (Thayer and Brown, 1966). Permian U-Pb zircon ages of these Baker terrane plutonic blocks (Carpenter and Walker, 1992) are in excellent agreement with detrital zircon ages from the Fields Creek Formation (see following).

The presence of two distinct petrofacies in the Fields Creek Formation—volcaniclastic and quartzolithic (Fig. 6)—suggests a recycled orogenic source for this unit. Modern sediments in the southern Aegean Sea are composed of similar mixtures of volcaniclastic and quartzolithic sands. In this setting, a wide ancient orogenic belt borders an active forearc and supplies two types of sediment to local basins (Saccani, 1987). Additionally, in the modern Apennine backarc region, source-area variability along orogenic strike leads to deposition of sand with either magmatic *or* orogenic provenance (e.g., Garzanti et al., 2000, 2007). Notably, relict quartzolithic-volcaniclastic petrofacies are also documented in Upper Paleozoic to Upper Triassic sandstones in California and Nevada (Dickinson and Gehrels, 2000). This may suggest the presence of a recycled orogenic source area (Baker terrane and lateral equivalents) along a significant portion of the Cordilleran margin during Late Triassic time.

In the Keller Creek Shale and Weatherby Formation, distinctive well-rounded to subangular detrital pyroxene and abundant intact lithic fragments suggest relatively short transport distances for volcanic detritus. A low proportion of sedimentary or metamorphic lithic fragments suggests an active arc setting (cf. Graham et al., 1993; Critelli and Ingersoll, 1995).

Detrital Zircon Analysis

Outboard versus Inboard Sediment Sources

In this study, we benefit from preexisting paleontologic, sandstone petrographic, and paleocurrent data that provide useful constraints on sediment provenance (i.e., Dickinson and Thayer, 1978; Dickinson et al., 1979; Blome et al., 1986). A major source area change in the John Day region that is documented with sandstone petrofacies (Dickinson et al., 1979) is also recorded in detrital zircon age distributions. Chert- and metamorphic lithic-rich Late Triassic samples likely derived from outboard sources (i.e., the offshore Baker terrane) are dominated by Precambrian and Paleozoic ages (96%–100%; Fig. 10A) and include negligible amounts of Mesozoic-age detrital zircon grains (i.e., 0%–4%; Figs. 9 and 10A). Precambrian grains in these Late Triassic sediments are mostly late Paleoproterozoic and Archean (ca. 2.7–1.8 Ga), typical of northwestern Laurentian basement ages (cf. Gehrels et al., 1995, 2000) (Figs. 9 and 10B). In contrast, Jurassic volcaniclastic samples derived from inboard sources contain at least half Mesozoic-age detrital zircon grains (i.e., 52%–100%; Figs. 9, 10A, and 11). Precambrian grains in the Jurassic samples are mostly Late Paleoproterozoic to Neoproterozoic (ca. 2.0 Ga to 600 Ma), which are commonly considered typical of eastern and southwestern Laurentian basement ages (Figs. 9 and 10B). This suggests a change in provenance and an increase in local or regional magmatism from Late Triassic to Early Jurassic time (cf. Brown and Thayer, 1977).

At face value, the observed change from typical northwestern to eastern-southwestern Laurentian-type zircon ages is consistent with models for southward displacement of the Blue Mountains relative to North America during Triassic through Early Cretaceous time (i.e., Avé Lallemant and Oldow, 1988) and is in conflict with faunal evidence that suggests progressive northward transport of the Blue Mountains Province (i.e., Pessagno and Blome, 1986; Pessagno, 2006). However, well-documented sandstone detrital modes show that Triassic deposits have a provenance distinct from overlying Jurassic deposits (Dickinson and Thayer, 1978; Dickinson, 1979; Dickinson et al., 1979). Thus, the change in detrital zircon ages is more directly related to a change from outboard to inboard sources and does not necessarily reflect southward translation through time. In this case, a priori knowledge of sediment sources from sandstone petrofacies analysis is critical to the interpretation of associated detrital zircon age distributions. This highlights the need to interpret detrital zircon age distributions in the context of sandstone petrography.

Late Triassic Samples: Outboard Provenance

Detrital zircon ages in the Vester and Fields Creek formations characterize the outboard Baker terrane accretionary subduction complex source area and suggest two distinct detrital zircon sources: one that supplied middle to late Paleozoic, late Paleoproterozoic, and late Archean zircons to the Vester Formation and another that supplied Permian–Triassic, Silurian–Devonian, Mesoproterozoic, and late Paleoproterozoic zircons to the Fields Creek Formation (Figs. 8, 9, and 10). Existing Ar/Ar and U-Pb ages for pre-Jurassic rocks from the Baker terrane, however, document only Late Triassic to Permian plutonic ages, even though sedimentary rocks as old as Middle Devonian are present (Savage and Amundson, 1979; Avé Lallemant et al., 1980; Morris and Wardlaw, 1986; Walker, 1986, 1995; Blome and Nestell, 1991; Carpenter and Walker, 1992).

The presence of late Paleozoic, late Paleoproterozoic, and late Archean grains in Triassic sandstone of the Vester Formation suggests a Baker terrane subduction-accretionary complex source analogous to Paleozoic subduction-accretionary complexes of the Eastern Klamath and Northern Sierra terranes, which bear similar detrital zircon age distributions. For example, the Lang-Duncan-Culbertson allochthons of the Shoo Fly complex (Northern Sierra terrane) contain abundant late Paleoproterozoic and late Archean detrital zircon grains (Harding et al., 2000) and are intruded by Late Devonian plutons (i.e., Bowman Lake suite, ca. 378–370 Ma; Saleeby et al., 1987; Hanson et al., 1988; Sharp, 1988).

The Upper Triassic Fields Creek Formation appears to contain a "transitional" detrital zircon age distribution, with abundant Paleozoic ages similar to underlying samples, but with Precambrian ages rich in Mesoproterozoic and Neoproterozoic zircons similar to younger Jurassic samples (Figs. 8, 9, and 10). Detrital zircon and petrographic data presented here thus record a shift in provenance from the Vester to Fields Creek formations (Figs. 8, 9, and 10B). Significant differences in both sandstone detrital modes and detrital zircon signatures suggest that detritus in the Fields Creek Formation was not produced only by erosion and reworking of the Vester Formation, as suggested by Dickinson and Thayer (1978).

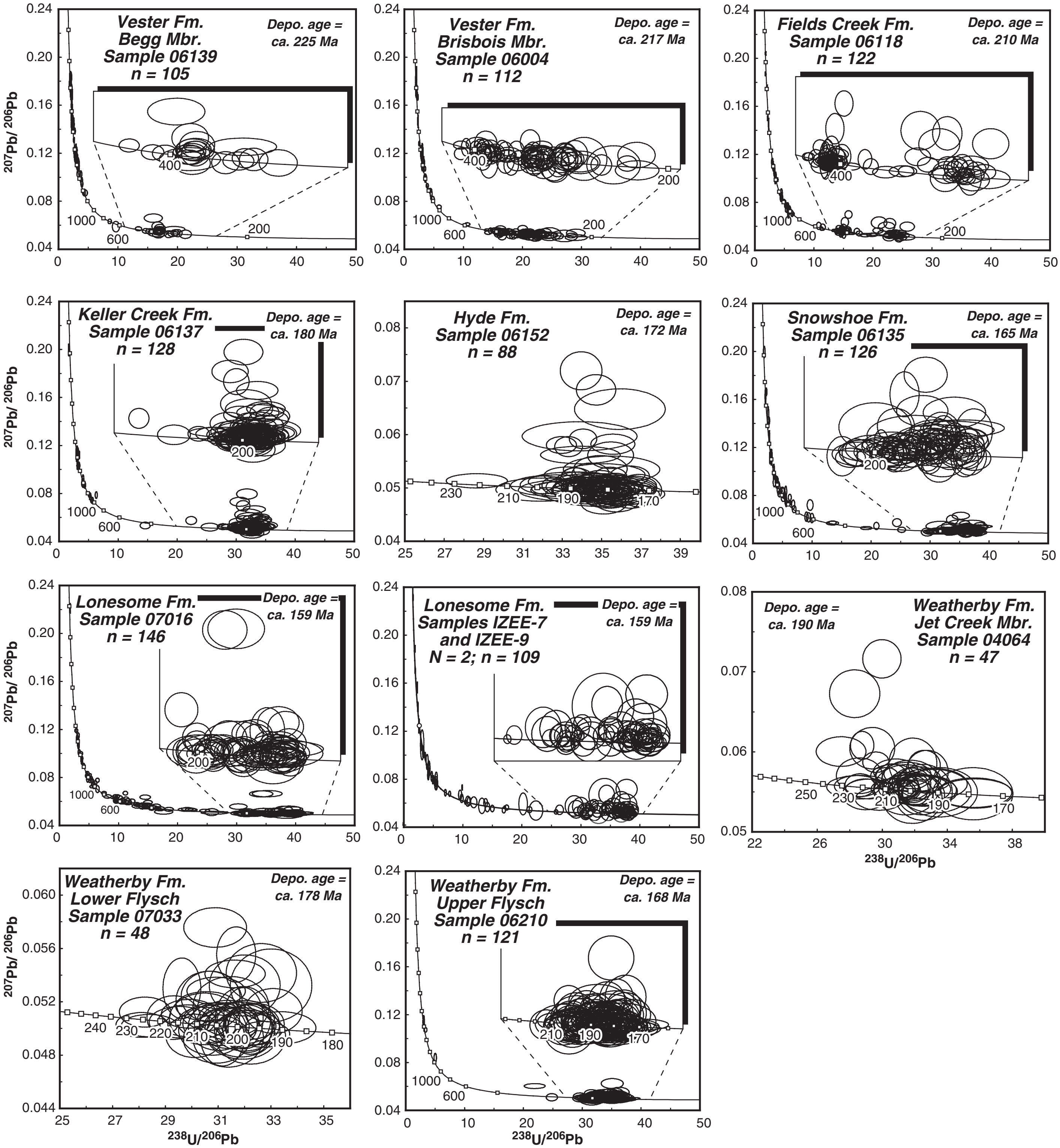

Figure 7. Tera-Wasserburg Pb-Pb/U-Pb concordia plots for detrital zircons from the Blue Mountains Province. Errors are shown at the 2σ level. Data shown have not been corrected for common Pb. Shadowed insets show additional detail for Paleozoic and Mesozoic zircon grains. Samples containing Precambrian-age zircon grains are plotted at the same scale. Samples 06152, 04064, and 07033 are scaled to fit.

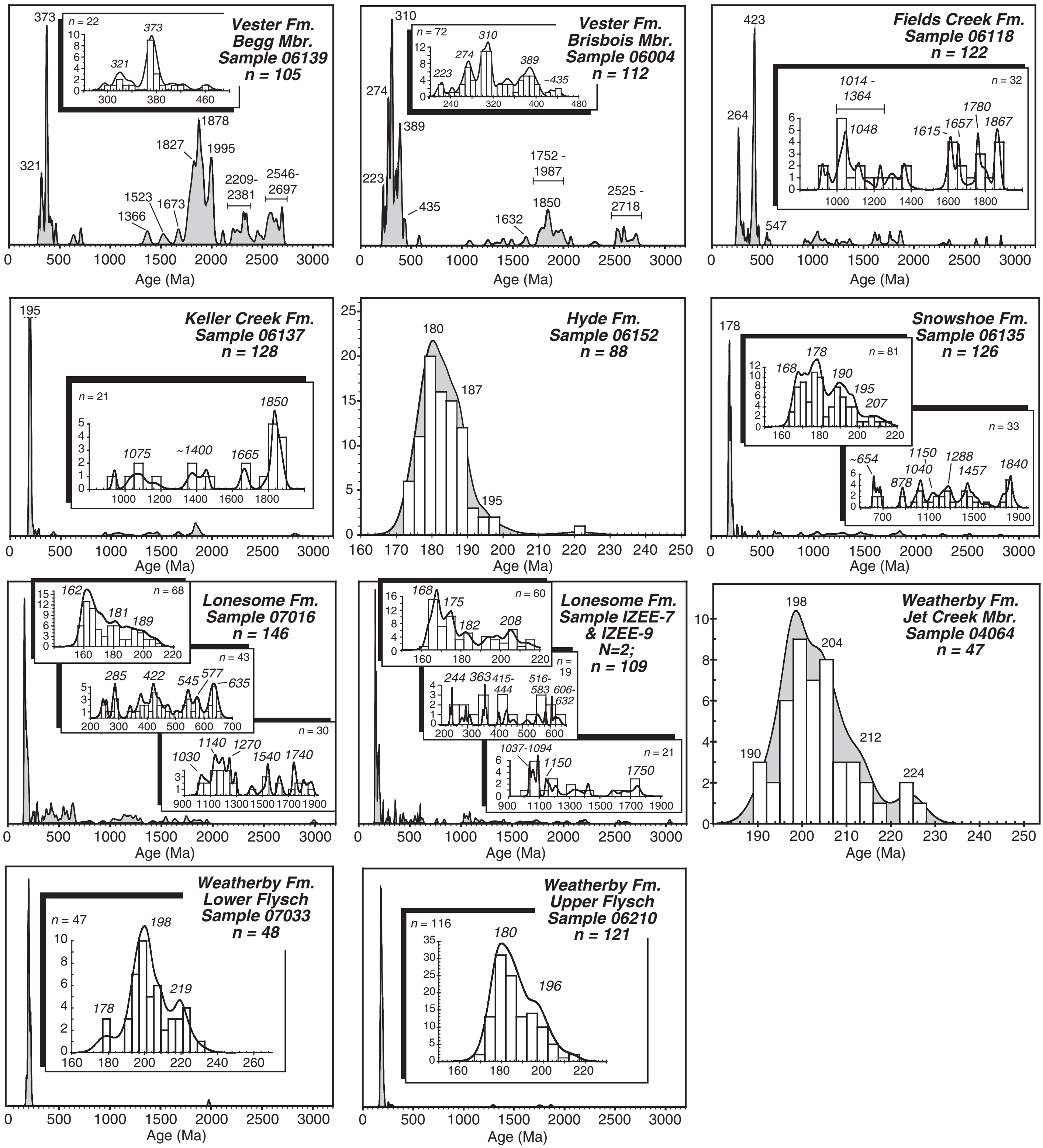

Figure 8. Relative probability plots and histograms for detrital zircons from the Blue Mountains Province. Curves represent the summation of individual detrital zircon ages and associated 2σ Gaussian errors; associated *y*-axes represent relative probability. Histograms are based on individual detrital zircon grain ages and do not incorporate errors; associated *y*-axes represent number of grains in a given age bin. Shadowed insets show additional detail. Samples containing Precambrian-age zircon grains are plotted at the same scale. Samples 06152 and 04064 are scaled to fit.

Evidence that detritus in the Fields Creek Formation was produced by reworking of older deposits in the Baker terrane includes an abundance of Permian–Triassic detrital zircon grains (ca. 280–242 Ma) that closely match ages from granophyric plutonic blocks found in the Baker terrane (ca. 272–236 Ma; published range of $^{206}Pb/^{238}U$ ages on multigrain zircon fractions *in* Carpenter and Walker, 1992). In addition, the Fields Creek Formation has a well-established Late Triassic radiolarian age (early Norian to late middle Norian; ca. 216–206 Ma; Blome et al., 1986; Yeh, 1989), but the youngest detrital zircon grains are Middle Triassic, representing a lag time of nearly 30 m.y. Together with the petrographic data presented previously, this indicates that the Fields Creek Formation detritus was not derived from an active-arc setting such as the inboard Cordilleran arc.

The presence of abundant metamorphic and sedimentary framework grains suggests a relatively short transport distance for detritus of the Fields Creek Formation. A potential source area is the Deer Creek Phyllite (Burnt River Schist subterrane of the Baker terrane), a unit that appears to be intruded by the ca. 230 Ma Blue Spring Gulch pluton (Ashley, 1995; Walker, 1995; sample BRC79-1). Comparable detrital U-Pb zircon ages are not present in our sample from the Fields Creek Formation, suggesting a source other than the Burnt River Schist. Little-studied schistose rocks are also present at Ironside Mountain to the east of the John Day region (Hooper et al., 1995). Further analysis of the Burnt River Schist and Ironside Mountain areas may yield insights into the source of Fields Creek Formation detritus.

Exposures of Paleozoic schist, graywacke, and sandstone in the Eastern Klamath terrane represent a possible source-area lithology and contain an appropriate detrital zircon age distribution that includes a ca. 420 Ma age peak, ca. 600–500 Ma Neoproterozoic-age grains, and Precambrian ages dominated by 2.0–1.0 Ga grains (Fig. 12; Gehrels and Miller, 2000; Grove et al., 2008). This suggests either derivation from metasedimentary rocks of the Eastern Klamath terrane or *more likely* indicates

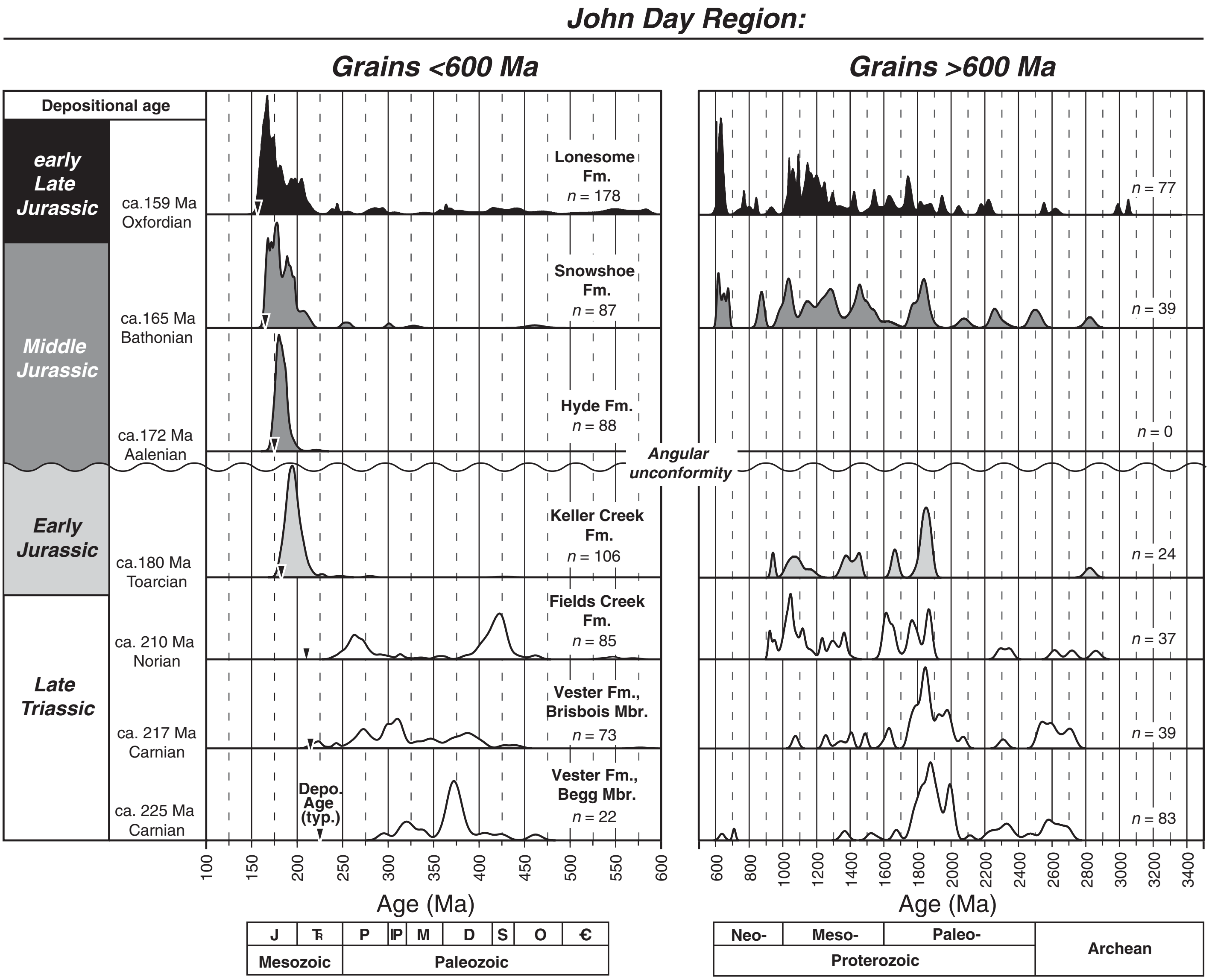

Figure 9. Detrital zircon age-probability distributions from the John Day region shown for ages younger than 600 Ma and ages older than 600 Ma for each sample. Samples are plotted on the *y*-axis in depositional order.

the presence of rocks in the Baker terrane that are similar to those of the Eastern Klamath terrane. This Baker terrane source area has either not yet been adequately characterized or is concealed beneath Miocene-age Columbia River Basalts. Petrographic and detrital zircon data therefore suggest that the Fields Creek Formation most likely was derived from an Eastern Klamath terrane–type source located in the Baker terrane.

Numerous plausible scenarios exist for Late Triassic erosion, transport, and deposition of detrital zircon grains in Blue Mountains basins. First, the grains may have been eroded from crystalline sources in the Baker terrane that are not currently exposed, have yet to be recognized, or have been tectonically removed since Triassic time. Second, they may have been reworked from Paleozoic clastic rocks in the Baker terrane. Third, grains in Triassic rocks of the Blue Mountains may have been reworked from Paleozoic clastic rocks in the Eastern Klamath–Northern Sierra terranes. Detrital zircon age distributions from subduction-accretion complexes in the Eastern Klamath and Northern Sierra terranes contain two distinct age distributions similar to the two Baker-terrane sources documented here (Gehrels and Miller, 2000; Harding et al., 2000; Grove et al., 2008). In the third scenario, detrital zircon grains eroded from exposed sources to the south must have been funneled into the Triassic trench, transferred to the Baker terrane accretionary prism (via underplating and/or offscraping), uplifted, eroded, and subsequently deposited in Triassic basins in the John Day region. Well-constrained sandstone and faunal provenance linkages to the immediately adjacent Baker terrane (Dickinson et al., 1979; Blome et al., 1986) suggest that the detrital zircon sources are present in exposed Paleozoic clastic rocks of the Baker terrane (e.g., Alexander and Schwartz, 2009).

Implications of Triassic Detrital Zircon Sources

The Paleoproterozoic- and Archean-dominated Precambrian ages documented here for the Late Triassic Vester Formation represent a

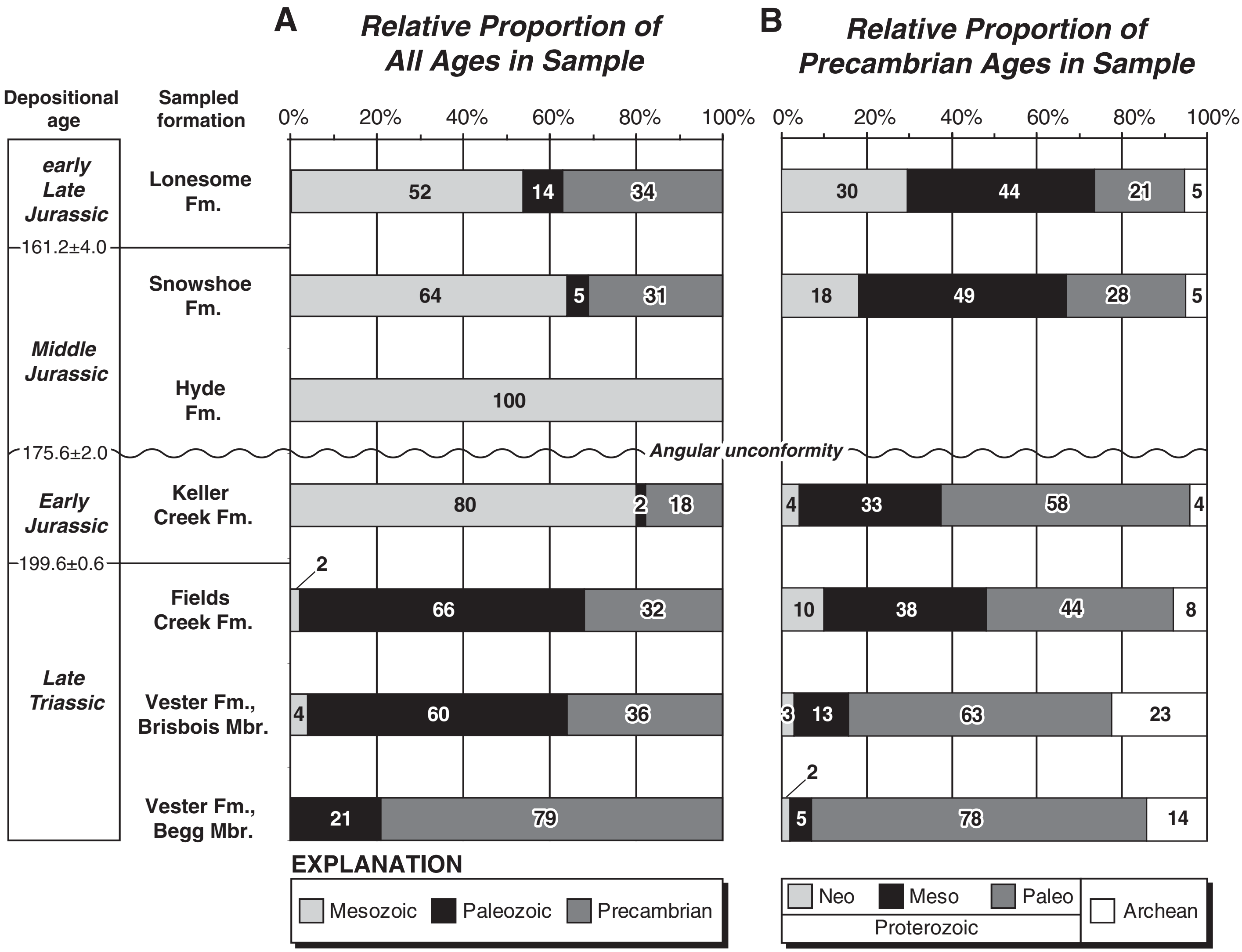

Figure 10. Plots illustrating proportion of detrital zircon ages based on major divisions of the geologic time scale. *Y*-axis is approximate depositional age and sampled formation. (A) Percentage of the total sample that is represented by Mesozoic, Paleozoic, and/or Precambrian ages. (B) Percentage of the Precambrian portion of the sample that is represented by Neoproterozoic, Mesoproterozoic, Paleoproterozoic, and/or Archean ages.

"Peace River Arch"–type signal, commonly interpreted to represent basement ages in northwestern Laurentia (e.g., Gehrels et al., 1995; Gehrels, 2000). This Paleoproterozoic–Archean age distribution is found in detrital zircon suites in numerous Cordilleran terranes from California to Alaska and is especially common in Paleozoic subduction-accretionary complexes (Gehrels and Kapp, 1998; Harding et al., 2000; Spurlin et al., 2000; Scherer, 2006; Brown and Gehrels, 2007). Precambrian ages in the Vester Formation and its Baker-terrane source therefore cannot be uniquely tied to a particular source area. Rather, continuity with detrital suites in other Cordilleran accretionary subduction complexes reinforces the interpretation that the Baker terrane is part of the late Paleozoic to Mesozoic paired accretionary complex and fringing-arc system of western North America (e.g., Wright, 1982; Miller, 1987; Miller et al., 1992; Gehrels et al., 2000; Dickinson, 2000). This interpretation implies multiple sedimentary recycling episodes of zircon grains that were ultimately derived from northwestern Laurentian basement rocks.

An alternative explanation, based on a recent model for the tectonic evolution of western North America (Wright and Wyld, 2006; Grove et al., 2008), proposes tectonic dispersal of originally peri-Gondwanan arc fragments from the southern Laurentian margin in Devonian time. According to this model, these "Alexander terrane–type" arc segments were accreted to western North America in mid-Paleozoic time as parts of the Eastern Klamath and Sierra Nevadan terranes and the Roberts Mountain and Golconda allochthons (Wright and Wyld, 2006; Grove et al., 2008). These blocks of allochthonous arc crust may have acted as basement for future arc growth in the western United States, parts of which rifted from the western Laurentian margin to form the offshore segment of the Permian–Triassic Cordilleran arc. Sedimentary rocks of these arc fragments contain two distinct detrital zircon signatures: Archean- to Paleoproterozoic-enriched, and Mesoproterozoic- to Neoproterozoic-enriched (Wright and Wyld, 2006). This interpretation implies multiple sedimentary recycling episodes of zircon grains that were ultimately derived from both Gondwanan and eastern Laurentian basement rocks.

Regardless of the ultimate origin of detrital zircons, our data strongly suggest that the Baker terrane source area has genetic links to the nearby Eastern Klamath and Northern Sierra terranes, either as an analogous allochthonous crustal fragment (further extending the geographic extent of Alexander-type crust of the "Cordilleran" Paleozoic arc; i.e., Wright and Wyld, 2006), or via a sediment-transport and recycling link. Future characterization of detrital zircon age distributions in the Klamath Mountains and Baker terrane is needed to clarify provenance relationships between these regions.

Jurassic Samples: Inboard Provenance

Detrital zircon age distributions in Jurassic deposits indicate derivation from inboard source areas that were dominated by volcanic rocks, and they provide a record of Jurassic magmatism in the Cordilleran arc. Previous correlations of Jurassic turbidites from the John Day region to eastern Oregon (Dickinson, 1979; Imlay, 1986; Pessagno and Blome, 1986; Avé Lallemant, 1995; Vallier, 1995; Dorsey and LaMaskin, 2007, 2008) are confirmed here by similar detrital zircon age distributions (Fig. 11). Early Jurassic samples from both the John Day region and eastern Oregon (Huntington area), as shown in Figure 11, contain a dominant signal of Late Triassic through Early Jurassic magmatism (ca. 210–185 Ma; mode at 198–195 Ma). The youngest Early Jurassic sample (Weatherby Formation, Lower Flysch) also contains three zircons ca. 178 Ma, suggesting onset of a subsequent Early to Middle Jurassic magmatic pulse. The subsequent pulse is well represented in succeeding Middle Jurassic samples from both the John Day region and eastern Oregon by age modes at ca. 178 Ma (Fig. 11). Finally, the Snowshoe and Lonesome formation samples also contain abundant Middle Jurassic detrital zircon grains (ca. 170–159 Ma).

These detrital zircon data suggest a distinctive pattern of neo- and paleomagmatic sources in an active-arc setting, where sandstone detrital modes can only identify a volcaniclastic petrofacies. A significant phase of Late Triassic magmatic activity in the Olds Ferry arc (Brooks et al., 1976; Brooks, 1979; Walker, 1986; Lund, 2004; LaMaskin, 2008; Unruh et al., 2008) is represented by only a *minor* component of the age distributions (Fig. 11). Lower Jurassic samples are dominated by ages from ca. 198 to 195 Ma, and Middle to early Late Jurassic samples are dominated by ages from ca. 180 to 175 Ma and ca. 168 Ma. Thus, in successively younger samples, older ages become less prominent and are replaced by progressively younger ages. These observations suggest that the majority of detrital zircon grains are from neovolcanic sources that blanketed local drainage basins. In this scenario, underlying older paleovolcanic material was only partially exposed, and "young" magmatic detritus dominates the detrital zircon age suite.

Overall, detrital zircon age distributions in Jurassic samples indicate a source area dominated by Early and Middle Jurassic rocks and containing dominantly Paleozoic, Neoproterozoic, and Mesoproterozoic zircons with subordinate late Paleoproterozoic and late Archean zircons (Figs. 8–11). Thus, any potential source area must contain abundant Early and Middle Jurassic igneous rocks. Middle Jurassic zircon ages do not provide a meaningful constraint on source areas for deposits of the Blue Mountains Province because appropriate age volcanic and plutonic rocks are ubiquitous along the Cordilleran arc (e.g., Wright and Fahan, 1988; Saleeby and Busby-Spera, 1992; Nokleberg et al., 1994; Busby et al., 2002, 2005; Schermer et al., 2002; Irwin, 2003; Barth et al., 2004; Day and Bickford, 2004; Unruh et al., 2008; many others). Early Jurassic igneous rocks are, however, less widespread in the Cordillera. North of the Blue Mountains, Early Jurassic igneous rocks in southern British Columbia (e.g., Mortimer, 1987; Mortimer et al., 1990; Parrish and Monger, 1992; Acton et al., 2001; Friedman et al., 2002; Schiarizza et al., 2002; Petersen et al., 2004) are not a possible source because Precambrian crystalline rocks and known detrital zircon suites from the region are dominated by ca. 2.0–1.7 and 2.8–2.5 Ga ages (Gehrels and Ross, 1998; Ross et al., 1997). Likewise, potential plutonic and sedimentary sources at the present latitude of the Blue Mountains (i.e., Belt Basin and Wyoming craton) are dominated by Paleoproterozoic and Archean zircon (Hoffman, 1989; Gehrels and Ross, 1988; Ross et al., 1997; Ross and Villenvue, 2003) and are a poor match for Jurassic rocks of the Blue Mountains.

More likely sources of Early Jurassic zircon grains *and* associated Paleozoic and Precambrian ages are (1) the Black Rock terrane of western Nevada (Wyld, 1990, 1996, 2002; Quinn et al., 1997), (2) the continental segment of the Cordilleran arc (e.g., Saleeby and Busby-Spera, 1992; Busby et al., 2002, 2005; Fackler-Adams et al., 1997; Kowallis et al., 2001; Schermer et al., 2002; Barth et al., 2004), and (3) selected terranes of the Sierra Nevada foothills (Day and Bickford, 2004). The presence of Early Jurassic zircon grains and associated Paleozoic and Precambrian ages support paleogeographic reconstructions in which the Blue Mountains Province is restored some distance to the south and invite comparisons to known potential inboard sources in the southwestern United States.

An excellent match for detrital zircon age distributions in Middle to early Late Jurassic rocks of the Blue Mountains Province is found in southwestern U.S.–enriched, Ouachita-Appalachian–derived sediment of the late Paleozoic–early Mesozoic transcontinental river system (Fig. 13; e.g., Rahl et al., 2003; Dickinson and Gehrels, 2003, 2008a, 2008b, 2009). Transcontinental sediment accumulated

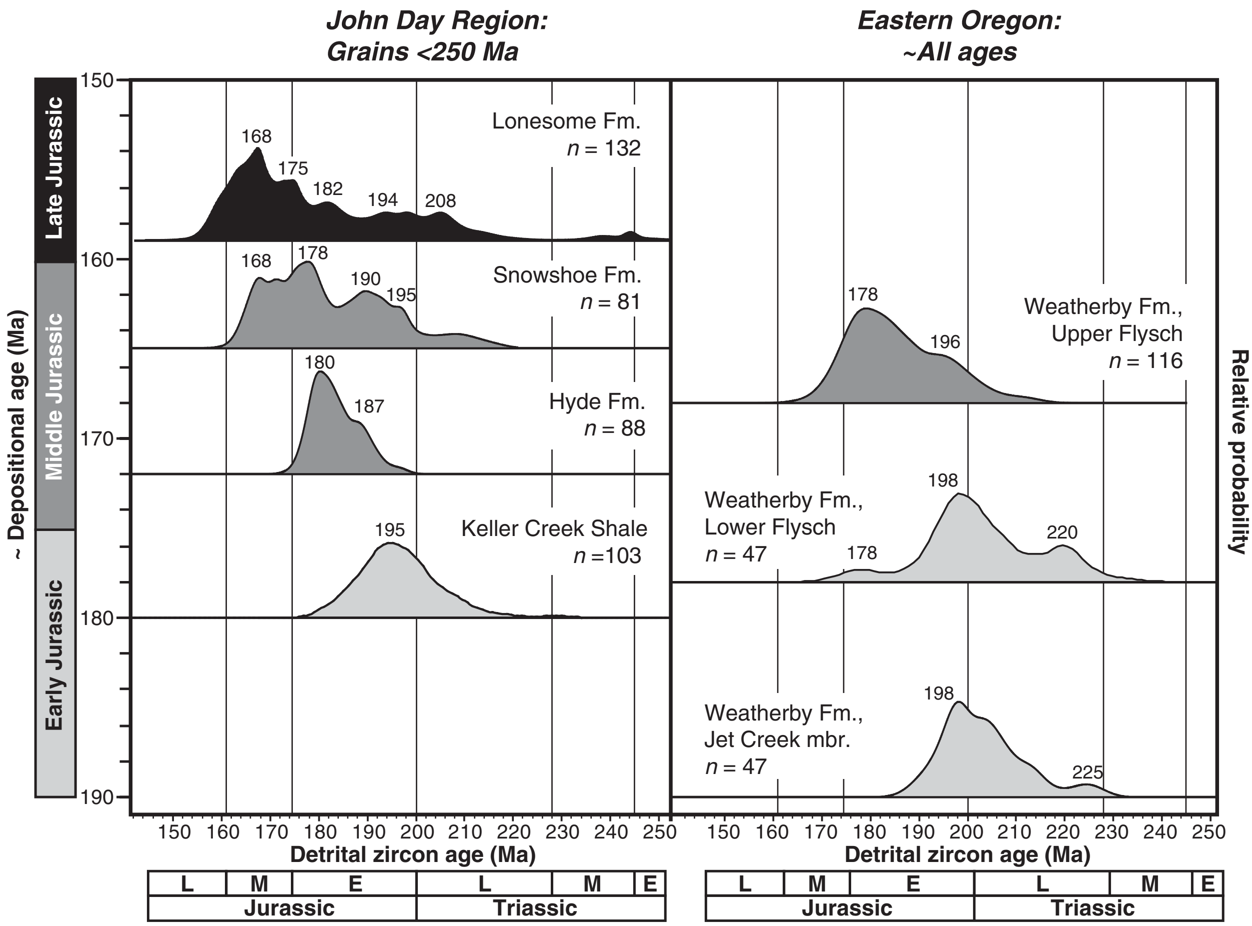

Figure 11. Relative probability plots for Mesozoic samples from the John Day and Huntington, Oregon, areas. Samples are plotted with detrital zircon ages for a given sample location (John Day region vs. Eastern Oregon area) on the *x*-axis and approximate depositional age on the *y*-axis. Vertical ruled lines are major divisions of the early Mesozoic time scale.

in the Triassic backarc basin in Nevada and provided the source for widespread Jurassic ergs of the Colorado Plateau. Jurassic erg sand was, in turn, supplied to the northward-deepening Cordilleran arc system (Busby-Spera, 1988; Saleeby and Busby-Spera, 1992; Riggs et al., 1996; Manuzak et al., 2000; Busby et al., 2002, 2005; Schermer et al., 2002; Dickinson and Gehrels, 2003, 2008a, 2009; Barth et al., 2004; Leggett et al., 2004).

Robust data sets for detrital zircon ages of transcontinental sand are available for Triassic fluvial sandstones of the Colorado Plateau, which were ultimately deposited in the backarc basin of Nevada (recycled backarc-basin source; Dickinson and Gehrels, 2008a), and for Jurassic erg deposits of the southwest Cordillera (Dickinson and Gehrels, 2003, 2009). These data provide a compelling comparison to coeval Jurassic deposits of the Blue Mountains Province (Fig. 13). Each of these data sets includes notable probability peaks in the range of ca. 485–295 Ma (Appalachian Paleozoic intrusions) and at ca. 635–615 Ma (peri-Gondwanan terranes and pre-Iapetan rift belts). Grenville age peaks at ca. 1.15 and 1.04 Ga in Blue Mountains samples are strikingly similar to grains in the age range of ca. 1.15 and 1.03 Ga in Triassic backarc basin sands and with age peaks from Jurassic erg samples at ca. 1.16 and 1.05 Ga. We note that Grenville-age detrital zircon signatures from Mexican and Gondwanan sources farther to the south include a distinctly younger age peak (ca. 994–981 Ma; Gillis et al., 2005, and sources therein; Eriksson et al., 2003; Tassinari et al., 2000), likely precluding derivation of Blue Mountains Province sands from those regions. Finally, Blue Mountains, recycled backarc basin, Jurassic erg, and Cordilleran arc sands all contain notable enrichments in ca. 1.45–1.3 Ga intracratonic granite ages (also called "anorogenic" granites; cf. Anderson, 1983; Whitmeyer and Karlstrom, 2007) and ca. 1.8–1.6 Ga, southwestern U.S. (Yavapai-Mazatzal)–derived zircons (Fig. 13). Thus, we conclude that the age distribution of detrital zircon grains in Jurassic samples of the Blue Mountains Province reflects an Ouachita-Appalachian provenance enriched by southwestern U.S. and active early Mesozoic Cordilleran arc sources (cf. Dickinson and Gehrels, 2003, 2008a, 2009; Kimbrough et al., 2006).

Implications of Jurassic Detrital Zircon Sources

We consider two likely scenarios by which Early to Middle Jurassic detrital zircon grains and transcontinental sand were delivered to Jurassic basins of the Blue Mountains Province: (1) erosion of Jurassic orogenic highlands in western and central Nevada that contained sand originally deposited in an older, Triassic backarc basin (Fig. 13; recycled backarc-basin source), or (2) transport of reworked Jurassic erg sands along a northwestward-flowing arc-parallel, axial river system along the northwestward-deepening Cordilleran arc (Fig. 13; Jurassic

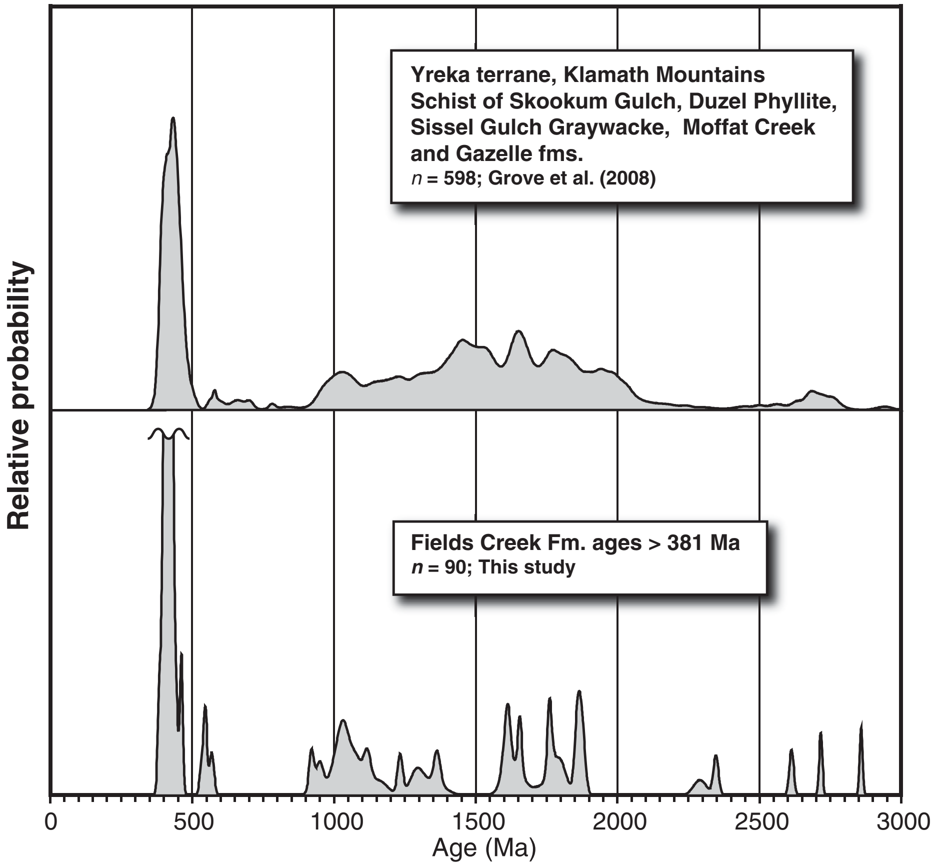

Figure 12. Comparison of detrital zircon age distributions among samples from the Yreka terrane, Klamath Mountains, and the Fields Creek Formation. Note large difference in sample size. Only ages older than 381 Ma are plotted (youngest grains in Yreka terrane). Note, ca. 420 Ma and 1.0–2.0 Ga ages occur in both distributions. Yreka samples contain an abundance of ca. 1.5 Ga ages not seen in Fields Creek Formation sample.

erg–type source *and* Cordilleran arc–type source). It is also possible that both sediment-dispersal pathways were active in Middle to early Late Jurassic time.

Detrital zircon age distributions representing both scenarios are strikingly similar to samples from the Blue Mountains Province (Fig. 13). Close comparison of these data sets, however, suggests that sandstones in the Blue Mountains Province *most closely* resemble recycled back-arc basin sands. Both suites include a distinctive age peak at ca. 550 Ma, contain a relatively high abundance of ca. 900–700 Ma grains, and lack significant enrichment in Archean grains. Thus, we favor the interpretation that Jurassic sand in the Blue Mountains Province was derived from eroding orogenic highlands in western Nevada (i.e., reworking of deposits from the former backarc basin). This conclusion is speculative because of the relatively small data set for Blue Mountains Province samples. Note that Dickinson and Gehrels (2008b) interpreted detrital zircon age-distributions in the Upper Jurassic Morisson Formation to represent recycling from Jurassic erg deposits that were uplifted during the nascent, Middle to Late Jurassic stages of Sevier thrust-belt deformation. Additional detrital zircon dating of samples from the Blue Mountains, from interstratified quartzose sands of the Cordilleran arc, and from backarc basin deposits in Nevada, is needed to further test and refine our preferred interpretation. Regardless of which sediment-dispersal pattern was dominant during early Mesozoic time, the new data presented here indicate that far-traveled, transcontinental sediment was delivered to marginal basins of the Blue Mountains and that these basins were proximal to the craton margin during deposition (i.e., Wyld and Wright, 2001; Dorsey and LaMaskin, 2007; LaMaskin et al., 2008a).

Olds Ferry–Black Rock Link

Wyld and Wright (2001) proposed that the Black Rock terrane of western Nevada and the Olds Ferry terrane of eastern Oregon are dismembered fragments of the same arc. This model predicts that Late Triassic through Middle Jurassic sedimentary rocks of the Blue Mountains were derived from volcanic centers in the Black Rock arc, a prediction that is supported by similarities in deformation history and provenance geochemistry between these regions (Wyld et al., 1996; LaMaskin et al., 2008a). If sediments of the upper Aldrich Mountains Group (Keller Creek Shale) were derived from the Olds Ferry–Black Rock arc, this would require initiation of uplift and erosion of the Luning-Fencemaker fold-and-thrust belt (former backarc basin) no later than ca. 181 Ma (LaMaskin, 2009; maximum depositional age of Keller Creek Shale). This is in agreement with constraints on the timing of initial deformation in the Luning-Fencemaker fold-and-thrust belt (ca. 190 Ma; Wyld, 2002; Wyld et al., 2003), the Black Rock arc in the Jackson Mountains and the Pine Forest Range (ca. 201–185; Wyld et al., 1996; Wyld et al., 2003, and references therein), and Late Triassic–Early Jurassic deformation in central Oregon (ca. 215–190; Dickinson and Thayer, 1978). The presence of abundant Early Jurassic detrital zircon grains in Jurassic turbidites of the Blue Mountains Province, and apparent similarities between Blue Mountains Province sands and recycled backarc basin sands provide additional support for a direct linkage between the Olds Ferry and Black Rock arcs.

Implications for Recycling of Detrital Zircon Grains

Our analysis shows that the detrital zircon age distribution in a sandstone sample may reflect a wide variety of tectonic and sedimentary recycling scenarios. Recycling of zircon grains is likely to be the rule rather than the exception, suggesting that caution must be exercised when interpreting detrital zircon U-Pb age data. In particular, the presence of abundant Precambrian detrital zircon grains in sediment derived from an offshore accretionary subduction complex highlights the importance of sediment reworking in detrital zircon studies (cf. Dickinson and Gehrels, 2008b); the presence of Precambrian detrital zircon grains does not necessarily mean that deposition occurred in proximity to a continental margin. In addition, progressive homogenization of detrital age suites as a result of sedimentary and tectonic recycling means that different potential sediment source areas may possess only slight differences in detrital age spectra (e.g., recycled backarc basin versus Jurassic erg/Cordilleran–arc source; Fig. 13). We therefore suggest that in certain scenarios, a large number of single-grain analyses per sample (i.e., >>100) may be needed to adequately evaluate the presence or absence of diagnostic ages and draw conclusive results.

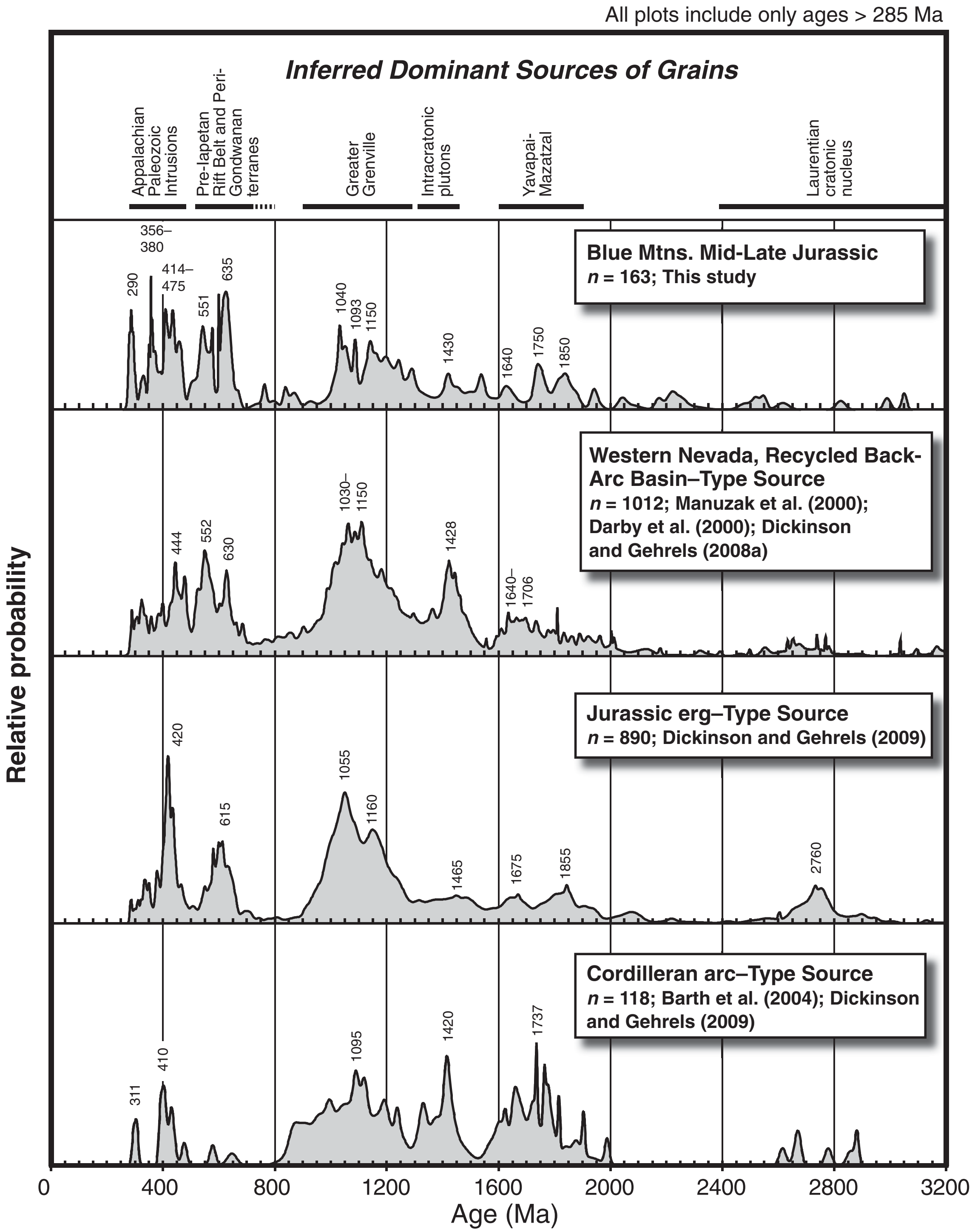

Figure 13. Comparison of detrital zircon age distributions in Middle to early Late Jurassic samples from the Blue Mountains (Snowshoe and Lonesome formations) and potential source areas representing recycled backarc-basin transcontinental sand from western Nevada, transcontinental sand from the Jurassic ergs of the Colorado Plateau, and interstratified quartzose sands of Cordilleran arc. For clarity, only ages older than 285 Ma are plotted (cf. Dickinson and Gehrels, 2009). Inferred dominant sources of grains have been modified from Dickinson and Gehrels (2003, 2009) and Whitmeyer and Karlstrom (2007). Data for western Nevada, recycled backarc-basin–type rocks, are published data from Triassic and older assemblages of western Nevada (Luning and Lovelock assemblages—Manuzak et al., 2000; Pass Creek unit and Bishop Canyon Formation—Darby et al., 2000), and from sediment known to have been delivered to the backarc basin during Late Triassic time (Dickinson and Gehrels, 2008, data from their fig. 13). Data for Jurassic Erg–type source are from Dickinson and Gehrels (2009, data from their fig. 7). Data for Cordilleran arc–type source are from Barth et al. (2004; McCoy Mountains Formation, Jurassic samples MC7 and MC9 only) and from Dickinson and Gehrels (2009; Mount Wrightson Formation, sample CP2).

Sediment-Dispersal and Tectonic Models

Prevailing models for the western U.S. Cordillera suggest that the early Mesozoic arc system was partitioned into a southern continental arc and a northern oceanic arc, with the transition located approximately at the latitude of the Northern Sierra Nevada (Sharp, 1988; Wright and Fahan, 1988; Oldow et al., 1989; Burchfiel et al., 1992; Cowan and Bruhn, 1992; Wyld and Wright, 2001; Gray and Oldow, 2005). Mudrock geochemistry (LaMaskin et al., 2008a) together with the detrital zircon data presented here support previous suggestions that the Olds Ferry–Black Rock arc is a northward continuation of continent-fringing arc systems of the northernmost Sierra Nevada and Klamath Mountains terranes. Next, we propose two analogs for the early Mesozoic western U.S. Cordillera: the Kamchatka-Kuril and Molucca Sea regions for Middle and Late Triassic time (Fig. 14), and Papua New Guinea region for Jurassic time (Fig. 15).

Middle to Late Triassic

The Kamchatka-Kuril arc region of the northwest Pacific provides a useful modern analog for the Middle Triassic tectonic setting of the southwestern United States (Figs. 14A and 14B). Both regions are (were) characterized by a continent-fringing volcanic arc built on inherited basement of accreted terranes, with continental lithosphere that passes along strike to an active offshore arc located outboard of an extensional backarc basin (Figs. 14A and 14B; Geist et al., 1994; Bindeman et al., 2002; Schellart et al., 2003; and references therein). Although the location of the Wallowa terrane during this time interval is uncertain, mudrock geochemistry and detrital zircon geochronology suggest that it was an offshore, intra-oceanic arc (LaMaskin et al., 2008a, 2008b).

Dorsey and LaMaskin (2007, 2008) suggested that the Blue Mountains region underwent a Molucca Sea–type arc-arc collision during Late Triassic time (Figs. 14C and 14D). Detrital zircon and petrographic data presented here support this model. The large volume of conglomeratic, chert-rich detritus preserved in synorogenic Late Triassic basins requires derivation from a rapidly eroding, topographically elevated, active thrust-belt source in the Baker terrane accretionary subduction complex. The combined data sets support a model for a complex Late Triassic collision zone between facing accretionary wedges of (1) the intra-oceanic Wallowa arc and (2) either the Olds Ferry–Black Rock arc or perhaps other arc-related crustal blocks within the Baker terrane (Fig. 14C; LaMaskin et al., 2008a; cf. Schwartz et al., 2010). Figure 14C illustrates the advance of a growing Baker terrane fold-and-thrust belt into the adjacent Olds Ferry–Black Rock forearc, associated reversal of thrust vergence, and Molucca Sea–style consumption of the intervening plate.

It is not clear at present how this Late Triassic–Early Jurassic (?) collision zone relates to known structures and more intensely deformed rocks to the south in the Klamath Mountains and Sierra Nevada. We do note, however, that Dickinson and Lawton (2001) and Dickinson (2006, 2008) suggested a similar double-subduction setting for southward-propagating, diachronous consumption of the Mezcalera plate beneath portions of the Klamath Mountains and Sierra Nevada, apparently from Early through Middle Jurassic time. It is possible that Late Triassic–Early Jurassic (?) deformation in the Blue Mountains Province represents an early phase in this long-lived period of plate consumption. Potential correlation of the outboard Wallowa terrane with outboard terranes of the Klamath Mountains and Sierra Nevada is problematic and beyond the scope of this paper. We propose, however, that rocks and structures in Blue Mountains province may provide insights into the history of the more intensely deformed Klamath-Sierran tectonostratigraphic belts during Late Triassic time (cf. Dickinson, 2008; Ernst et al., 2008).

Middle Jurassic

The tectonic setting of the western U.S. Cordilleran margin underwent a fundamental change in late Early to Middle Jurassic time (e.g., Wyld, 2002; Wyld et al., 2003). Based on previous stratigraphic synthesis (Dorsey and LaMaskin, 2007, 2008) and new petrographic and detrital zircon data presented here, we suggest that the Middle Jurassic Cordilleran margin could have resembled the late Cenozoic oblique collision of amalgamated arc terranes with the northern margin of Australia in Papua New Guinea (Figs. 15A and 15B; Cooper and Taylor, 1987; Pigram and Davies, 1987; Cloos et al., 2005). Despite some notable differences between the Papuan margin and the Jurassic western United States, both regions have amalgamated arc terranes that are (were) buttressed against a continental margin in a collisional setting, resulting in construction of a large orogenic thrust belt flanked by synorogenic sedimentary basins (Figs. 15A and 15B).

We suggest that Middle–Late Jurassic intra-arc extension in the Klamath Mountains (i.e., Rouge-Chetco arc and Josephine ophiolite) changed along strike to compressional deformation in the Blue Mountains and western Nevada. Rouge-Chetco subduction along the western margin of the Klamath belts may have permitted plate convergence to continue following closure of the former backarc region to the east and north (cf. Backarc Geodynamics *in* Dickinson, 2006). Modern settings such as Papua New Guinea display large variability in tectonic style along strike of the active plate margin (Fig. 15B; Cloos et al., 2005). Thus, seemingly disparate tectonic histories in Oregon, Nevada, and California may be manifestations of complex microplate interactions that are characteristic of an evolving convergent collisional margin.

We also note strikingly similar detrital zircon age distributions in Jurassic turbidites of numerous Cordilleran terranes, including the Mariposa Formation (Sierra Nevada Foothills), rocks of the North Fork terrane (Klamath Mountains), the basal Great Valley Group (California Coast Ranges), the Galice Formation (Klamath Mountains), and metagraywackes of the Western Cascades (Washington State) (Surpless et al., 2006; MacDonald, 2006; Izsak et al., 2007; Snow and Ernst, 2008; Scherer and Ernst, 2008). These

Figure 14 (*on following page*). Proposed tectonic models for central western North America during Middle and Late Triassic time. Palinspastic base in A and C is modified from Wyld et al. (2006). Rocks of the Blue Mountain Province have been restored ~400 km to the south. OF—Olds Ferry; BR—Black Rock; KM—Klamath Mountains; SN—Sierra Nevada; CA—Cordilleran arc; NAM—North American; H—Huntington; IZ—Izee; WA—Wallowa; BT—Baker terrane. (A) Middle Triassic time. (B) Proposed modern analog of the Kamchatka-Kuril arc region modified from Schellart et al. (2003). Note north arrow. The Kuril backarc basin has rifted from the accreted lithosphere of the Okhotsk microplate. (C) Late Triassic time. Sediment deposited in the John Day region is derived from the outboard Baker terrane accretionary subduction complex. Sediment deposited in the backarc basin is derived from rivers draining the southwestern United States and the Appalachian chain far to the east (i.e., Riggs et al., 1993; Dickinson and Gehrels, 2008). (D) Proposed modern analog of the Molucca Sea region modified from Macpherson and Hall (1999, 2002). The Molucca Sea plate is being subducted to the east and west beneath the Halmahera (HA) and Sangihe (SA) arcs, which form the margins of an orthogonal arc-arc collision. Modern analog does not apply for regions to the south of the Molucca Sea collision.

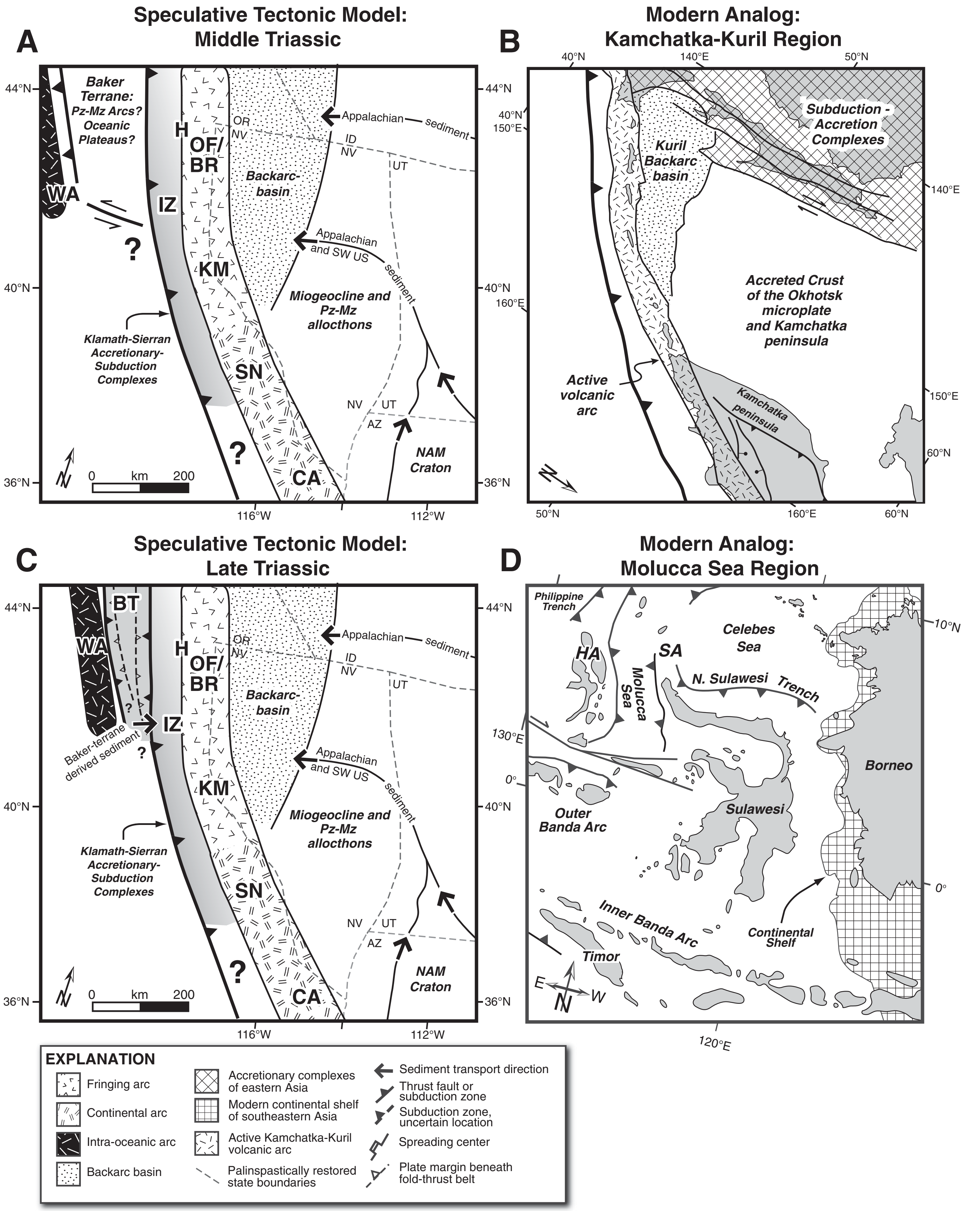
A
Speculative Tectonic Model: Middle Triassic
B
Modern Analog: Kamchatka-Kuril Region
Baker Terrane: Pz-Mz Arcs? Oceanic Plateaus?
WA
H
OF/BR
IZ
KM
SN
CA
Backarc-basin
Appalachian sediment
Appalachian and SW US sediment
Miogeocline and Pz-Mz allocthons
Klamath-Sierran Accretionary-Subduction Complexes
NAM Craton
OR
NV
ID
UT
AZ
44°N
40°N
36°N
116°W
112°W
0 km 200
Subduction - Accretion Complexes
Kuril Backarc basin
Accreted Crust of the Okhotsk microplate and Kamchatka peninsula
Active volcanic arc
Kamchatka peninsula
40°N
140°E
50°N
150°E
160°E
60°N
C
Speculative Tectonic Model: Late Triassic
D
Modern Analog: Molucca Sea Region
BT
Baker-terrane derived sediment
Philippine Trench
HA
SA
Molucca Sea
Celebes Sea
N. Sulawesi Trench
Borneo
Sulawesi
Outer Banda Arc
Inner Banda Arc
Timor
Continental Shelf
10°N
0°
130°E
120°E
E
W
N
EXPLANATION
Fringing arc
Continental arc
Intra-oceanic arc
Backarc basin
Accretionary complexes of eastern Asia
Modern continental shelf of southeastern Asia
Active Kamchatka-Kuril volcanic arc
Palinspastically restored state boundaries
Sediment transport direction
Thrust fault or subduction zone
Subduction zone, uncertain location
Spreading center
Plate margin beneath fold-thrust belt

Figure 14.

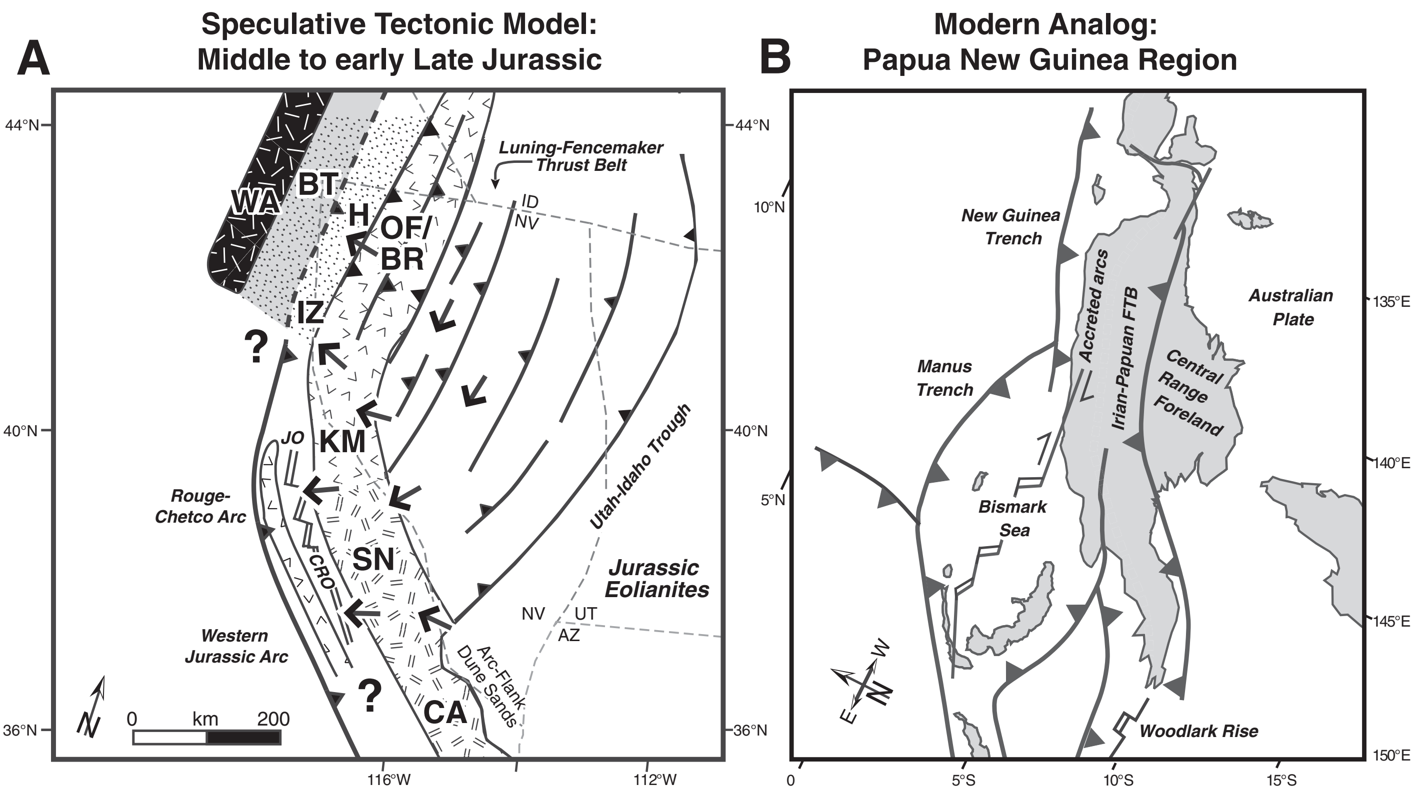

Figure 15. Proposed tectonic models for central western North America during Middle to early Late Jurassic time. See Figure 14 for explanation of symbols and abbreviations used. Palinspastic base in A is modified from Wyld et al. (2006). Rocks of the Blue Mountain Province have been restored ~400 km to the south. (A) Middle to early Late Jurassic time. Sediment deposited in the John Day region is derived from (1) tectonic closure, uplift, and erosion of the Triassic backarc basin and formation of the Luning-Fencemaker fold-and-thrust belt, and/or (2) mixed arc and erg dune sands. Similar sediment is deposited in the intra-arc Josephine–Galice (JO) and Coast Range–Basal Great Valley basins (CRO). (B) Proposed modern analog of the Papua New Guinea region modified from Cloos et al. (2005). Note north arrow and flipped E-W arrows. Accretion of the Melanesian arcs has resulted in formation of the Irian-Papuan fold-and-thrust belt (FTB) and deposition in the Central Range foreland. Concomitant transtension is occurring in the Bismark Sea region.

similarities suggest that during Jurassic time (1) transcontinental and recycled sediment-dispersal pathways were widespread, (2) transcontinental sediment was commonly delivered to the Cordilleran arc and forearc region, (3) active orogenic structures and the Mesozoic arc itself were not significant barriers to sediment dispersal from the craton to the forearc region, and therefore (4) many Jurassic basins of the Cordillera were pericratonic and are not far traveled (i.e., >1000 km) with respect to southwestern North America.

SUMMARY AND CONCLUSIONS

Detrital zircon data from central and eastern Oregon confirm the presence of compositionally distinct sediment source areas that changed from Late Triassic to Late Jurassic time. Upper Triassic sediments were derived from the adjacent, outboard Baker terrane and contain two suites of detrital zircon ages: (1) Archean, Paleoproterozoic, Devonian–Mississippian, and Pennsylvanian ages in the Vester Formation, and (2) dominantly Mesoproterozoic, Silurian–Devonian, and Permian zircons in the Fields Creek Formation. Similarities in detrital zircon age distributions suggest a genetic link between the Baker terrane source and rocks of the Eastern Klamath and the Northern Sierra terranes, either as an analogous crustal block or via sediment transport and recycling.

Jurassic sandstones contain abundant Mesoproterozoic, Neoproterozoic, Paleozoic, and Early to Middle Jurassic detrital zircon grains. In the John Day region, detrital zircon age distributions in Jurassic sediments closely resemble those of transcontinental sand that was delivered to the western U.S. Cordillera during Triassic and Jurassic time. We infer that sediment was delivered to Jurassic basins of the Blue Mountains Province by transport of transcontinental sand via either (1) a river system that flowed north along the axis of the Cordilleran arc, or (2) by erosion and recycling of Triassic backarc basin deposits from collisional orogenic highlands in western and central Nevada (Luning-Fencemaker fold-and-thrust system). Our data support the latter hypothesis, but both are plausible.

Two end members of detrital zircon age distributions recognized elsewhere in Cordilleran basins are represented in the Blue Mountains Province in (1) Triassic samples with abundant Archean, Paleoproterozoic, and Paleozoic zircons (i.e., "northwestern Laurentian"), and (2) Jurassic samples enriched in Paleoproterozoic, Mesoproterozoic, and Neoproterozoic zircons, as well as, Paleozoic and approximately syndepositional Jurassic zircons (i.e., "eastern-southwestern Laurentian"). We suggest that here, and in other early Mesozoic Cordilleran basins, the strong northwestern Laurentian signature may have been recycled from mobile, tectonically translated crustal fragments of subduction-accretionary origin, whereas the eastern-southwestern Laurentian transcontinental sand signatures may represent an in situ cratonal-recycled provenance.

We propose that the Kamchatka-Kuril and Molucca Sea regions are modern analogs for the western U.S. Cordillera during Middle and Late Triassic time, respectively, and that terrane-continent collision in the Papua New Guinea region is a modern analog for the western U.S. Cordillera in Jurassic time. Apparent differences between the tectonic setting of accreted terranes in Oregon, Nevada, and California during Middle and Late Jurassic time may be typical aspects of an evolving convergent margin.

ACKNOWLEDGMENTS

This study was supported by funds from the National Science Foundation to Dorsey (EAR-0537691) and Vervoort (EAR-0537913), and grants from the Geological Society of America, the American Association of Petroleum Geologists, SEPM, Sigma Xi, and the University of Oregon to LaMaskin. We thank Daniel Norfleet, Todd Sieber, Leland O'Driscoll, and Andy Lutz for assistance in the field, Charles Knaack and Garret Hart for support with U-Pb laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) analyses, and Diane Wilford and John Donovan for assistance with sample preparation. Paul Wallace generously provided materials and space for sample preparation, and Bill Dickinson miraculously supplied his original thin sections from the John Day region. Marty Grove supplied data from the Yreka area. Discussions with Bill Dickinson, Arthur Snoke, Mark Ferns, Leland O'Driscoll, John Oldow, Tom Peryam, and Sandra Wyld are all appreciated. We specifically extend our gratitude to Ken Ludwig and George Gehrels for making their data analysis and plotting programs freely available and for providing user support. An earlier version of the manuscript benefited from reviews by Tracy Vallier, Ilya Bindeman, and Greg Retallack. *GSA Bulletin* reviewers Joshua Schwartz, Gary Ernst, and an anonymous reviewer provided comments that greatly improved the paper. We thank *GSA Bulletin* Editor Nancy Riggs and Associate Editor Quentin Crowley for their assistance and comments.

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Science Editor: Nancy Riggs
Associate Editor: Quentin Crowley

Manuscript Received 29 January 2010
Revised Manuscript Received 29 September 2010
Manuscript Accepted 29 October 2010

Printed in the USA